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A simulation-based study to evaluate the cooling potential of nocturnal radiative cooling systems for residential buildings in Egypt

Nermeen Abdelnour [a,b,*], Reiner Braun [c,d], Herena Torio [b], Ursula Eicker [d]

[a] Center of Applied Research Sustainable Energy Technologies (zafh.net), University of Applied Sciences (HFT-Stuttgart), Schellingstraße 24, 70174 Stuttgart, Germany
[b] Postgraduate Programme Renewable Energy (PPRE), University of Oldenburg, Carl-von-Ossietzky-Str. 9-11, 26129 Oldenburg, Germany
[c] Reutlingen University, Herman Hollerith Zentrum (HHZ), Danziger Str. 6, 71034 Böblingen, Germany
[d] Dept. of Building, Civil and Environmental Engineering, Concordia University, 1455 Maisonneuve W. Montreal, QC H3G 1M8, Canada

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ABSTRACT

During the first years of the last decade, Egypt used to face recurrent electricity cut-offs in summer. In the past few years, the electricity tariff dramatically increased. Radiative cooling to the clear night sky is a renewable energy source that represents a relative solution. The dry desert climate promotes nocturnal radiative cooling applications. This study investigates the potential of nocturnal radiative cooling systems (RCSs) to reduce the energy consumption of the residential building sector in Egypt. The system technology proposed in this work is based on uncovered solar thermal collectors integrated into the building hydronic system. By implementing different control strategies, the same system could be used for both cooling and heating applications. The goal of this paper is to analyze the performance of RCSs in residential buildings in Egypt. The dynamic simulation program TRNSYS was used to simulate the thermal behavior of the system. The relevant issues of Egypt as a case-study are firstly overviewed. Then the paper introduces the work done to develop a building model that represents a typical residential apartment in Egypt. Typical occupancy profiles were developed to define the internal thermal gains. The adopted control strategy to optimize the system operation is presented as well. To fully understand and hence evaluate the operation of the proposed RCS, four simulation cases were considered: 1. a reference case (fully passive), 2. the stand-alone operation of the RCS, 3. ideal heating & cooling operation (fully-active), and 4. the hybrid-operation (when the active cooling system is supported by the proposed RCS). The analysis considered the main three distinct climates in Egypt, represented by the cities of Alexandria, Cairo and Asyut. The hotter and drier weather conditions resulted in a higher cooling potential and larger temperature differences. The simulated cooling power in Asyut was 28.4 W/m^2 for a 70 m^2 absorber field. For a smaller field area of 10 m^2, the cooling power reached 109 W/m^2 but with humble temperature differences. To meet the rigorous thermal comfort conditions, the proposed sensible RCS cannot fully replace conventional air-conditioning units, especially in humid areas like Alexandria. When working in a hybrid system, a 10% reduction in the active cooling energy demand could be achieved in Asyut to keep the cooling set-point at 24 °C. This percentage reduction was nearly doubled when the thermal comfort set-point was increased by two degrees (26 °C). In a sensitivity analysis, external shading devices as a passive measure as well as the implementation of the Egyptian code for buildings (ECP306/1–2005) were also investigated. The analysis of this study raised other relevant aspects to discuss, e.g. system-sizing, environmental effects, limitations and recommendations.

1. Introduction

Between 2011 and 2014 Egypt faced frequent energy shortage, mainly in summer. The national electricity consumption is dominated by the residential building sector [1,2]. In 2014, the national electricity tariff restructuring plan (ETRP) came into force. The five-year plan aimed at gradually phasing-out the subsidy and hence promoting the concepts of energy efficiency and rational consumption in the Egyptian society. An annual increase of the electricity tariff has been varyingly applied to the seven customer-categories of the residential sector since then, taking the standard of living into account to protect poor families

* Corresponding author.
E-mail addresses: nermeen.abdelnour@hft-stuttgart.de (N. Abdelnour), reiner.braun@reutlingen-university.de (R. Braun), herena.torio@uni-oldenburg.de (H. Torio), ursula.eicker@concordia.ca (U. Eicker).

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Nomenclature

F	factor (of muscular activity level in rooms)
$Light$	lighting thermal gains [W]
$\dot{m}$	mass flow rate [kg/hr]
OCC	occupancy thermal gains [W]
Q	thermal energy [J]
$\dot{Q}$	thermal power [W]
$\dot{Q}_N$	specific thermal power [W/m^2]
T_a	ambient air (absolute) temperature [K]
T_{amb}	ambient air temperature [°C]
T_{in}	(absorber) fluid inlet temperature [°C]
T_m	mean (absorber) temperature [°C]
T_{OP}	operative room air temperature [°C]
T_{out}	(absorber) fluid outlet temperature [°C]
T_{sky}	sky (absolute) temperature [K]
ΔT_{OP}	operative (room) temperature difference [°C]

Acronyms

AC	air-conditioning
DHW	domestic hot water
ETRP	electricity tariff restructuring plan
FY	fiscal year
HTF	heat transfer fluid
PVT	photo-voltaic thermal
RCS	radiative cooling system
RE	renewable energy
RH	relative humidity
SAC	solar assisted cooling
SC	shading coefficient (of glass)
SH	space heating
SHGC	solar heat gain coefficient (equals to the g-value)
STC	solar thermal collector
TABS	thermally activated building systems
U-value	thermal transmittance (W/m^2.K)
WWR	window-to-wall ratio

Subscripts

Avg	average
CC	chilled-ceiling
Ch.BR	children bedroom
Coll	collector
LR	living room
M.BR	master bedroom
P	person

Greek Letters

α	absorptance [-]
ε	emittance [-]

[1]. Alternative unconventional energy sources are therefore worthy to be investigated for the Egyptian case.

Nocturnal radiative cooling to the clear night sky is a passive, clean and renewable cooling method that utilizes the cold sky as a heat sink during summer nights [3]. The potential of nocturnal radiative cooling depends to a great extent on the local climate conditions [4,5]. The location of Egypt enjoys favorable climatic conditions that are expected to result in promising outcomes for radiative cooling applications [4–6]. The three cities: Alexandria, Cairo, and Asyut well represent the diverse Egyptian climate. Radiative cooling panels are similar to flat plate solar collectors [7]. With a modified control strategy, the same system can be used during winter days for heating applications as well.

The building construction plays an important role in the indoors thermal conditions and hence in the effectiveness of any implemented cooling technology [8]. Unfortunately, the existing built environment in Egypt is characterized by poorly constructed residential blocks [9,10]. The enforcement of the Egyptian code for energy efficiency in buildings (ECP306/1–2005) is likely to affect how the proposed radiative cooling system (RCS) functions. On the other hand, the authors think that the common definition of the set-points of air-conditioning units (AC-units) for the indoors thermal comfort is too rigorous. A more flexible set-point temperature during the cooling season (e.g. 26 °C instead of 24 °C), and also the usage of external shading, are foreseen as acceptable simple and potential measures to tackle the high cooling demand of the residential sector in Egypt.

For the Egyptian case, some relevant studies were conducted. However, on one hand the interlink between the three topics (electricity market, the technology of RCSs and building codes) has been missing. On the other hand, the technology tackled in previous research was mainly about solar cooling to eventually operate thermally-driven cooling machines. Moreover, the analysis adopted in those researches usually considered only one climate of Egypt [11,12]. For example, in [12] the practical feasibility of an adsorption chiller was studied in a demonstration project in Asyut. While the idea of an integrated desiccant/enhanced nocturnal radiative cooling-solar regenerated system was addressed in [11], where a mathematical model was developed for analyzing the heat and mass transfer in the system. The model was verified using data also for Asyut. In [9,13-15] a number of different energy and building models were studied. But only in [13] the issue of occupancy profiles was soundly addressed, considering a case-study in Cairo. That study highlighted the lack of accurate occupancy behavior and the interaction with the building model over the different seasons.

The aim of this paper is to investigate the feasibility of RCSs in the residential buildings in Egypt, as a simple technology and as a potential renewable energy (RE) alternative (or supplementary) for both cooling and heating purposes. The local electricity market is explored over the past fifteen years (from 2005/2006 till 2019/2020) using statistical data as officially published by the Egyptian electricity holding company (EEHC). The data was thoroughly analyzed to provide a comprehensive review about the energy situation in Egypt. This study is simulation-based, where the dynamic simulation program TRNSYS was used to simulate the whole system. The diversified climates of Egypt were considered for the analysis. In a companion paper [16], the parameters of four uncovered plastic solar absorbers were identified using an outdoor test-stand for dynamic testing and then using GenOpt for mathematical optimization. The coefficients of the absorber that showed the best thermal performance (mainly for cooling applications) are directly used in this paper to configure the solar thermal collector (STC) component in the TRNSYS model. To develop the simulation model, the focus was on the thermal modeling of a typical residential apartment in Egypt, with a closer look on the building design as well as the consumption patterns, so that the building model is well representing the existing conditions of residential buildings in Egypt. Due attention was paid in this study to generate detailed occupancy profiles, yet customized for other simulation conditions. Internal thermal gains were accordingly defined in TRNBuild, so that the building model (Type56) represents the total thermal load on the cooling power provided from the proposed RCS. Good simulation models offer the possibility to assess different operation scenarios, e.g. effect of set-points, applying different control strategies, using shading devices, implementing various building construction, and considering multiple locations of different weather conditions. Hence, they can be used for system optimization as well. The next level to mathematical modeling is validation using measurement data from real physical models (prototypes/demos). A verified simulation model for any RE-technology-based system helps in predicting the annual yield and hence evaluating the system feasibility. Although the developed simulation model in this study is not validated itself by measurements, the two main components of the system (absorber and building), which influence the dynamic behavior of the system, are separately validated in previous work [16,17].

In this work, a number of simulation cases were considered to answer the following research questions: Can RCSs replace the conventional AC-units, which are vastly used in the residential buildings in Egypt? If only partially, how much is their contribution in reducing the cooling and heating demands? Does improving the existing characteristics of buildings help (e.g. implementing better shading)? To what extent would the Egyptian building code improve the operation of the proposed system?

2. Literature review

This section reviews the main relevant characteristics and statistics of Egypt as a potential case-study where RCSs could be used.

2.1. Energy situation in Egypt

In 2011, a power blackout problem started to be obviously noticed countrywide. The most affected sector was residential buildings [2,9]. Until 2014/2015, most of the Egyptian households suffered power-outage in a systematic manner, especially in summer when demand from AC-units exceeded the generation. When tracing the peak load in the national statistics reports over the past fifteen years (Fig. 1), the highest annual increase rate of the peak load reached 9.5% in 2011/2012 in summer [1].

