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# 1 **Development of a night-time radiative sky cooling** 2 **production & storage system: a proposal for a robust** 3 **sizing and potential estimation methodology**

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## 12 **Abstract**

13 This paper proposes a sizing method to guide the design of water-circulating radiative sky  
14 cooling systems and water-based energy storage solutions. Following this method, the choice  
15 of operational flow rate in the radiative sky cooling (RSC) panels and the water storage is  
16 based on four indicators: sub-ambient temperature, cooling power density, minimum storage  
17 temperature and useful energy stored. The method is applied to the BaityKool Solar  
18 Decathlon Middle East (SDME) prototype in order to design a water-radiative sky cooling  
19 system with storage in the climatic conditions of Dubai. We developed passive strategies for  
20 the BaityKool prototype, including a multi-functional innovative exterior wall and a semi-  
21 indoor courtyard space, combined with active solutions (in particular a hydraulic radiative sky  
22 cooling system). The experimental campaign conducted on the RSC system over three  
23 successive nights in November (ambient air temperature between 22.7 to 31.4°C) indicates an  
24 average cooling power of 30-45 W m<sup>-2</sup> for a maximum sub-ambient temperature drop of

25 2.8°C, and shows that great attention to the water pipes and storage insulation can lead to an  
26 increase in the thermal performance of radiative sky cooling systems.

27 **Keywords:** Radiative sky cooling; design method; thermal modeling; extreme climate  
28 conditions; effective sky temperature; energy balance model

### Nomenclature

a	Coefficient (-)
A	External surface of the storage tank (m <sup>2</sup> )
A <sub>rsc</sub>	Area of the RSC panels (m <sup>2</sup> )
A <sub>p</sub>	External surface of the pipe (m <sup>2</sup> )
b	Coefficient (-)
C <sub>p<sub>s</sub></sub>	Heat capacity of the fluid in the storage tank (J kg <sup>-1</sup> K <sup>-1</sup> )
C <sub>p<sub>w</sub></sub>	Water heat capacity (J kg <sup>-1</sup> K <sup>-1</sup> )
e <sub>aal</sub>	Thickness of the anodized Aluminum (m)
e <sub>al</sub>	Thickness of the Aluminum (m)
e <sub>g</sub>	Thickness of the glue (m)
e <sub>is</sub>	Thickness of the insulation (m)
e <sub>p</sub>	Thickness of the panel (m)
E <sub>useful</sub>	Useful energy in the storage system (J)
e <sub>wi</sub>	Depth of the water (m)
F'	Collector efficiency (-)
h <sub>cv</sub>	External convective exchange coefficient (W m <sup>-2</sup> K <sup>-1</sup> )
h <sub>f</sub>	Internal convective heat transfer coefficient between the fluid and the walls of the channel (W m <sup>-2</sup> K <sup>-1</sup> )
h <sub>p</sub>	Overall heat exchange coefficient along the pipe (W m <sup>-2</sup> K <sup>-1</sup> )
h <sub>rs</sub>	Radiation heat exchange coefficient between the surface of the panel and the sky (W m <sup>-2</sup> K <sup>-1</sup> )
I <sub>s</sub>	Short wavelength solar radiation (W m <sup>-2</sup> )
k <sub>is</sub>	Thermal conductivity of the insulation (W m <sup>-1</sup> K <sup>-1</sup> )

$k_w$	Water thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
$L$	Length (m)
$L_g$	Length of the glue (m)
$L_p$	Length of the panel (m)
$l_p$	Width of the panel (m)
$L_{wi}$	Length of the heat transfer fluid channel (m)
$\dot{m}$	Flow rate through the hydraulic circuit ( $\text{kg s}^{-1}$ )
$m_s$	Mass of the fluid (kg)
$n$	Coefficient (-)
$Nu$	Nusselt number (-)
$P_{c,l}$	Output power of the cooling load (W)
$P_{elec}$	Electrical power consumed by the pump (W)
$P_{l,p}$	Thermal loss to the ambient air (W)
$P_{l,s}$	Thermal loss from the tank (W)
$P_p$	Perimeter of the panel (m)
$Pr$	Prandtl number (-)
$P_{RSC}$	Power of RSC (W)
$P_{th-diss}$	Thermal loss from the pump (W)
$r$	Channel form factor (-)
$R$	Solar heat flux density absorbed by the panel in the infrared spectrum ( $\text{W m}^{-2}$ )
$Re$	Reynolds number (-)
$S$	Solar heat flux density absorbed by the panel in the visible spectrum ( $\text{W m}^{-2}$ )
$T_a$	Temperature of ambient air (K)
$\hat{T}_a$	Average ambient temperature (K)
$T_{al}$	Front surface temperature of the panel (K)
$T_{fi}$	Temperature of inlet water (K)
$T_{fo}$	Temperature of outlet water (K)
$T_s$	Average storage temperature of the tank (K)

$T_{s,exp,i}$	Measured water storage temperature (K)
$T_{s,min}$	Minimum storage temperature in the early morning (K)
$T_{s,num,i}$	Modeled water storage temperature (K)
$T_{set}$	Desired set temperature in the cooled room (K)
$T_{sky}$	Average value of effective sky temperature (K)
$U$	Heat loss coefficient ( $W m^{-2} K^{-1}$ )
$UA$	Overall heat exchange coefficient of the storage tank ( $W K^{-1}$ )
$U_L$	Overall heat loss coefficient of the panel ( $W m^{-2} K^{-1}$ )
$U_t$	Top heat loss coefficient of the panel ( $W m^{-2} K^{-1}$ )
$U_b$	Bottom heat loss coefficient of the panel ( $W m^{-2} K^{-1}$ )
$U_e$	Edge heat loss coefficient of the panel ( $W m^{-2} K^{-1}$ )
$V_s$	Storage volume of the tank ( $m^3$ )
$\hat{V}_w$	Average wind speed ( $m s^{-1}$ )
$V_w$	Wind speed (m/s)
$\alpha$	Solar absorption coefficient of the external surface of the panel (-)
$\Delta T_{sub-a}$	Sub-ambient temperature drop (K)
$\varepsilon$	Emissivity (-)
$\eta$	Pump efficiency (-)
$\lambda$	Thermal conductivity of the fluid ( $W m^{-1} K^{-1}$ )
$\mu$	Dynamic viscosity of the fluid ( $Pa s^{-1}$ )
$\rho$	Density ( $kg m^{-3}$ )
$\sigma$	Boltzmann coefficient ( $W m^{-2} K^{-4}$ )

### Abbreviations

BIPV	Building-Integrated Photovoltaic
HVAC	Heating, ventilation, and air conditioning
NSC	Night Sky Cooling
PVT	Photovoltaic thermal
RMSE	Root mean square error

RSC	Radiative Sky Cooling
SDME	Solar Decathlon Middle East
TEC	Thermoelectric cooler

## 29 **1 Introduction**

30 The world today is experiencing significant growth and urbanization, both synonymous  
31 with high energy consumption. The building sector accounts for about 42% of world energy  
32 consumption due to the intensive use of heating, ventilation, and air conditioning (HVAC)  
33 systems for heating and cooling combined with the low performance of building envelopes  
34 [1]. The use of efficient systems for cooling is a major issue to reduce energy bills as well as  
35 greenhouse gas emissions.

36 Radiative Sky Cooling (RSC), or Night Sky Cooling (NSC), is a promising passive  
37 solution to dissipate heat with low energy consumption. The principle is to exploit the sky as a  
38 radiative heat sink where the temperature is colder than in our immediate environment; this  
39 can be achieved by exchanging heat by longwave radiation between 8-14  $\mu\text{m}$  where the  
40 atmosphere is transparent (atmospheric window). This phenomenon depends largely on  
41 location and climatic conditions, such as wind speed, sky cover and humidity [2–5].

42 Many researchers have investigated different approaches to exploit night-time RSC on  
43 building roofs by means of air and water systems. The average cooling power using these  
44 techniques ranges between 30-50  $\text{W m}^{-2}$  [6]. Liu et al. [7] designed a duct-type heat exchanger  
45 installed on the roof of a building in Hohhot (China) to produce cool air during summer nights  
46 and reduce solar absorption during the day. An air system of this kind can reduce the inlet air  
47 temperature by 6.8°C in a cold semi-arid (steppe) climate [8]. Meir et al. [9] used an unglazed  
48 polymer flat plate radiator with water circulation as an economical alternative to active  
49 systems on a building located in Oslo, Norway. Their 5.3  $\text{m}^2$  radiative sky panel was coupled  
50 to a storage tank to evaluate cold production during the night. It was shown that in a warm

51 summer humid continental climate, such a panel can cool down a 280 L storage tank by 20°C.  
52 Other experiments have been carried out in different locations and weather conditions around  
53 the world. Al-Nimr et al. [10] showed that a water circulation RSC panel in Irbid, Jordan  
54 (Mediterranean Climate) with an area of 0.6 m<sup>2</sup> can cool down a 120 L storage tank by 15°C.  
55 A roof constructed with embedded water pipes was installed in Greece (Mediterranean  
56 Climate) by Dimoudi and Androutsopoulos [11] showing a radiative cooling power ranging  
57 from 9.5 W m<sup>-2</sup> to 97.8 W m<sup>-2</sup>. Tevar et al. [12] tested three RSC panels in Almeria, Spain  
58 (hot semi-arid-steppe climate) with high, medium and low emittance; maximum cooling  
59 power (63.7 W m<sup>-2</sup>) was naturally observed for the organic panel with high emissivity while  
60 the panel with medium emittance resulted in 42.2 W m<sup>-2</sup> and the one with low emissivity in  
61 7.7 W m<sup>-2</sup>. In Owerri, Nigeria (Tropical monsoon climate), Okoronkwo et al. [13] conducted  
62 an experimental study using a RSC panel made of steel pipes and covered by an aluminum  
63 sheet to cool a water storage tank during the night; the cooled water was used during the day  
64 to maintain a room temperature between 26°C and 28°C by circulating it through a heat  
65 exchanger for space cooling. Bokor et al. [14] evaluated experimentally a commercial  
66 transpired solar air collector for night-time cold production by RSC. The maximum cooling  
67 performance measured was 66.5 Wm<sup>2</sup> for an average value of 34.6 W m<sup>-2</sup> in Erding, Turkey.  
68 A combination of uncovered photovoltaic thermal (PVT) panels and RSC was investigated by  
69 Eicker and Dalibard [15] to provide electricity during the day and cooling energy during the  
70 night; the cooling power measured depends on the use of the cold production, and was  
71 estimated at between 60-65 W m<sup>-2</sup> for cooling a warm water storage tank and 40-45 W m<sup>-2</sup> for  
72 cooling a ceiling. Chen et al. [3] compared glazed/unglazed PVT with switchable film  
73 insulation in a Tropical climate (Sanya, China). They found that PVT panels with film  
74 insulation satisfactorily combine solar thermal cooling and nocturnal passive cooling  
75 performances, with an annual total energy yield that is 10% and 32% higher than that of  
76 glazed and unglazed PVT collectors. The same combination was used by Zhao et al. [16]