The residential building sector has the highest share of the national electricity consumption (*sold at the medium & low voltage levels). As an average of all available reported data (s. Appendix), the annual share of residential electricity consumption represents 51% (Fig. A.1). According to the statistics reports of the Egyptian electricity holding company (EEHC), the average of the annual growth rate of the electricity sold for residential purposes was 7.7% over the period from 2009/2010 till 2015/2016 (Fig. A.2). Since 2017 the electricity consumption (and production as well) has started to behave differently. There is also missing data impeding concluding a trend for that period, but obviously consumption stopped surpassing production. This might be due to the significant expansion in the installed capacity for electricity generation nation-wide that took place during 2017 and 2018 (Figs. A.3 and A.4). According to latest published report from the EEHC (2019/2020), the installed capacity started to stabilize in 2020 with only 2% annual growth rate, compared to the remarkable average annual growth rate of 14.7% over the prior three years (Fig. A.4). This is the lowest annual growth rate in the installed capacity over the previous ten years. From 2009/2010 till 2015/2016, the average annual growth rate was 7.5% [1].

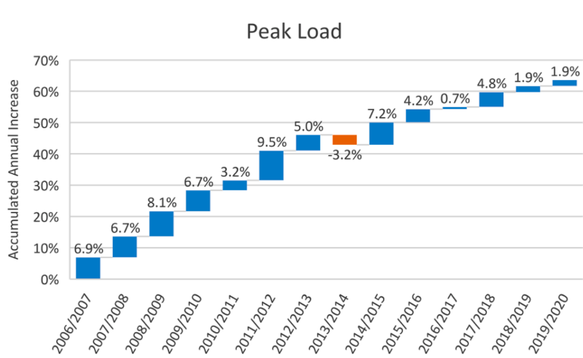

Fig. 1. The growth rate of the electricity peak load in Egypt (the annual growth rate indicated on top of each bar - the y-axis indicates the accumulated growth rate) [1].

The expansion of power generation plants was one of the national development goals of electricity companies. To help achieving this goal, the power sector considered (among other measures) reforming the electricity tariff structure and prices. In Egypt, tariff varies according to the type of consumption (industrial, residential, commercial, agriculture, street lighting, etc.). The tariff structure applied to the residential sector is based on six ascending blocks[1]. The higher the consumption the higher the tariff. Over ten years (from 1994 to 2003), the electricity tariff didn't change for the consumers of the residential sector. Only slight increases have been applied to some consumption blocks during the period 2004–2012. The highly-subsidized electricity tariff contributed to the unwise ever-increasing energy consumption, especially in the residential sector. Additionally, the invariable tariff applied for a long time resulted in a distortion of the tariff structure, a lower performance of economic and financial indicators, and a deficit in the cash flow of electricity companies. To face this situation and to align with a couple of national initiatives to save and rationalize energy consumption, a noticeable increase in the electricity tariff was first applied in 2013. However, this unusual increase on the residential sector (of total average of 20.7%) considered social justice. The percentage increase varied according to the six consumption blocks in an ascending pattern from 0% (for the first consumption block which corresponds to the low-income families) to 40%. In 2014, the electricity tariff restructuring plan (ETRP) came into force. The five-year plan aimed at a gradual phase out of the subsidy by gradually increasing electricity tariff annually as depicted in Fig. 2. By the end of the ETRP (FY 2018/2019), the Electricity Utility and Consumer Protection Regulatory Agency (Egypt-ERA) was assigned with reviewing the electricity selling prices of the 5th year, and developing a proposal for adjusting prices that achieves balance between the interest of the electricity companies and maintaining their continuity in providing the service entrusted to them, taking into account low-income population and gradation in electricity selling prices to different segments of consumers according to amount of consumption. The adjustment was approved in 2019 which was reflected on the electricity selling tariff for FY 2019/2020 (6th year of ETRP) with tendency to significantly reduce the annual increase. In 2020, a decision was issued by Egypt-ERA approving the electricity selling tariff for the coming five years as from 2020/2021 [1].

Conventional AC-units for cooling are responsible for the significantly high energy consumption in residential buildings in Egypt [7,9]. Global warming has resulted in longer and hotter summers in the region of the sun-belt countries, like Egypt. In addition, continual urbanization leads to a heat-island effect, in which heat losses from high concentrations of electrical equipment and lighting, from heavy traffic and from the thermal mass in built-up areas, increase ambient temperatures in a city [18]. Moreover, the relative economic growth and improved standard of living in the Egyptian society by the beginning of the millennium promoted the demand for more rigorous comfort requirements [1,9,18]. And generally, there is a continuous population growth paired with urbanization and expansion of new communities [1,9]. All these factors resulted in an immensely increased cooling demand. On the other hand, in winters, electric water heating can account for large shares of electricity demand, even in warm-climate countries [9,18].

2.2. Radiative cooling systems

The RCS proposed in this project is a RE-based system which is foreseen to reduce the electricity consumption for cooling in the residential sector. RCSs are similar to solar thermal systems where uncovered flat plate STCs (i.e. only the absorber-plate) are viewed as radiative cooling panels. When such systems are operated during summer nights,

[1] A slightly different categorization strategy was introduced in 2014. However, the analysis in this work simplified the expanded blocks back to only 6-segments for consistent calculation over the study-period.

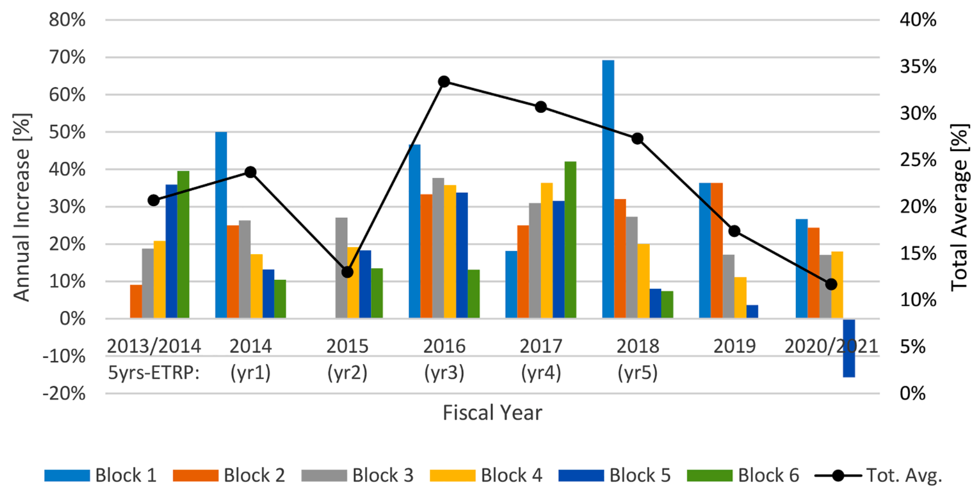

Fig. 2. The annual increase rate in electricity tariff for the different blocks of residential consumers [1]. The annual average increase rate of the six blocks is indicated on the right y-axis.

the temperature of the absorber-plate (facing the sky) can be lowered and consequently the temperature of the heat transfer fluid (HTF) used in the cooling system, thanks to the radiative heat loss from the absorber-plate to the cold night sky (in this mode it operates as a "radiator" surface rather than an "absorber"). RCSs hence represent a promising alternative (or supplementary) to the conventional cooling systems (AC-units) that are widely used in Egypt. The technology of RCSs is based on the principle of heat loss through long-wave radiation to the cold night sky. More details about the phenomenon of nocturnal radiative cooling and about the technology are presented in a companion paper [16] which introduces the first part of this research project.

A synergy could be realized when using the same system for heating applications. By applying a different control strategy during the heating season, RCSs can still be operated in winter days, to provide both domestic hot water (DHW) and space heating (SH). Most residential buildings in Egypt do not have SH systems for the cold days in winter. Thereby, nocturnal RCSs can offer a simple and promising solution to reduce power capacity requirements all over the year, and hence reducing the electricity bills. A schematic diagram to show the basic idea of the system is presented in Section 3. Worthy to mention is that the newest researches about the topic of radiative cooling focus on daytime radiative cooling. This is due to recent advances in materials science and technology that optimize optical properties to maximally manipulate solar radiation [19–21]. The control of daytime radiative cooling systems is expected to be complex, should DHW be considered in summer. On the other hand, it has to be notable that such radiative cooling systems in general require pump(s) to operate. Hence, radiative cooling as a technology is not purely passive.

The sky temperature (T_{sky}) is a key factor that determines the potential of nocturnal radiative cooling [5,6]. This phenomenon is discussed in more detail in the companion paper of this project [16]. In a nutshell, the calculation of T_{sky} involves the ambient air temperature (T_a) and the relative humidity (RH) [22]. On the other hand, RCSs are also affected by convection, since the absorber-plate is directly exposed to the ambient air. But convection affects the cooling power output of the absorber, facing the night sky, by either heat losses (further assisting cooling effect) or unfortunately heat gains (a counteracting effect). This depends mainly on the local weather conditions (T_a and the wind speed, in particular) and the mean temperature of the absorber (T_m). The most favorable environmental conditions, for night-cooling applications, is a clear, dry atmosphere with no wind. The location of Egypt is expected to result in promising outcomes for radiative cooling applications [4–6].

2.3. *Egypt climate*

Lying between latitudes 22° and 32° N and having diverse terrain, Egypt has various climatic conditions. There are sophisticated classifications for the climate in Egypt as well as the very basic one. The housing and building national research center (HBRC) in Egypt, divides the country into eight climatic zones [23]. Taking the population of those zones into account, the simplest classification can still be considered, which divides Egypt into four main climate zones [24]. The Mediterranean climate dominates the area all over the north coast of Egypt, that overlooks the Mediterranean Sea till few kilometers to the south. This Mediterranean climate is characterized by a mild temperature profile throughout the year, a high relative humidity especially in winter, and the highest precipitation on the country level. The semi-desert climate continues as going to the south till latitude 28° N. This climate has a higher temperature in summer, and less precipitation in winter. The relative humidity is low in winter but increases in summer. On the other hand, the desert climate represents the highest temperatures in Egypt, especially on summer days (> 40 °C). This climate prevails the Egyptian land from 28° N till the southern borders with Sudan. In the desert climate, the relative humidity is low all over the year, and it is rarely to rain [24]. The fourth climate (the heights climate) is not considered in this work, as it represents the mountain areas, on the eastern coast of the Red Sea, which are not considerably inhabited.