77 using air as a heat carrier to produce cool air for buildings during the night. To enhance the  
78 space cooling energy density, Kwan et al. [17] investigated coupling PV panels and  
79 thermoelectric cooler (TEC) modules in two functioning modes (with and without batteries).  
80 Aketouane et al. [18] simulated energy-saving potential by coupling a watertowater heat  
81 pump and a water-cooling RSC system; this reduces the electrical consumption of the heat  
82 pump by up to 20% over the summer period. Recently, in order to enhance radiative sky  
83 cooling production over 24h, some authors have also achieved radiative cooling during the  
84 day using surfaces that combine high solar reflection and high thermal emission; these  
85 surfaces were produced from high-technology materials such as ultrabroadband photonic  
86 structures or scalable-manufactured glass-polymer hybrid metamaterials [19–28]. For  
87 example, Goldstein et al. [29] built a circulated water-cooling system (total panel surface area  
88 of 0.74 m<sup>2</sup>), with a surface of a visibly-reflective extruded copolymer mirror on top of an  
89 enhanced silver reflective surface [30], and showed a temperature drop of between 3°C and  
90 5°C under a flow rate of 12 L h<sup>-1</sup> m<sup>-2</sup>. Similarly, Zhao et al. [31] studied a kilowatt-scale  
91 radiative cooled-cold collection system with 13.5 m<sup>2</sup> radiative cooling surface area, and  
92 investigated the influence of two flow rate strategies: controlling intermittent flow and  
93 continuous flow to produce water with constant sub-ambient temperatures, and maximizing  
94 cooling energy generation; their RSC system provided a maximum cooling power of 1296 W  
95 at night at a water volumetric flow rate of 26.5 L h<sup>-1</sup> m<sup>-2</sup>).

96 Most of the RSC systems cited previously produce cold air or water during the night-  
97 time, or during night-time and daytime, using high-technology film composites or  
98 metamaterials to enhance the response to achieve higher cooling needs. Another common  
99 point in these studies is the evaluation of cooling production based solely on climatic  
100 conditions, whereas system performances depend on the cooling needs (especially the  
101 temperature of the fluid to be cooled), the size and the design of the RSC installation. These



102 new coatings are capable of radiative cooling during daytime and even under intense solar  
103 radiation, and will have a major impact on the energy consumption of buildings if combined  
104 with passive [4,32,33] or active techniques [18,29,34]. Since the latest promising advances in  
105 Daytime Radiative Sky Cooling, various strategies have been explored to improve the thermal  
106 performance of this technology [35]. Nevertheless, for commercial and technological  
107 diffusion reasons, in this paper we choose to work on the dimensioning and experimentation  
108 of a low-technology night-time RSC production-storage-distribution system, using panels  
109 made of a classic commercial material, anodized steel.

110         Using numerical modeling and experimental calibration, the aim of this article is firstly  
111 to propose a sizing method, which simultaneously guides the choice of the operating flow in  
112 the RSC panels and the choice of the water storage volume. Previous studies [e.g. [29,36]]  
113 based the RSC panel model only on the flow rate. We propose to go further and also size the  
114 tank volume so that the whole system performs to respond to cooling needs, even depending  
115 partially on the roof surface available to house RSC panels. Secondly, we evaluate  
116 performance of the whole system (and improvement potential) under extreme weather and  
117 sand storm conditions (near Dubai city). The aim of this paper is to guide the design of RSC  
118 systems in order to meet the cooling demand.

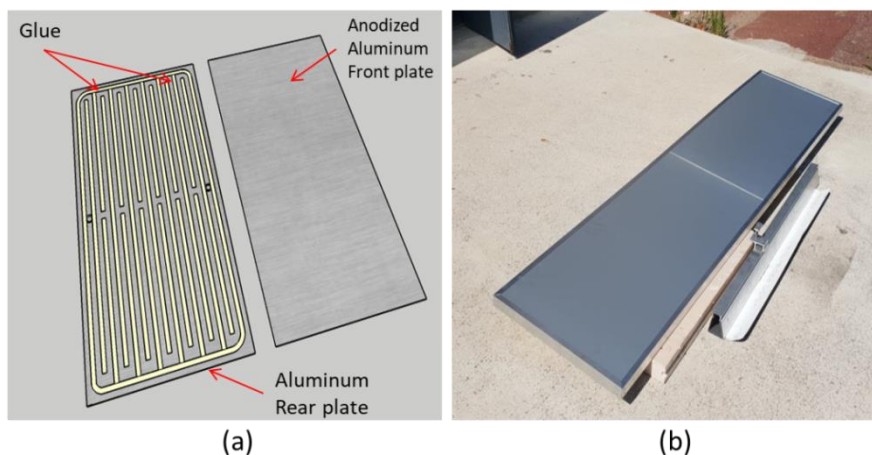
119         The remainder of this study is organized as follows. Section 2 describes the RSC panels.  
120 Section 3 investigates the RSC sizing method. Sections 4 and 5 present the study areas, data,  
121 and methods. Section 6 discusses the performance of the RSC panels and section 7 concludes  
122 this study.

## 123 2 Description and modeling of the RSC System

### 124 2.1 Presentation of the RSC system

125 In the Solar Decathlon Middle East (SDME) Dubai 2018 [37], a water-circulating RSC  
126 system was developed for the BaityKool project [38].

127 In this study, the BATISOL<sup>®</sup> unglazed solar collector is considered. It was first  
128 developed and tested by Nobatek-INEF4 as an Innovative Thermal Solar Façade [39], and is  
129 used in this study, on the roof of BaityKool, as an RSC panel to produce cooled water during  
130 the night. This panel consists of an anodized aluminum front plate measuring  
131 600 mm × 1200 mm × 2 mm and an aluminum rear plate of the same dimensions  
132 (see Figure 1a). The two plates are assembled with glue deposited to form circuits in which  
133 the heat transfer fluid (water in our case) circulates in the panel. The whole is insulated with  
134 40 mm of expanded polystyrene and assembled with two panels in each metal frame, as  
135 presented in Figure 1b.

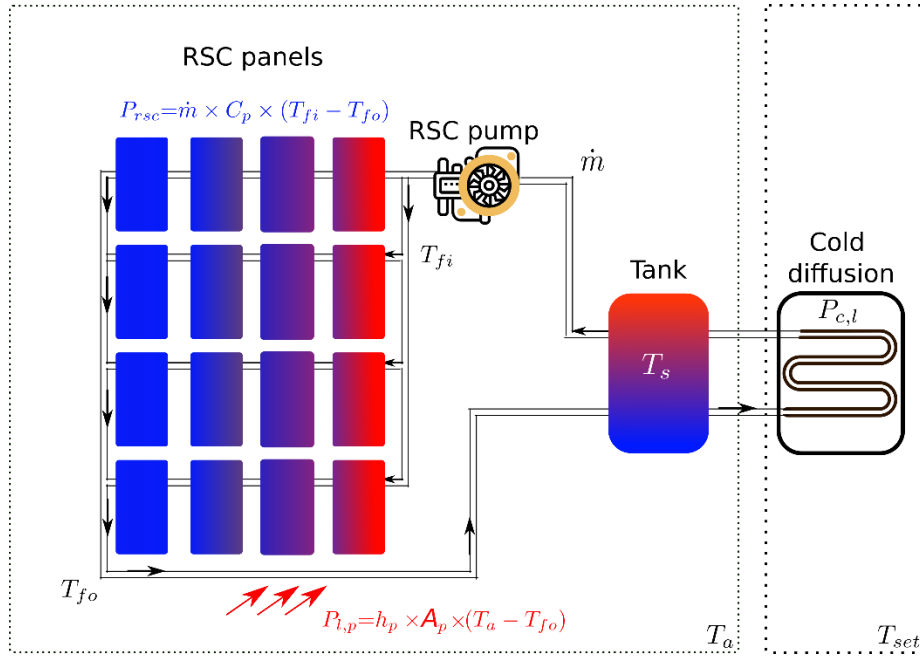


136  
137 **Figure 1 (a) Diagram of BATISOL<sup>®</sup> RSC panel composition, (b) Photo of two RSC panels insulated and assembled on**  
138 **the same metal frame.**

139 Anodized aluminum has been chosen here as the front plate of the RSC panel, because it  
140 has excellent radiative properties in the infrared radiation range between 8-14  $\mu\text{m}$ ,  
141 corresponding to the atmospheric window. Using an EM4 Emissometer from Themacs

142 Engineering [40], the normal emissivity of this anodized aluminum has been estimated to be  
 143 0.96.

144 The proposed RSC system is presented in Figure 2. It consists of RSC panels that cool  
 145 down a storage tank during the night. The stored cold water is then used for cooling one of the  
 146 rooms in the BaityKool house (cold diffusion) during the day using radiative panels.



147  
 148 **Figure 2** Schematic representation of the Radiative Sky Cooling (RSC) system developed and installed in the  
 149 BaityKool house.  $P_{l,p}$  is the heat loss (heat gains) from the pipe to the ambient air.  $h_p$  is the heat exchange coefficient  
 150 by convection between the pipes and the ambient air ( $\text{W m}^{-2} \text{K}^{-1}$ ).  $P_{c,l}$  is the cooling load of the considered room in  
 151 BaityKool.  $P_{RSC}$  is the RSC power produced by the panel.