The psychrometric chart shown in Fig. 3 illustrates the diversity in weather conditions (mainly in ambient temperature and humidity) between the three main Egyptian climates. The three central metropolitan cities: Alexandria, Cairo, and Asyut were selected in this study to represent those three climates, respectively. The main weather factors for the three Egyptian cities, which affect the night-cooling phenomenon, are enclosed in the Appendix.

2.4. *Residential buildings in Egypt*

Building design can help in decreasing the cooling loads and hence reducing the electricity peak load experienced in summer [8]. The construction industry in Egypt has been unfortunately suffering from low-standard building materials, poor thermal insulation, lack of awareness of the topic energy efficiency in buildings [9,10]. The traditional knowledge of appropriate environmental design and construction has been neglected in Egypt since the mid-20th century [9]. For example, passive design strategies such as shading, orientation, thermal mass, natural lighting and ventilation are usually no longer used. To

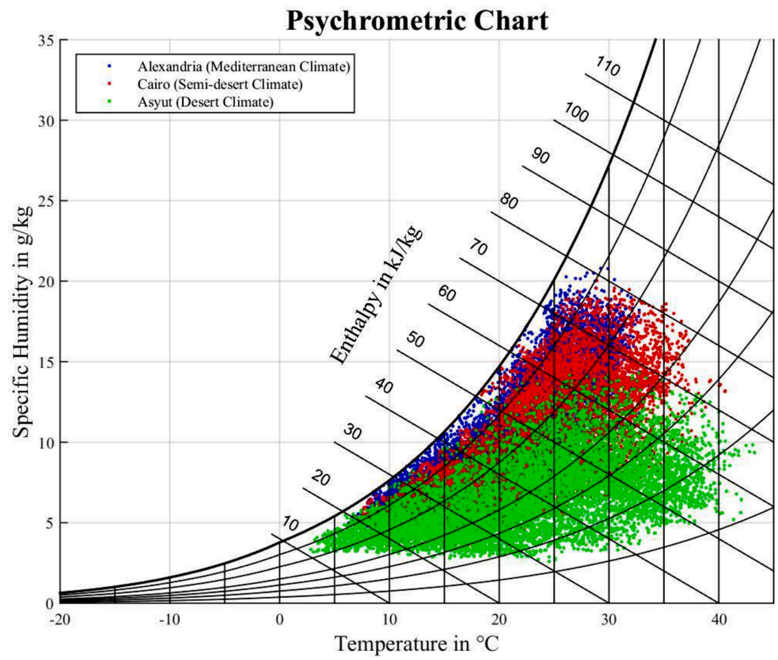

Fig. 3. Psychrometric chart for three Egyptian cities representing the main three climates of Egypt, [Data-Source: Meteonorm Weather Files].

improve the energy efficiency of buildings, an energy code had been developed for new residential and non-residential buildings in Egypt [25]. In 2004, the United Nations Development Programme (UNDP) granted the Egyptian Housing and Building Research center (HBRC) funding to develop energy standards for buildings [9,25]. In 2005, the Egyptian code to improve the efficiency of energy utilization in residential buildings (ECP306/1–2005) was completed and published [9, 26]. The code follows the ANSI/ASHRAE standard 90.2 Energy-Efficient Design of Low-Rise Residential Buildings in many aspects [10]. The regulations of the Egyptian code focus on aspects of heat loss through construction materials, and state the minimum required insulation levels [27,28]. The requirements of the Egyptian code for buildings vary by territory to better suit the different climates of the country. Moreover, there are two different requirements for each territory. Non-air-conditioned buildings require less thermal insulation than air-conditioned buildings. For the latter, the high thermal insulation helps in keeping the controlled indoor thermal conditions isolated from the harsh environment outdoors. This is not recommended for non-air-conditioned buildings in hot climates like Egypt, where the need for cooling is dominant. A well thermally insulating surface restrains heat dissipation to the exterior ambient. Without air-conditioning, this causes higher temperature profiles during night compared to the indoors of poorly insulated construction, and sometimes compared to the ambient temperature.

2.5. Thermal comfort

The purpose of the proposed RCS is to reduce the electrical energy demand while maintaining comfortable living environment. There are several thermal comfort standards concerning design regulations for indoor thermal comfort. The most well-known are the EN ISO 7730:2005 and the ASHRAE 55. Design regulations deal mainly with air temperature and relative humidity [23]. In Egypt, indoor comfort conditions are based on recommendations of the ASHRAE Standard 55–2013[2] [2]. The indoor design conditions followed in Egypt are listed in the Appendix. With an accepted tolerance of ±1 °C, the set-points for the indoor room air temperature were assumed in this work at 24 and 21 °C for summer and winter, respectively. However, in response to the energy crisis and the high cooling demand, a cooling set-point of 26 °C was also investigated in this work, as some studies mentioned that this higher value might still be accepted [29]. Concerning the relative humidity, the standard recommends 50% RH for summer. However, the tolerance in the acceptable range of relative humidity is quite flexible. 60% RH can be considered within the limits of the thermal comfort zone [2,29].

3. Methodology

By incorporating the proposed RCS, configured as water-based absorber system, on the roof of a residential building in Egypt, and operating the system at night during the cooling season, water can be cooled down thanks to nocturnal radiative cooling as explained in Section 2.2. The chilled water can then be directly used within the building hydronic system (direct cooling), or stored in a thermally-insulated storage tank located in shade, to be ready for usage whenever cooling is needed. Depending on the type of the hydronic system, the room air temperature, the wall surface temperature, or thermal mass will be consequently cooled down. The direct cooling technique is simpler and less expensive, which is more convenient for the already existing residential buildings in Egypt. In this work, chilled-ceilings are considered as the hydronic system to be implemented inside the conditioned spaces of the building, for both cooling and heating purposes, during summer and winter, respectively. Fig. 4 depicts the proposed operation of the RCS. Although radiant-floors would perform more efficiently for space heating applications, chilled-ceilings were chosen since the main focus of the proposed system is to provide cooling during summer months. Worthy to mention is that such a simple system is a sensible cooling system and doesn't deal with humidity. The system has no means to provide ventilation either. This section overviews the steps taken to set up the simulation model of the whole system.

3.1. Building model

The goal here is to develop a building component in TRNSYS (Type56) that models the thermal behavior of the building divided into

[2] Feedback from a local HVAC-office in Cairo.

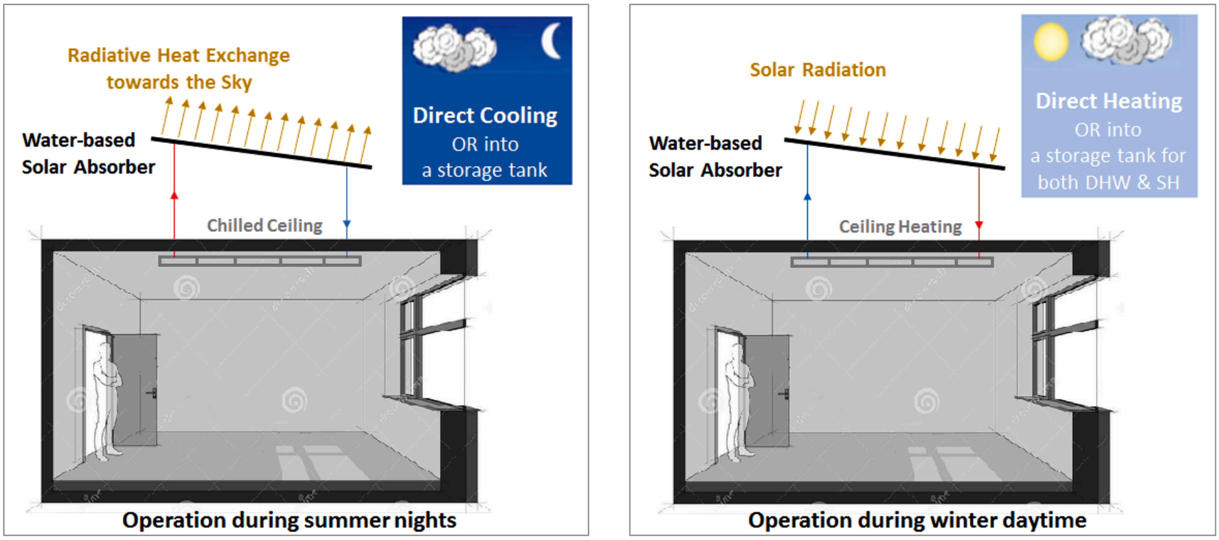

Fig. 4. A schematic diagram showing the basic idea of implementing solar absorbers for both radiative cooling applications in summer (left) and heating in winter (right).

different thermal zones. TRNBuild is the tool used to enter all input data for multi-zone buildings in TRNSYS. The building was selected from a previous study to represent typical residential buildings in the three cities under study. This would demonstrate the existing conditions in terms of construction materials against the local climate, which represents the external portion of the thermal load.

3.1.1. Building description

According to the results of the field surveys conducted in the work of [9], a typical common block typology was selected. Each block in its urban context consists of three adjacent identical buildings, with an offset for the middle one. Each building in this typology has six floors and two apartments per floor. In this study, only one apartment on the top floor was considered to be air-conditioned by the proposed RCS. And for simplification, it was assumed that the building under study was isolated from its block context. Consequently, it was accepted not to consider the adjacent building(s) as a shading group in the simulation. Table 1 summarizes the building data used to set-up the building model in TRNBuild. The basic building construction is a reinforced-concrete post and beam structure with 12–15 cm thick brick infill walls [9,25]. Windows are single glazed, transparent and have 4 mm thick glass pane[3]. All windows are external and have only internal shading devices. The total glazing area of one apartment is 15 m^2 [9,25,30].