## 152 2.2 Modeling the RSC system

### 153 2.2.1 RSC panel model

154 The following thermal modeling is considered to describe the RSC panel behavior. This  
 155 model is based on the well-known Duffie and Beckmann equation for a flat plate solar  
 156 collector [41], used by Farmahini Farahani et al. [4]. It represents the outlet water temperature  
 157  $T_{fo}$  (K) (Eq. 10) of the RSC panels as a function of the inlet water temperature  $T_{fi}$  (K):

$$\frac{T_{fo} - T_a - (S - R)/U_L}{T_{fi} - T_a - (S - R)/U_L} = \exp\left(-\frac{U_L A_{rsc} F'}{\dot{m} C_p}\right) \quad \text{Eq. 1}$$

158  $A_{rsc}$  (m<sup>2</sup>) is the area of the panel.  $\dot{m}$  (kg s<sup>-1</sup>) represents the flow rate through the hydraulic  
 159 circuit.  $F'$  (-) is the collector efficiency factor.  $U_L$  (W m<sup>-2</sup> K<sup>-1</sup>) is the overall heat loss  
 160 coefficient. In addition to the solar heat flux density absorbed by the panel  $S$ , the term  $R$  has  
 161 been added to the equation to consider the net radiative flux density exchanged in the far  
 162 wavelength in the infrared radiation between the panel surface (at temperature  $T_{al}$ ) and the  
 163 sky. A detailed description of the model can be found in Appendix A.

### 164 2.2.2 Storage tank model

165 The thermal behavior of the storage tank can be predicted using the following energy  
 166 balance, based on studies by Aili et al. [36] and Goldstein et al. [29]. Five forms of heat flow  
 167 are taken into account, namely  $P_{RSC}$  cooling power,  $P_{l,p}$  heat gain from the pipes,  $P_{l,s}$  heat gain  
 168 from the storage tank,  $P_{c,l}$  cooling load and  $P_{th,pump}$  heat gain from the pump:

$$m_s C_p \frac{dT_s}{dt} = P_{RSC} - P_{l,p} - P_{l,s} - P_{c,l} - P_{th-pump} \quad \text{Eq. 2}$$

169 where  $m_s$  is the fluid mass (kg).  $T_s$  is the average storage temperature of the tank (K).  $C_p$  is  
 170 the heat capacity of the fluid (J kg<sup>-1</sup> K<sup>-1</sup>).  $P_{RSC}$  is the cooling power (W) generated by the  
 171 RSC panels:

$$P_{RSC} = \dot{m} \times C_p \times (T_{fo} - T_s) \quad \text{Eq. 3}$$

172 Unfortunately, part of this cooling power is not effective: there may be some heat gains  $P_{l,p}$   
 173 from the ambient air along the pipe that links the RSC panels to the storage tank:

$$P_{l,p} = h_p \times A_p \times (T_{fo} - T_a) \quad \text{Eq. 4}$$

174 where  $h_p$  is an overall exchange coefficient along these pipes ( $\text{W m}^{-2} \text{K}^{-1}$ ),  $A_p$  is the area of  
 175 pipes ( $\text{m}^2$ ), and  $T_a$  is the ambient air temperature (K). Thermal losses (heat gains)  $P_{l,s}$  (W)  
 176 from the tank to the ambient air are expressed as follows:

$$P_{l,s} = U \times A \times (T_s - T_a) \quad \text{Eq. 5}$$

177 where  $U \cdot A$  is the overall heat exchange coefficient ( $\text{W K}^{-1}$ ) between the storage tank and the  
 178 ambient air.  $P_{c,l}$  is the cooling load (W) of the considered room (cf. Figure 2).

$$P_{th-diss} = (1 - \eta) \times P_{elec} \quad \text{Eq. 6}$$

179 where  $\eta$  is the pump efficiency (-) and is equal to 0.8.  $P_{elec}$  is the electrical power consumed  
 180 by the pump (W).

### 181 3 Sizing Method

182 In a given building, every effort is made to fulfil the cooling requirements using RSC.  
 183 The production per  $\text{m}^2$  of such systems for fluid temperature around an ambient air  
 184 temperature range is about  $50 \text{ W m}^{-2}$  [6]; thus, it is often the available surface area on the roof  
 185 that sizes the surface of RSC panels  $A_{RSC}$ , and not the cooling needs of the building, which are  
 186 often greater. Hence our choice of a sizing method that considers a fixed value for  $A_{RSC}$ . Here  
 187 we propose a robust method which allows the choice of flow rate  $\dot{m}$  based on the  
 188 methodology of Aili et al. [36] and Goldstein et al. [29] and the water storage volume  $V_s$   
 189 based on the following 4 indicators:

- 190 - sub-ambient temperature drop  $\Delta T_{sub-a} = T_a - T_{fo}$  (K) [29,36,42]
- 191 - cooling power density  $P_{RSC}/A_{RSC}$  ( $\text{W m}^{-2}$ ) [29,36,42]
- 192 - minimum storage temperature in the early morning (after night cooling period)  
 193  $T_{s,min}$  (K)
- 194 - useful energy (stored in the storage system)  $E_{useful}$  (J)

195 We improve the design of an RSC panel by adding two indicators, namely  $T_{s,min}$  and  $E_{useful}$ . In  
 196 fact, the RSC system works mainly during the night to cool the tank to a minimum  
 197 temperature value. During the daytime, the need for cooling in the house involves using the  
 198 stored cold water, which contributes to the increase in the storage temperature (in the  
 199 BaityKool prototype, this stored cold water circulates in panels that constitute the kitchen  
 200 credenza). The storage system must therefore both assume the amount of energy required for  
 201 cooling and ensure a lower cooling water temperature than the desired set temperature in the  
 202 cooled room  $T_{set}$ . The useful energy present in the storage tank is then calculated as:

$$E_{useful} = m_s \times Cp_s \times (T_{set} - T_{s,min}) \quad \text{Eq. 7}$$

203 In this work, we assume a set temperature value around  $T_{set} = 26^\circ\text{C}$  [43]. The proposed  
 204 method is based on the four indicators defined above and is carried out in two stages (see  
 205 Figure 3):