3.1.2. Thermal zones

In this work, Trnsys3d was used to implement the geometry of the building as described above. Trnsys3d is a plugin for Trimble SketchUp, where it is more convenient to create the multi-zone building envelope, compared to the same process within TRNBuild. The output file of this step (.idf file) can be imported by TRNBuild, and hence the building model component (Type56) is created within the TRNSYS project. As shown in Fig. 5, the apartment under-study has a corridor, a kitchen, a bathroom, a dining room (with balcony), and three conditioned rooms (two bed-rooms and the living-room). These are seven thermal zones[4] out of the total eleven of the building model. The other four thermal zones are: the stairs, the neighbor apartment, the adjacent floor downstairs, and finally the rest of the building. Depending on the social-economic level and the family size, a residential apartment in Egypt can have more or less rooms, fully or partially air-conditioned (or not at all). The apartment layout can differ to a great extent from a family-type to another. Assumptions were made in this study as will follow in the next section.

3.2. Internal gains

The building component in TRNSYS (Type56) should simulate the total thermal load, internal and external. To be able to define the internal thermal gains in the simulation model, the occupancy profiles as well as the energy consumption patterns have to be first analyzed. In this section, this analysis is done, but only for the three conditioned spaces

Table 1
Building data used in the simulation model [9,25,30].

Building Description	
Shape	Rectangular (25 m x 11 m)
No. of floors and height	6 and 2.8 m height per floor
Floor Description	
Net floor area	245.45 m^2
No. of apartments per floor	2
Stairs floor area	15.75 m^2
Stairs WWR	0.3N
Apartment Description	
Net floor area	114.85 m^2
Volume	321.58 m^3
External wall area	105.42 m^2
Windows area	15.00 m^2
WWR (N)	22.29%
WWR (S)	25.28%
Exterior wall U-value	1.71 $W/m^2.K$
Roof U-value	1.39 $W/m^2.K$
Floor U-value	1.58 $W/m^2.K$
Glazing U-value	5.68 $W/m^2.K$
Wall surface absorptance	0.7
Roof surface absorptance	0.6
Net conditioned area	56.95 m^2
Glazing Description	
SHGC (g-value)	0.86
Shading coefficient of glass (SC)	0.78
Shading Factor	0 - 0.8

[3] It was mentioned 3 mm thick windows in [9]. However, all glazing parameters were approximated to the WinID1001 offered in the WinID-Lib of TRNBuild.
[4] Assuming doors of all rooms are closed as a default-condition, so normally no air flow.

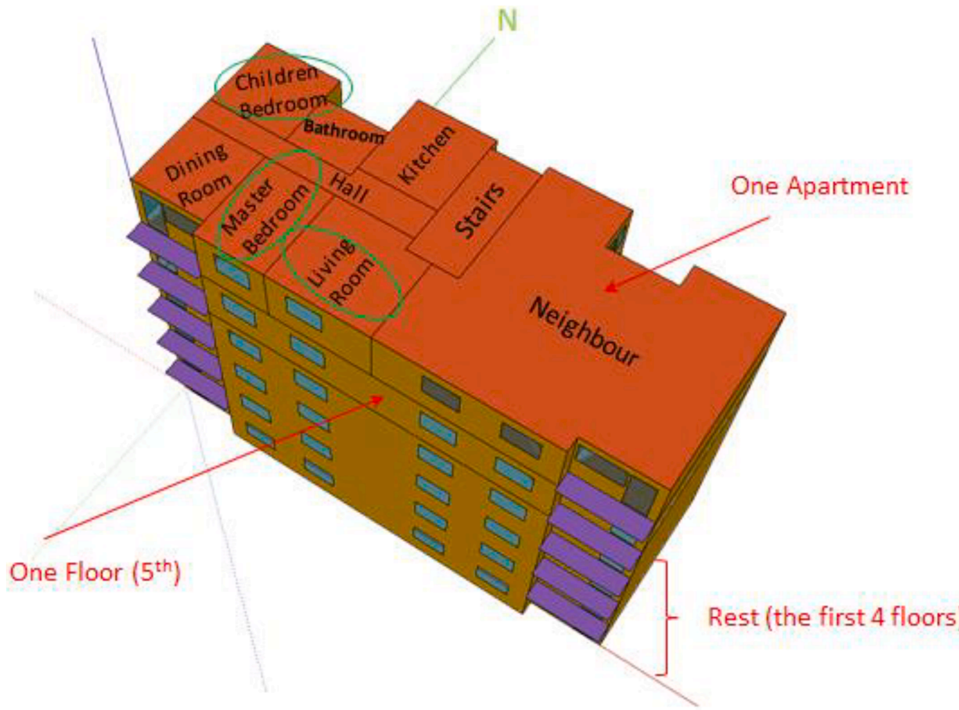

Fig. 5. A top-view of the building model indicating the 11-thermal zones and highlighting the 3-conditioned spaces.

under study (marked in green in Fig. 5), where the proposed RCS is planned to operate. Ventilation is also discussed, as it can cause heat gains or losses.

3.2.1. *Occupancy profiles*

Such profiles are needed to calculate the internal gains due to occupants. For steady indoors conditions, humans are usually in a thermal steady-state with respect to their surroundings. Our living bodies generate heat. The total thermal power produced from an "average" person at rest is nearly 105 Watts. However, this rate is a function of the muscular activity level. Inside bed-rooms (reclining) a factor of 0.8 should be considered, whereas typical standing or relaxing activities in living-rooms use a higher factor of 1.2 [31–33]. Unless the organism has more heat than can be eliminated by radiation and convection, evaporation (through perspiration) is not required and conduction is negligible. Although evaporation plays a significant role in hot environments like Egypt, it was not considered in this work, since the proposed cooling system doesn't deal with latent loads. Accordingly, only radiative and convective heat loss from the human body were considered in the simulation. The convective heat loss rate is about half the radiative rate [31].

Occupancy density together with occupancy schedule form the occupancy profile. A highly detailed level of data was required to define occupancy profiles of a representative family in a typical residential apartment in Egypt. As a result, considerable assumptions were made in light of some previous studies [9,34,35].

The apartment under study was assumed to be inhabited by a 4-member family. The most consuming scenario of cooling power was assumed, by presuming long stays at home from the occupants' side: an adult staying at home during the daytime, a full-time employee (08:00 – 19:00)[5], and two children go to school/university (07:00 – 15:00). In Egypt, weekends are on Fridays and Saturdays, where all family members would stay at home in line with the adopted assumption, except for nearly three hours on Fridays for Al-Jomoaa Prayer and/or socialization. And in order to unify the occupancy profile for the weekend, family visits were assumed on Saturdays during the same time slot. Fig. 6 depicts the resulting occupancy profiles over the week, in the three conditioned spaces, during three different seasons. In this work, the occupancy density was represented as a percentage of the total number of occupants, e.g. 0.25 (1 person), 0.5 (2 persons), 0.75 (3 persons) or 1.00 which means full occupancy of the space. That was done to allow more flexibility in producing a generic simulation model for future users.

Seasons influence the occupants' behavior. Therefore, three main seasons in Egypt were roughly considered while generating the occupancy profiles. Two climate-related seasons (summer & winter) in addition to the religious (traditional) month of Ramadan. According to recent classifications, a hot summer from May to September was presumed, complemented by a mild winter from October to April [24,36]. There is a real need for cooling during the summer season, while the need for SH in winter is limited. However, those will be referred to as the "cooling season" and "heating season" respectively, in order to distinguish them from the occupancy-pattern seasons mentioned on Fig. 6. In this work, Ramadan was assumed to synchronize with the last month of the cooling season, i.e. September. Fig. 7 illustrates those two different segmentations of seasons.

According to the national schools' system in Egypt, the cooling season approximately coincides with the school summer vacation [35, 37]. For simplicity and in compliance with the scenario of the highest energy consumption, it was assumed that the two children stay at home during summer vacation. The Holy (lunar) month of Ramadan is a seasonally shifting month. It begins approximately 11 days earlier each (solar) year. During Ramadan, life style is changed to a great extent on a national level. The official working hours are reduced (09:00 – 16:00), and the times of daily habits and activities of the society are shifted. To simplify, the same occupancy profile was assumed on all days of Ramadan.

3.2.2. *Energy consumption*

This mainly includes electrical appliances and artificial lighting. The usage pattern of artificial lighting is highly dependent on both

[5] This assumption includes transportation time.

Fig. 6. Occupancy profiles during the three main seasons: Winter (top), Summer (middle), and Ramadan (bottom) - over the working-days (left) and weekends (right).

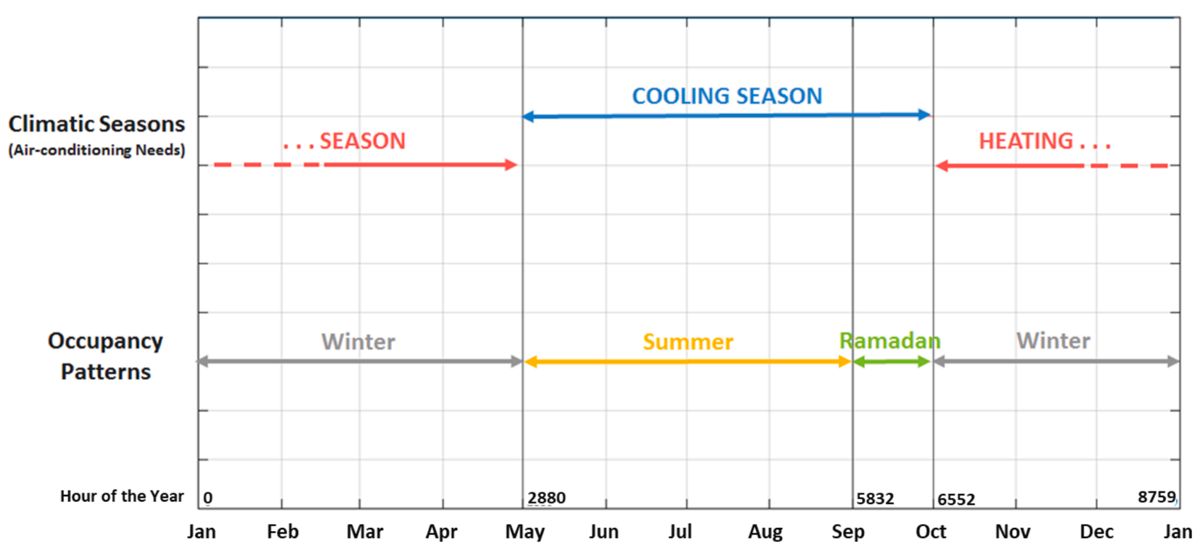

Fig. 7. Seasons definition according to the climatic and occupancy patterns segmentation.

occupancy schedules and seasons (in particular the daylight hours). In the apartment under study, there is at least one window in every room. Moreover, Egypt enjoys considerably enough daylight hours. During winter, daylight is on average from 07:00 till 17:00. While the daylight span lasts for more than twelve hours during the cooling season (from 06:00 till 18:30, on average) [38]. Accordingly, light bulbs are in operation only during the few darkness hours whenever there is an activity inside the space. Based on the surveys conducted in the work of [9], it was assumed in this work to have incandescent lamps of average lighting power of 17 and 13 W/m^2 for the living-room and bed-rooms, respectively [9]. The daily usage profiles of artificial lighting that were assumed in this study are presented in the Appendix. The heat generated by the filament of incandescent lamps is about 95% of the lamp power. Numerically, the heat is taken out of the bulb to the surrounding in form of infra-red radiation (about 83%) and also by conduction and convection (about 12%) [39].