- 206 - 1<sup>st</sup> step: Choice of flow rate of water  $\dot{m}$  in the RSC panels (*considering only the*  
 207 *behavior of the panel, without storage*)

208 In this step, 0 is used to calculate  $P_{RSC}$  and  $\Delta T_{sub-a}$  depending on the flow rate per  
 209 unit area  $\dot{m}/A_{RSC}$  ( $\text{l min}^{-1} \text{m}^{-2}$ ). The average values of  $\bar{T}_a$ ,  $\bar{T}_{sky}$  and  $\bar{V}_w$  during a  
 210 typical night are needed as input for the model. In order to calculate the  
 211 temperature drop  $\Delta T_{sub-a}$ , we assume that the water inlet temperature is equal to  
 212 the ambient temperature ( $T_{fi}=T_a$ ) [29]. Therefore, Eq. 1 becomes:

$$\frac{T_{fo} - T_a - (S - R)/U_L}{(S - R)/U_L} = \exp\left(-\frac{U_L A_{rsc} F'}{\dot{m} C_p}\right) \quad \text{Eq. 8}$$

213 Based on the calculation results, the flow rate should be chosen either to  
 214 maximize  $P_{RSC}$  or depending on the application needed.

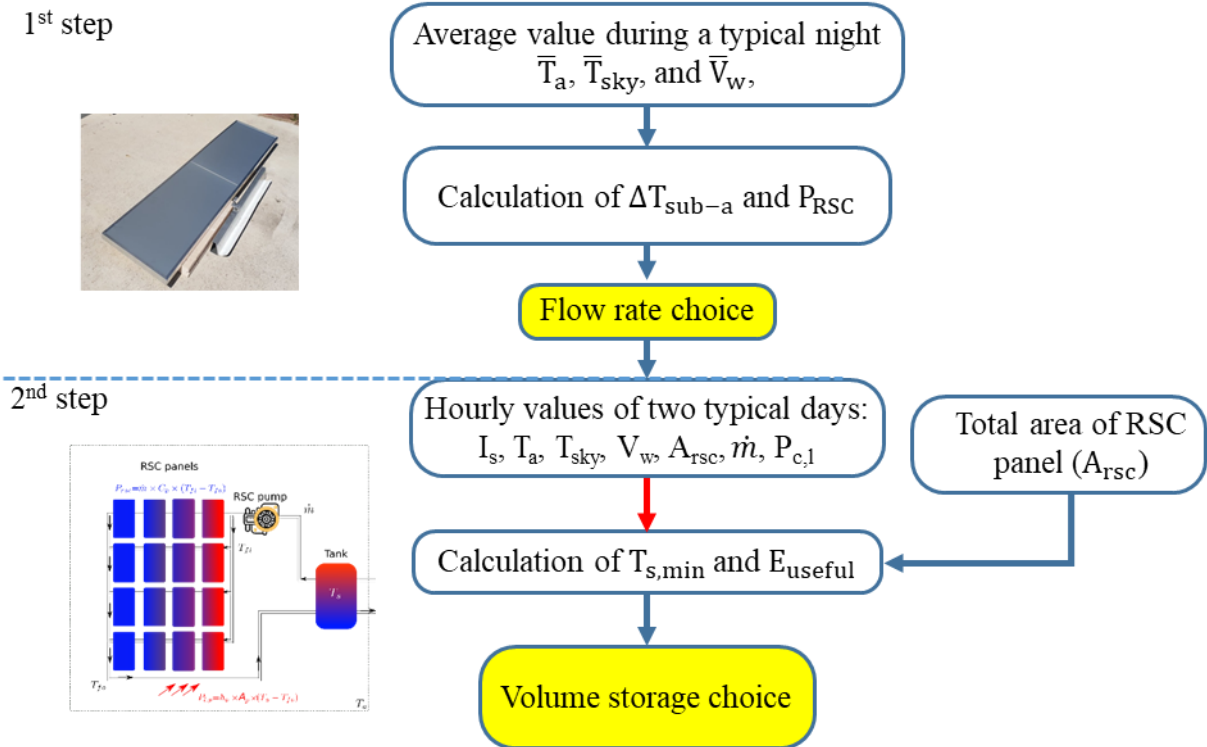
- 215 - 2<sup>nd</sup> step: Choice of storage volume  $V_s$  (*considering entire system with storage*)

216 After choosing the flow rate and fixing the total area  $A_{RSC}$  of the RSC panels,  
 217  $T_{s,min}$  is determined by the overall energy balance of the system (see Eq. 9) that  
 218 combines Eq. 1; Eq. 2 and considers ( $T_{fi}=T_s$ ):

$$m_s C p_s \frac{dT_s}{dt} = \dot{m} C_p (T_{fo} - T_s) - P_{l,p} - P_{l,s} - P_{c,l} - P_{th-pump} \quad \text{Eq. 9}$$

$$\text{Where } T_{fo} = \left( T_{fi} - T_a - \frac{S-R}{U_L} \right) \times \exp \left( - \frac{U_L A_{RSC} F'}{\dot{m} C_p} \right) + \left( T_a - \frac{S-R}{U_L} \right) \quad \text{Eq. 10}$$