On the other hand, by categorizing the electrical appliances according to their power consumption, the following assumptions were made in this study. The plug-loads which exist in the three conditioned rooms (such as TV, PC, laptop, phone charger, or satellite decoder) are of low power consumption. Therefore, their thermal loss can be neglected. Furthermore, the high consumption plug-loads are either not so often used (e.g. the vacuum-cleaner and electric iron), or they are located in other unconditioned spaces like the kitchen or the bathroom (e.g. water heater, washing machine, refrigerator, kettle, etc.). As a result and to simplify, their heat losses were also disregarded as thermal internal load on the air-conditioning systems installed in the conditioned spaces. Consequently, the heat gains due to electrical appliances were not considered in this study.

3.2.3. *Natural ventilation*

Typically, a minimum level of outdoor air has to be distributed throughout the space to ensure good indoor air quality. In the ASHRAE's standard for residential ventilation (Standard 62), the air change rate requirement varies by the size of the house and by occupancy [40]. Because the proposed RCS doesn't provide ventilation in the spaces where it is installed, natural ventilation is required in the conditioned rooms (same as it is needed in the unconditioned rooms). In natural ventilation, windows are manually opened to allow the flow of external fresh air indoors. For naturally ventilated buildings, control of ventilation rates is difficult and attention should be given to the minimum ventilation rate [41]. Based on the windows' areas of the building model, the average wind speed in Egypt, and the size of conditioned rooms in the model, a ventilation rate of 50 L/s was considered in the simulation. The ventilation schedule was assumed to be from 18:00 till 06:00 every day during the cooling season. In winter, windows were assumed to be opened for one hour in the morning. The ventilation schedules in the three conditioned rooms are enclosed in the Appendix.

3.3. Simulation model

The main components of the simulation model are: the absorber field and the building model. In Type56, a chilled ceiling was defined as the inner layer of the external roof of each conditioned room. Additionally, the model included the weather data, a few controllers, and some hydraulic components to connect the entire system together. Fig. 8 shows a schematic of the system that was modelled in TRNSYS17. Several inputs and outputs were defined in the simulation model as quantities of interest for the purpose of control and monitoring. This section briefly describes the control strategy to optimize the operation of the system. Then the configuration of the basic components in the simulation model is highlighted.

3.3.1. Control strategy

The operation of the system for direct cooling applications is during the cooling season only (s. Fig. 7). This can be ensured in the simulation by a single-level forcing function. In addition to this season triggering signal, the system would operate whenever it is possible to enhance the thermal condition in any of the three rooms through the RCS. The controlled valve of the chilled-ceiling at any of the three conditioned rooms (s. Fig. 8) should operate only when the absorber outlet temperature is lower than the room air temperature. In that manner, the hydronic system would absorb heat from the room. If at least one room meets this condition (during the cooling season), the pump signal is activated and the absorber system will be turned-on. Fig. A.8 in the Appendix shows the control logic of the system. A hydraulic shunt was used as a mass flow buffer between the absorber field side and the building side, since the direct cooling approach doesn't consider a storage tank. The mass flow calculations are discussed in the Appendix.

3.3.2. Model configuration

Weather Data: Type15–2 from TRNSYS standard library reads weather data files in the Typical Meteorological Year Version 2 (TMY2) format (.tm2). The weather data files of the three Egyptian cities (Alexandria, Cairo, and Asyut) were generated using Meteonorm Version 5. The weather and radiation data are based on monthly values that Meteonorm generates stochastically to hourly values [42].

Solar Absorber Field: Type1289-Unglazed from TESS solar library models uncovered solar collectors according to the dynamic efficiency approach (1D IAMs) of the EN12975 Standard [43]. The parameters of the AQSol absorber (which were identified in a companion paper of this research [16]) were used to configure Type1289 in the system model. The AQSol absorber (1 m standard width) can be ordered in a very flexible and user-customized way. The absorber field was assumed to consist of seven modules, each of 10 m length, connected in series. This forms a 70 m^2 field which covers more than 61% of the apartment (roof) area.

Building Model: Type56 was created as described in Section 3.1. To complete the definition of the building model, the internal gains presented in Section 3.2 had to be defined as follows:

For each of the three occupancy-pattern seasons (s. Fig. 6), the weekly occupancy profile of each room was defined in the TRNSYS simulation model as a data-file read by Type9 (the data file reader component in TRNSYS). Type9 repeats reading the values of the data-file over the whole simulation period (one year in this analysis). Forcing functions (Type14l and Type14k) were used to assign each of the three

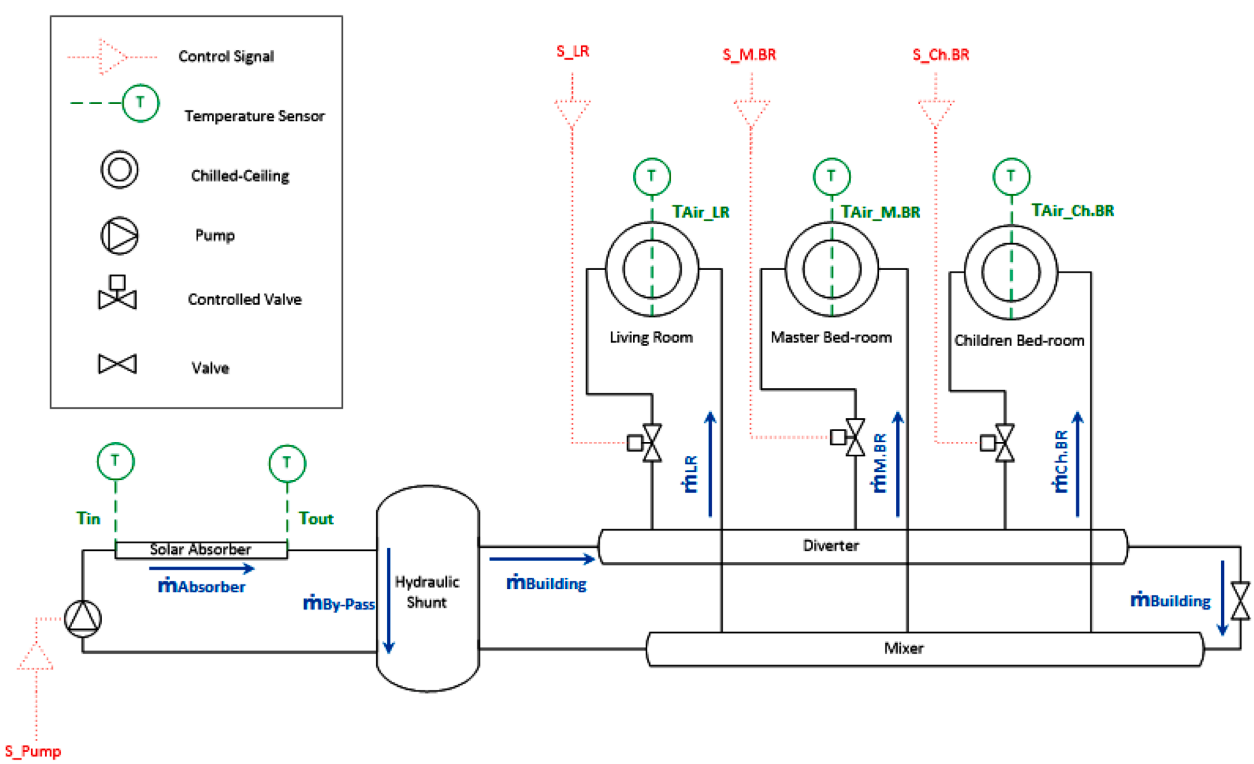

Fig. 8. A schematic of the system operation (with a focus on cooling applications) showing both the hydraulic and control schemes.

profiles into the right corresponding time-slot of the year (s. Fig. 7). Further processing was done to result in a yearly occupancy profile, which can be directly used in equations at any time-step of the simulation. Accordingly, to calculate the internal heat gains due to occupants in any of the three thermal zones, the occupancy profile of the corresponding room is multiplied by the total number of occupants and by the average power emitted from one person ($\dot{Q}_{Avg,p}$), considering the factor (F) of the physical activity of that specific room as explained in Section 3.2.1. Eq. (1) shows the formula used in the thermal zone “Living Room” to define the occupancy gains (OCC_{LR}), as an example:

$$OCC_{LR} = Occupancy\ Schedule_{LR} * No.\ of\ Family\ Members * \dot{Q}_{Avg,p} * F_{LR} \tag{1}$$

In TRNBuild definition window of internal gains (the Gain/loss Type Manager), the thermal power has to be characterized as radiative or convective. As mentioned in Section 3.2.1, the radiative part of the heat loss dissipated from occupants was assigned to ($0.67 \times OCC_{LR}$). The convective power was hence defined as ($0.33 \times OCC_{LR}$). The same process was applied in the two other thermal zones “Master Bedroom” and “Children Bedroom” to define the internal heat gains due to occupants.

In a similar way, lighting was defined in TRNBuild as three new internal gains, one in each of the three conditioned thermal zones. Eq. (2) shows the formula used in the “Living Room” to define the lighting gains (**$Light_{LR}$**), where the lamp power is declared as a global variable in W/m^2. And as requested in the definition window of this new Gain/loss Type Manager for lighting, 0.83 and 0.12 were the ratios used to identify the radiative and convective thermal powers, respectively, due to lighting (s. Section 3.2.2).

$$Light_{LR} = Lighting\ Schedule_{LR} * Lamp\ Power_{LR} * Area_{LR} \tag{2}$$

Similarly, the ventilation was defined within Type56. The ventilation schedules were provided in the simulation model as readable data files, then processed and connected as inputs to Type56. Natural ventilation was defined however in all thermal zones of the building model, except the “Hall” where no windows exist. In each of those ten zones, an infiltration input was also defined. Infiltration accounts for the uncontrolled air flow into the zone from outside the zone, i.e. through windows and/or doors [30]. According to the recommendation of the Egyptian code for energy efficiency in residential buildings, a value of 1.8 l/s.m^2 was assumed [26]. This value represents the maximum allowed infiltration rate for sliding windows and/or doors [26]. For hinged types, the value is 1.7 l/s.m^2. An external data file for infiltration was prepared with the equivalent values in the units requested by the infiltration type manager in TRNBuild (1/h).

Chilled-Ceilings: To model a cooling ceiling panel in TRNBuild, a new layer of type “chilled ceiling” has to be defined. This layer can only be added on position 1 (i.e. from the inside) [30]. The construction-type "external roof", which was created in this work to define the ceiling of all unconditioned thermal zones in the top floor of the building, was hence cloned. Only the newly defined chilled-ceiling layer was added to it from the front to eventually define a new construction-type “external roof chilled” in Type56 to simulate the ceiling of the three conditioned rooms. More details about the definition of chilled-ceilings in TRNBuild are presented in the Appendix.

Hydraulics: A four-outlet-port diverter, a four-inlet flow mixer, and a pump are the main components of the hydraulic group. The hydraulic shunt function was simulated by one of the diverter outlets. The three types were imported from the TESS hydronics library. The diverting valve (Type 647) splits the inlet absorber mass flow into four fractional outlet mass flows, three equal fractions go to the three chilled-ceilings in the building model and the forth represents the by-pass in the hydraulic shunt (s. Fig. 8). The fractions are calculated so that they are triggered by the room control signals, as described in the previous section. The returns of the chilled-ceilings are mixed within the mixing valve (Type 649), and also with the by-pass flow, so that a single outlet mass flow goes back to the absorber field. To compensate the pressure losses of the system, a single speed pump is used (Type 654) that is able to maintain a constant fluid outlet mass flow rate.

Controllers: Three ON/OFF differential controllers with lock-outs (Type 911) were used. For each conditioned room, the absorber outlet temperature was compared to the room air temperature. To trigger the control signal, the temperature difference (T_{OP} - T_{out}) should be greater than 2 °C. To go to the OFF state, the lower band of the controller was set to 1 °C.

4. Results & discussion

Four different operation cases of the above described system were simulated in order to evaluate the cooling potential of the proposed RCS when implemented in a typical residential apartment in Egypt (the base-case). Then a sensitivity analysis was carried out to assess possible ways for improvement. Namely, implementing external shading devices and applying the Egyptian energy efficiency code for buildings. Finally, the system operation is considered during the winter season for heating applications.

4.1. *Cooling potential*

Firstly, a "reference case" was simulated, where no means of air-conditioning exist in any of the three conditioned rooms in the apartment understudy. The thermal conditions in the three rooms were monitored. This represents the base line to benchmark the added-value of the RCS when operating as a “stand-alone” air-conditioning system. In this second case, the system as described in Section 3.3 was simulated. The results were analyzed over the cooling season only (from May till end of September). Table 2 shows the output results of the RCS at the stand-alone operation. As theoretically predicted (s. Section 2.2), the drier the weather, the higher the radiative cooling potential. The highest potential is in the city of Asyut, followed by Cairo, and lastly comes Alexandria which has the highest humidity ratio (s. Section 2.3). The specific cooling power is in general low. This is mainly due to two reasons: the counteracting convective effect (s. Section 2.2) and the oversized absorber field area. During most of the operation hours of the system, the absorber mean temperature is less than the ambient air temperature (s. Fig. A.14 in Appendix). This causes convective heat gains to the HTF rather than a heat loss effect that assists radiative cooling. On the other hand, using the available roof area (70 m^2 for the absorber field) led to an over-sized system. The same simulations and analysis were repeated for a smaller system that consists of only one absorber module (10 m^2). The cooling energy was reduced by nearly 45% only, which is not proportional to the reduction in the area of the absorber field (85%). Hence, the specific power of the smaller system was almost 4 times higher. This indicates an oversizing of the system. The results and analysis of the smaller size system is documented in the Appendix.

In the stand-alone operation, the operative air temperature (T_{OP}) and

Table 2
The absorber field output results while operating during the cooling season.

Absorber Field	Alexandria	Cairo	Asyut	Unit
Cooling energy $(\int \dot{Q}_{Coll})_{array}$	2,671	3,170	3,693	[kWh]
Specific cooling energy output of the absorber array	38.2	45.3	52.8	[kWh/m^2]
Cooling power $(\overline{\dot{Q}_{Coll}})_{array}$	1,387	1,693	1,986	[W]
Specific cooling power output of the absorber array	19.8	24.2	28.4	[W/m^2]
Operation time during the cooling season (3672 hr) (Length of the pump control signal)	52.4 1,924	51.0 1,872	50.6 1,858	[%] [hr]

relative humidity (RH) in the three conditioned rooms were monitored and compared to their counterparts of the reference case. The temperature difference (ΔT_{OP}) between the reference case (no cooling system) and the stand-alone case was calculated (at each time-step over the simulation period). The resulting positive values of ΔT_{OP} indicate lower (cooler) room air temperature profiles in case 2 thanks to the RCS stand-alone operation. In the three cities, it was noticed that the RCS has the best cooling effect in the living-room. That is because the living-room had the highest room air temperatures in general at the reference case. This allows for higher cooling power output of the RCS. According to the assumptions, the living-room is south oriented and is subjected to high internal thermal load due to occupancy. The results of only the living-room in the three cities are presented in this manuscript.

Fig. 9 shows the improvement in the room air temperature. In the three cities, the RCS reduces the time periods at high temperatures (above approx. 30 °C in Cairo and Alexandria, and above approx. 32 °C in Asyut). In return, those times are shifted to occur at a lower temperature range (left of the graph). However, it was observed from the analysis of (ΔT_{OP}) that, the maximum achievable temperature difference hardly exceeds 4 °C. For most of the time in the three cities, the temperature difference is between 1 – 2 °C (s. Fig. A.15 in Appendix). In general, Asyut showed the best results.

Besides the room air temperature, the RH plays an important role to achieve thermal comfort. Although the proposed RCS doesn't deal with humidity, it was necessary to monitor the RH-levels. In contrast to the behavior of (T_{OP}), a slight increase in the RH-levels was noticed in the three cities when comparing case 2 to the reference case (s. Fig. A.16 in Appendix). In the stand-alone operation, the RH increases as a result of the lower air temperatures developed by the sensible effect of the RCS as discussed above. Since the system doesn't deal with latent loads, the value of the absolute humidity inside the rooms is indeed the same in both cases. Consequently, at the lower room air temperatures in case 2, the RH increases. Fig. 10 shows this undesirable effect in the living-room. It was chosen as an example to show the results, since there was no significant difference in the RH values among the three rooms. In the stand-alone operation of the RCS, the times at low RH values decreased compared to the reference case (the left of each graph). In return, those durations are shifted to the right of the graph, i.e. at higher RH values. Even with the extended acceptable range of RH for indoors thermal comfort (s. Section 2.5), the situation in Alexandria is the worst. The Mediterranean climate already suffers the highest humidity levels. With the proposed RCS, the RH reached 90% in Alexandria. Nevertheless, this issue is not critical in Cairo, because 70% RH (and higher) happen for short time periods only. In Asyut, RH doesn't represent a problem at all. As indicated on the graph of Asyut, the RH-range doesn't exceed the maximum limit of thermal comfort (60%) even when operating the RCS.

Another aspect of the proposed RCS is the positive contribution it could make to the existing conventional air-conditioning system (AC-units). This could be measured by the reduction in the energy consumption of those active cooling systems. For such an analysis, two other simulation cases were considered. The third case "fully-active" simulates the system without the proposed RCS (i.e. no solar absorber field), whilst the idealized cooling control (offered by TRNBuild) was defined in the three conditioned rooms of the building model. From this simulation case, the energy consumption to achieve the thermal comfort criteria could be determined. The forth simulation case "hybrid-operation" is when the RCS is in operation together with the active system, i.e. a combination of case 2 and case 3. Employing case 3 in the "hybrid-operation" ensures keeping the thermal comfort conditions when operating the RCS. The reduction in the ideal cooling demand of the active system of Type56 (compared to case 3) is then the added-value of the RCS.

In compliance with the thermal comfort conditions as defined in Section 2.5, the cooling set-point of the active cooling system was adjusted at 24 °C. To cope up with the ever-critical energy crises, the simulations of those two cases were repeated at a cooling set-point of 26 °C. In case 3 (fully-active), there was a 44% reduction in the ideal cooling demand in Alexandria when the cooling set-point increased by only two degrees. The reduction was 32% and 29% in Cairo and Asyut, respectively. In the hybrid-operation (case 4), using the higher cooling set-point was expected not only to reduce the energy demand of the active system, but also to allow for a larger contribution of the proposed RCS. As resulted earlier, RCSs have more cooling potential at warmer conditions.