219  $E_{useful}$  is calculated using Eq. 7. Hourly values of  $I_s$ ,  $T_a$ ,  $T_{sky}$ ,  $V_w$  and  $P_{c,l}$  during  
 220 two typical days are needed as input for the model. The storage system is then  
 221 sized based on the results of  $T_{s,min}$  and  $E_{useful}$  depending on the storage volume.  
 222 The chosen volume must be sufficient to cover the total or partial energy needs  
 223 for cooling the room under consideration.



224  
 225 **Figure 3** Sizing method of Radiative Sky Cooling (RSC) system with storage.  $A_{RSC}$  is the area of RSC panels ( $m^2$ ).  $I_s$  is  
 226 the short wavelength solar radiation ( $W m^{-2}$ ).  $V_s$  is the storage volume for a given area of RSC panels.

## 227 **4 Application to BaityKool house**

228 In this section, the BaityKool prototype is considered as a case study of the application  
229 of the proposed method. This prototype has been developed by the University of Bordeaux,  
230 and involves a consortium of 3 Universities (University of Bordeaux in France, An-Najah  
231 National University in Nablus-Palestine, Amity University in Dubai-United Arab Emirates), 2  
232 French “*Grandes Écoles*” (*École Nationale Supérieure d'Architecture et de Paysage de*  
233 *Bordeaux, École Nationale Supérieure d'Arts et Métiers de Bordeaux*), and an applied  
234 research center (Nobatek/INEF4). The BaityKool house has a useful floor area of 80 m<sup>2</sup> and  
235 was designed with the hot Middle Eastern climate in mind. It uses passive strategies,  
236 including a multi-functional innovative exterior wall and a semi-indoor courtyard space. It is  
237 powered by Building-Integrated PhotoVoltaic panels (BIPV in an openable-closable canopy  
238 over the courtyard to benefit from direct sky radiation during the night, and in the house's  
239 East-South-West high-performance concrete skin) and is based on an energy management  
240 strategy that aims to reduce consumption while ensuring comfort inside the house (ranked 1<sup>st</sup>  
241 in the Energy Efficiency contest). During the experimental phase of the SDME-2018  
242 competition, a positive energy balance between PV production and consumption for all uses  
243 (including an electric vehicle) led to the lowest level of electrical power taken from the grid of  
244 all prototypes in competition and a very good level of comfort, controlled regarding  
245 temperature, humidity, CO<sub>2</sub> and lighting. BaityKool also promotes the use of biological  
246 technology in buildings (lumbri-filtration & solar UV grey water treatment, an aquaponic  
247 system wall in the courtyard space, and a green roof).

248 As part of the energy efficiency strategy, an RSC system was designed and installed in  
249 the BaityKool house to provide some of its cooling needs.



250 RSC panels were designed for installation on the roof in order to cool one of the rooms  
251 (Kitchen). The architecture of the house is U-shaped, facing north; this means that 3 roof  
252 sections are available for the installation of system components (in the East, West and South).  
253 The south side is reserved for the solar thermal collectors that produce domestic hot water for  
254 the house; thus, two sides (East and West) are available for the installation of the RSC panels  
255 (see Figure 4). Considering the dimensions of the panel ( $600\text{ mm} \times 1200\text{ mm}$ ), and the  
256 surface area available on both sides of the roof, 16 RSC panels were installed, with a total  
257 surface area of  $A_{RSC} = 11.5\text{ m}^2$ .