Fig. 11 depicts the simulation results of case 3 (the left blue bars)

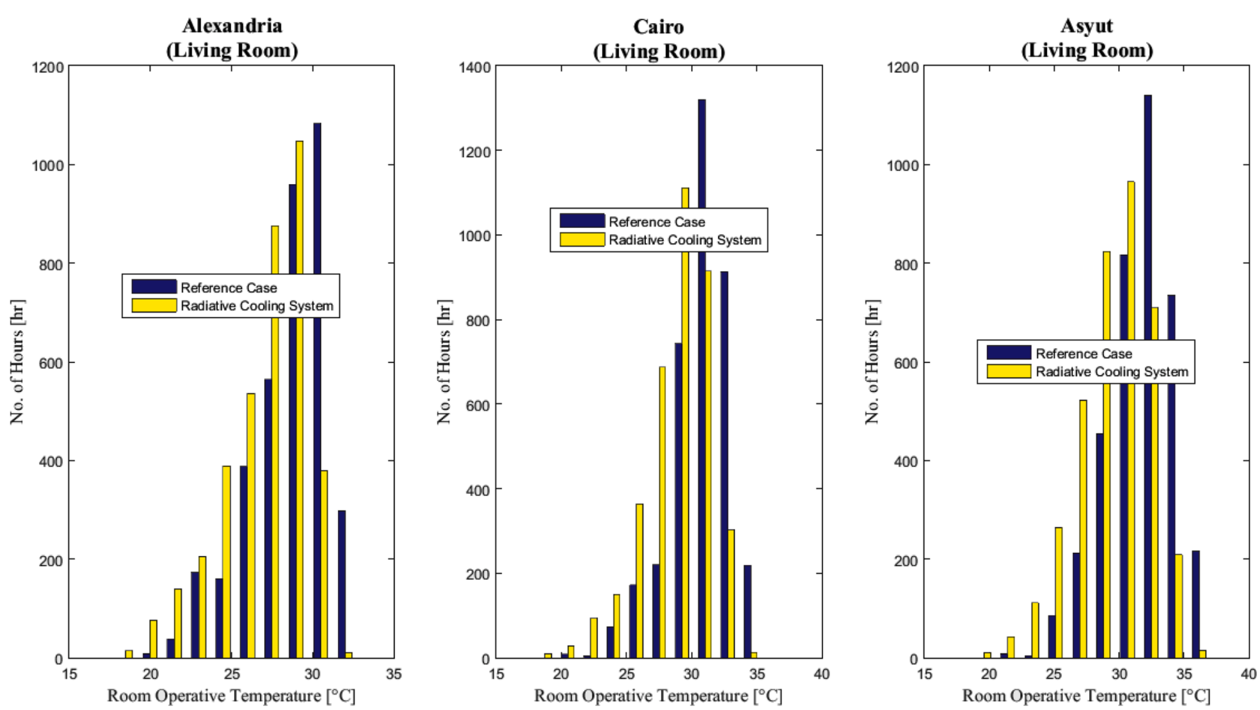

Fig. 9. A histogram of the room temperature range, in the living-room in the three cities, over the cooling season, indicating the positive effect of the radiative cooling system compared to the reference case.

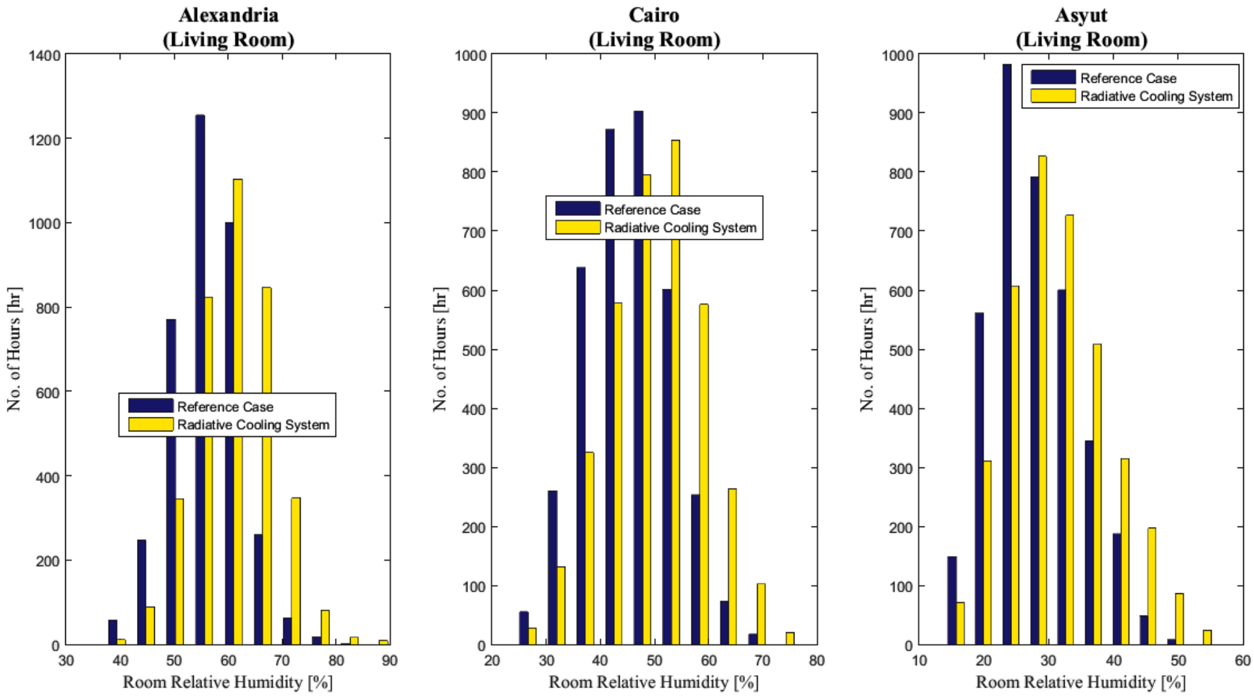

Fig. 10. A histogram of the RH-range, for the living-room in the three cities, over the cooling season.

versus case 4 (the right hybrid bars) in the three cities. The calculated cooling energy is the sum of the three conditioned rooms, i.e. for the apartment under study as a whole over the cooling season. As predicted, the ideal cooling demand of the active system in the hybrid-operation (the yellow bars) is less than its counterpart in the fully-active case (the blue bars). And This behavior applies to the two graphs (which represent the two set-points). In general, the RCS lowers the range of room air temperatures (s. Fig. 9) which helps reducing the peak cooling power on the conventional active system. Moreover, as indicated on the right figure (at the higher cooling set-point at 26 °C), the percentage reduction in the active energy demand reaches 21% in Alexandria, and nearly 18% in Cairo and Asyut. Whereas this percentage hardly exceeds 10% in Asyut and it is nearly 9% in the other two cities when the cooling set-point is 24 °C (the graph on the left). As expected, at the higher cooling set-point the RCS better supports the conventional cooling system, since it performs more efficiently at higher temperatures.

It is noted from both graphs of Fig. 11 that, the total cooling energy provided by the hybrid-system (case 4) is higher than that of the active system only (case 3), i.e. the difference in height of any two adjacent bars. This is because the RCS is an open system. It operates even when the room temperature falls below the cooling set-point. This results in a pre-cooling of the conditioned rooms of the building. Fig. 12 compares the air temperature in the living-room in Cairo, as an example, at both cases. When the room air temperature is below 24 °C (the cooling set-point), the room temperature profile is lower (colder) at the hybrid-operation (case 4) than at case 3 when only the active cooling is in operation.

4.2. Sensitivity analysis

Two of the various passive measures that could enhance the thermal conditions within a building were considered in this work. Firstly, external shading was implemented for all windows in the apartment under study. Secondly, the building model was modified to adopt the construction requirements of the Egyptian code for buildings (ECP306/1–2005). The effect of each of those two variants on the performance of the proposed RCS was separately investigated. For that purpose, all simulation cases and the analysis as presented in the previous section were re-performed. This section highlights only the significant findings in brief.

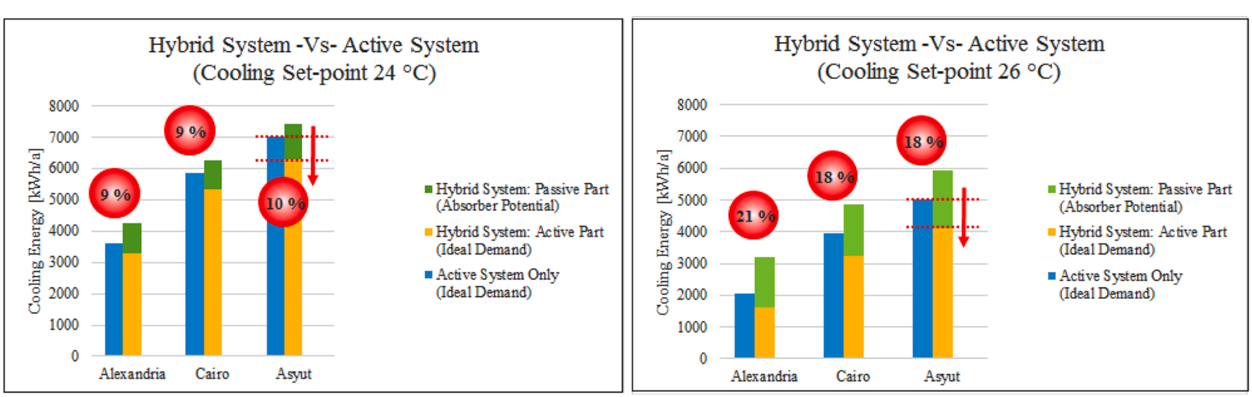

Fig. 11. The annual cooling energy demand of the apartment under study in simulation case 3 (fully-active – blue bars) and case 4 (hybrid-operation – stacked bars).

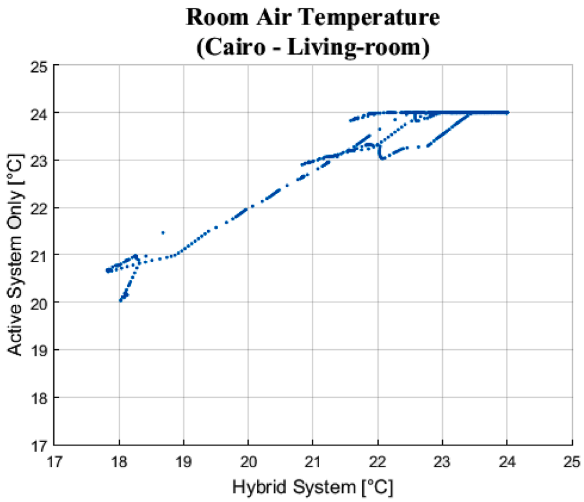

Fig. 12. A comparison between the room air temperature when the hybrid system is considered for cooling versus the active cooling system only. The data points are of the 1st week of May.

4.2.1. External shading

Only the building component in the TRNSYS model was modified. An external shading device was defined in Type56 for every window in the apartment under study. The shading factor was set to 0.8, according to the integrated radiation control, offered in TRNBuild environment.

Using external shading lowers the indoors temperature. As mentioned in the previous section, the RCS performs less efficiently at cooler temperatures. As a result, the cooling potential output of the RCS in the stand-alone operation was less than the case without external shading devices. However, it was only 3% less in Alexandria while 1.4% less in Asyut. The situation in Cairo usually lies in between, where it was 2% less. Accordingly, the improvement in the room air temperatures the RCS provides (ΔT_{OP}) was also less than the previous condition. On the other hand, the lower temperature profile due to external shading already increases the RH levels indoors. Operating the sensible RCS additionally resulted in even higher RH conditions.

Implementing external shading reduces the ideal cooling demand as a result of the reduced temperatures. In case 3 (fully-active) at a cooling set-point of 24 °C, the thermal energy consumption was reduced by 5% in Asyut, 6% in Cairo, and 8% in Alexandria compared to the previous condition with no external shading. In this section, the analysis of case 3 and case 4 considered only a cooling set-point of 24 °C. The contribution of the RCS to the active energy system in the hybrid-operation was similar to the results in the previous section. The reduction in the ideal cooling demand (compared to case 3) was 11% in Asyut, 9% in Cairo, and 10% in Alexandria. This is because external shading reduces the ideal energy demand in general, i.e. for the purely active system as well as for the hybrid system.

4.2.2. Energy efficiency building code (ECP306/1-2005)

Similarly, Type56 was the only component to be modified in the TRNSYS model. As presented in Section 2.4, the Egyptian energy code for buildings (ECP306/1-2005) has different requirements according to the territory. The analysis here considered the city of Cairo only. And the values specified for air-conditioned buildings were used. The construction of both "external roof" and "external walls" were changed to result in a u-value of 0.37 and 0.9 W/m^2.K, respectively (compare to Table 1). Although the orientation of external walls is considered in the energy standard, an average value of 0.9 for the u-value of all external walls was used in this part of the study, for simplicity. The ID number of all external windows was assigned to WinID15004 offered within TRNBuild library, which has the closest glazing properties as required in the building-code.

As stated in the theory (Section 2.4), simulating case 1 of the system "the reference case" resulted in higher room air temperatures than when the building adopted the typical construction conditions (with poor thermal insulation). Since the proposed RCS operates more efficiently at higher temperatures, the resulting ΔT_{OP} here was better than in Section 4.1. Nevertheless, the cooling potential of the RCS was in a different manner less (by 4.5%). That was because of the reduced operation hours of the RCS over the cooling season, due to the higher room temperatures which affect the length of the control signals.

On the other hand, the RH at this new building construction conditions cannot be compared to the former situation. The construction material and properties affect the absolute humidity which was not monitored during the simulation. However, for this new building conditions, the same conclusion was found. The cooler temperature profile thanks to the stand-alone operation of the sensible RCS increases the RH levels.

The benefit of complying with the Egyptian energy efficiency standard (for air-conditioned buildings) could be quantified when (active) cooling was provided in the simulation model. The higher thermal insulation and better glazing properties stipulated in the building code help keeping the (controlled) thermal conditions inside the conditioned spaces isolated from the harsh weather outdoors, especially during the day time. The ideal cooling demand of the fully-active system (case 3) to keep the cooling set-point at 24 °C was 25% less than required when the building model adopted the typical (poor) construction conditions (4397 kWh/a in this new analysis versus 5844 kWh/a as previously presented on Fig. 11- left). In the hybrid mode of operation (case 4), the contribution of the RCS was also better. The reduction in the energy consumption of the active part, thanks to the RCS, was 14% compared to only 9%. This higher contribution is because of the higher temperature profile during night as explained earlier in this section, which leads to a higher performance of the proposed RCS.

4.3. Heating applications

Furthermore, the system operation during winter (the heating season) was simulated. For direct heating, the same system model (Fig. 8) in its simple form with no storage tank was considered. The control signals of the three chilled-ceilings were reversed, so that the solar thermal system operates only when at least one room has an air temperature less than the absorber outlet temperature. In addition, the new control considered a threshold of 24 °C for the room temperature, in order to avoid overheating the three conditioned rooms. On the other hand, the idealized heating control was defined in all rooms of the apartment under study, except the corridor. The heating set-point was adjusted at 21 °C (s. Section 2.5). The internal shading was deactivated in Type56 to allow for more solar gains and hence reducing the heating energy demand. Only the hybrid system was considered in this analysis to assess the contribution of the proposed system in reducing the active energy consumption for space heating (SH). Besides the typical construction conditions specified in Type56, the simulations of this part considered also the Egyptian energy code for buildings for the sensitivity analysis.

The results of the ideal heating demand confirmed that the energy demand for SH in Egypt is much lower compared to the cooling demand. In Cairo as an example, the SH demand over the heating season (from October till end of April) was 2016 kWh/a versus a cooling demand of 5844 kWh/a. This is despite the fact that the ideal heating was defined in six rooms of the apartment under study, compared to only three rooms in the cooling case. When the same three rooms were only considered for SH, the energy demand was nearly one fifth of the cooling demand (as an average for the three cities under study). This is despite the chilled-ceilings hydronic system used in this study, which performs less efficiently for SH applications compared with radiant-floors. In the hybrid-operation, the solar absorber system reduced the active energy demand for heating by 11% in Asyut and by 9% in both Cairo and Alexandria.

The Egyptian code for buildings (ECP306/1–2005) greatly supports the thermal conditions within buildings in winter. In Cairo, the ideal heating demand was only 585 kWh/a (i.e. 71%reduction) thanks to the improved building conditions solely. Similar to the cooling case, the contribution of the hybrid system is higher, when the building code is implemented in Type56. The reduction in the ideal heating demand reached 15%, while it was only 9% (in Cairo).

5. Conclusion & outlook

This research was carried out as a step forward to promote RE technologies for cooling applications in the residential sector in Egypt. At first glance, the arid climate with little sky cover promotes the phenomenon of nocturnal radiative cooling. However, the cooling potential of the proposed RCS depends on a number of other environmental factors as well as the characteristics of the absorber itself, in addition to operation parameters which can lead to potential limitations. The ambient temperature should be considered more carefully. It can limit the absorber mean temperature, as it affects convection, which leads sometimes to counteracting heat gains. The sky temperature represents the main source for the pure radiative cooling. But the cooling potential depends also on the absorber optical parameter (ε/α)-ratio.

Despite the inability of the proposed RCS to achieve thermal comfort when operating as a stand-alone system, the simulation results were consistent with theory. The hot and dry city of Asyut showed the best results. The cooling power was 28.4 W/m^2 against 19.8 W/m^2 in humid Alexandria. The results of Cairo usually lie in between, where it corresponded to 24.2 W/m^2. Worthy to mention is that, the reduction in the room air temperatures was in general humble. On the other hand, the results highlighted the importance of system sizing. The previous values were for an over-sized absorber field (of 70 m^2 area). For a smaller field area of 10 m^2, the cooling power in Asyut reached 109 W/m^2, but even less temperature differences could be hence achieved. A parametric study is recommended to optimally size the system.

An interesting finding of this study was the increase in the RH levels. This side-effect didn't represent a problem in Asyut (and hardly in Cairo). The situation was critical in Alexandria, as the thermal comfort limits of RH were exceeded. A latent cooling system that provides dehumidification would be more advisable to operate at places of already high RH values.

Generally, the proposed sensible RCS is an open loop control system. It doesn't have feedback signals to ensure the user's pre-defined set-points. Consequently, RCSs cannot replace the conventional AC-units. Working as a supplementary system is more feasible. RCSs lower the range of room air temperatures which helps reducing the peak cooling power on the conventional active system and hence reducing energy consumption. Moreover, the simulation results of the hybrid-case showed that, the contribution of RCSs increases at higher cooling set-points. This is because RCSs have higher cooling potential at higher room temperatures. The proposed RCS reduced the active cooling energy demand by nearly 10% in Asyut to keep the cooling set-point at 24 °C. This percentage reached 18% when the cooling set-point was adjusted at 26 °C. Awareness about the significance of the cooling set-point in energy efficiency issues is very important.

The sensitivity analysis of this work showed that, a two-degree increase in the cooling set-point of the fully-active system (i.e. using typical AC-units only) saves much more active energy than using external shading as a passive measure. The reduction in the ideal cooling demand ranged between 29 – 44 % (in the three cities under study), when the cooling set-point was raised from 24 to 26 °C. Whereas energy savings due to external shading ranged between only 5 – 8 % to keep the desired cooling set-point of 24 °C. For the hybrid-system operation while having external shading, the added-value of the RCS was almost the same as in the base-case of the building model. Yet, more energy would be needed for lighting.

Furthermore, the sensitivity analysis considered the Egyptian energy code for buildings (ECP306/1–2005), for Cairo. The results of the different simulation cases confirmed the effectiveness of the energy standard in conditioned buildings as an independent passive measure for energy saving. It dramatically reduces the active energy demand for both cooling and heating. To keep the cooling set-point at 24 °C in Cairo, the ideal cooling demand was reduced by 25% in comparison with the base-case that adopted the typical poor building conditions. In the hybrid mode of operation, the contribution of the proposed RCS in reducing the active cooling energy demand increased to 14% instead of only 9%-reduction in Cairo at the base case. Although the energy demand for SH in Cairo is already low, following the energy efficiency code reduced it by 71%, leading to an insignificant demand. This trend was expected. Therefore, the chilled-ceilings used in this study were still a proper hydronic system. It was not critical to consider radiant-floors for optimizing the efficiency of the hydronic system specially for SH applications.

The overall results of this project recommend activated-ceilings for new buildings under construction which are not planned to implement the energy efficiency code. Thermally activated building systems (TABS) allow additional thermal mass to store the cold (or heat). This makes the temperature profile of the building more even. In summer for example, this offers better resistance to heating-up the building on the following day due to solar irradiance. Consequently, the proposed RCS, integrated with activated-ceilings as a hydronic system, is expected to result in a more significant cooling effect in terms of temperatures.

To bring this kind of systems into the market, operational behavior like stagnation or growth of microorganisms should be further investigated and benchmarked to the common maintenance guidelines of solar thermal systems. On the other hand, synergies are possible by harnessing different renewable cooling resources all over the day. Upgrading to PVT modules allows for solar assisted cooling (SAC), nocturnal radiative cooling, space heating and DHW applications, as well as electricity generation. This increases the RE share even further in the residential building sector.

Finally, due to the outstanding improvements in optical properties of materials, daytime radiative cooling should be also considered for such applications, on both simulation and experimental levels. On-site operation may reveal other challenges. For example, Egypt suffers from dust, in addition to impurities in the air in big cities, which might affect simulation results. Climate data can be used only as a first approximation of assessing the potential at a given location, but should not be taken as an indicator of the actual output. And generally, future research work in the field of renewable cooling should conduct economic studies for comprehensive assessment and optimization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.seja.2023.100044.

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