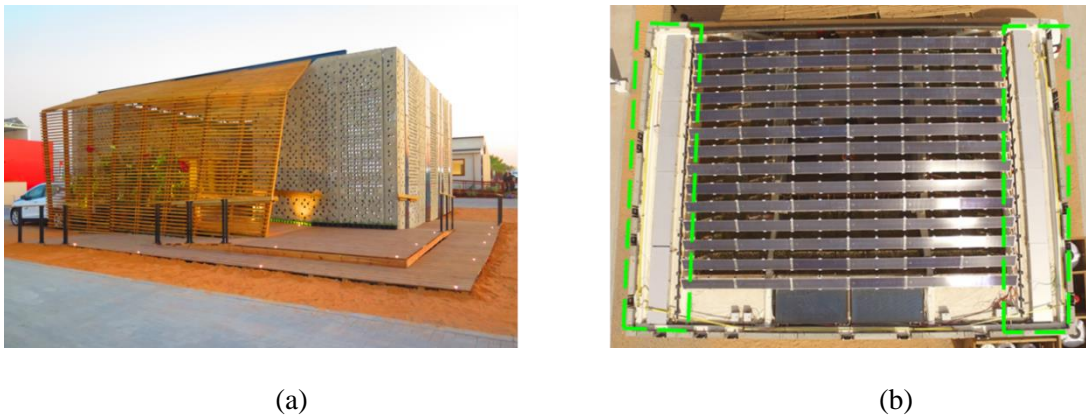


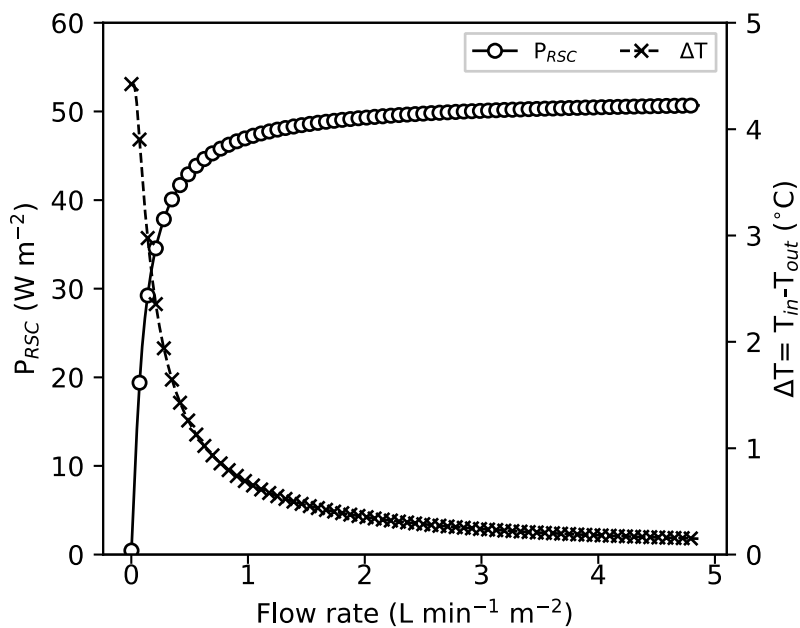
Figure 4 (a) BaityKool house during the Solar Decathlon Middle East 2018 in Dubai. (b) Representation of the installation of RSC panels on the roof of the BaityKool house.

#### 258 4.1 Mass flow rate choice and arrangement of RSC panels

259 Following the method described in section 3, Figure 5 shows the sub-ambient  
260 temperature drop and the cooling power density of the RSC panels for different flow rates in a  
261 typical night in Dubai (14-15 November). The calculations are based on the average value of  
262  $T_a$ ,  $T_{sky}$  and  $V_w$  from 19:00 to 07:00. Remember that here, the RSC system does not operate  
263 during the day due to the potentially high solar absorptivity of the anodized surface: cooling  
264 needs in the BaityKool prototype that cannot be covered by night free cooling (in Dubai)  
265 mostly occur during the summer season (June to September), and during this very hot period,  
266 the daytime average effective sky temperature is higher than a reasonable indoor air set-point

267 temperature (around 26°C, as assumed in this paper). It can be seen in Figure 5 that, at low  
 268 flow rate values, the temperature difference is maximal ( $\Delta T=4.4^\circ\text{C}$ ). In contrast, at high flow  
 269 rate (4.85 L min<sup>-1</sup> m<sup>-2</sup>), we obtain the maximum cooling power (50.6 W m<sup>-2</sup>). Depending on  
 270 the application, the flow rate can be chosen to maximize either the temperature difference  $\Delta T$   
 271 or the cooling power.

272 In our case, the flow rate is chosen in order to ensure a compromise between cooling  
 273 power and temperature difference. We chose a flow rate of 0.25 L min<sup>-1</sup> m<sup>-2</sup>, which  
 274 corresponds to a sub-ambient temperature  $\Delta T_{sub-a}=2.1^\circ\text{C}$  and a cooling power density  
 275  $P_{RSC}/A_{RSC}=36.6 \text{ W m}^{-2}$ . For the total surface area of the panels (11.5 m<sup>2</sup>), the corresponding  
 276 value of total mass flow rate that the pump must provide is 172.5 L h<sup>-1</sup>.



277  
 278 **Figure 5 Cooling power ( $P_{RSC}$ ) (W m<sup>-2</sup>) (black continuous line with round markers) (left y-axis) and sub-ambient**  
 279 **temperature drop  $\Delta T_{sub-a}$  (°C) of the Radiative Sky Cooling (RSC) panels (black dashed line with cross markers)**  
 280 **(right y-axis) in Dubai during a typical night (14 -15 November).**

281 BATISOL<sup>®</sup> panels were designed to support a maximum pressure of 2 bars. Thus, the  
 282 arrangement of the 16 panels (in series and in parallel) is considered, in order to limit the  
 283 pressure drop across them to less than 2 bars while minimizing the whole water circuit

284 complexity (for installation and maintenance reasons). Basically, four arrangements are  
285 considered:

- 286 - 1 circuit with 16 panels in series
- 287 - 2 circuits with 8 panels in series in each circuit
- 288 - 4 circuits with 4 panels in series in each circuit
- 289 - 8 circuits with 2 panels in series in each circuit

290 For a total flow rate of  $172.5 \text{ L h}^{-1}$ , the pressure drop values for these four arrangements  
291 are presented in Table 1. It considers pressure losses in the circuit panels, regular pressure  
292 losses all along the pipes and singular pressure losses due to the different hydraulic  
293 accessories used in the installation (elbow, non-return valve, etc.).

294 **Table 1 Pressure drop as a function of number of circuits in the Radiative Sky Cooling (RSC) system**

Number of circuits	1	2	4	8
Pressure drop (bar)	4.8	1.88	0.93	0.46

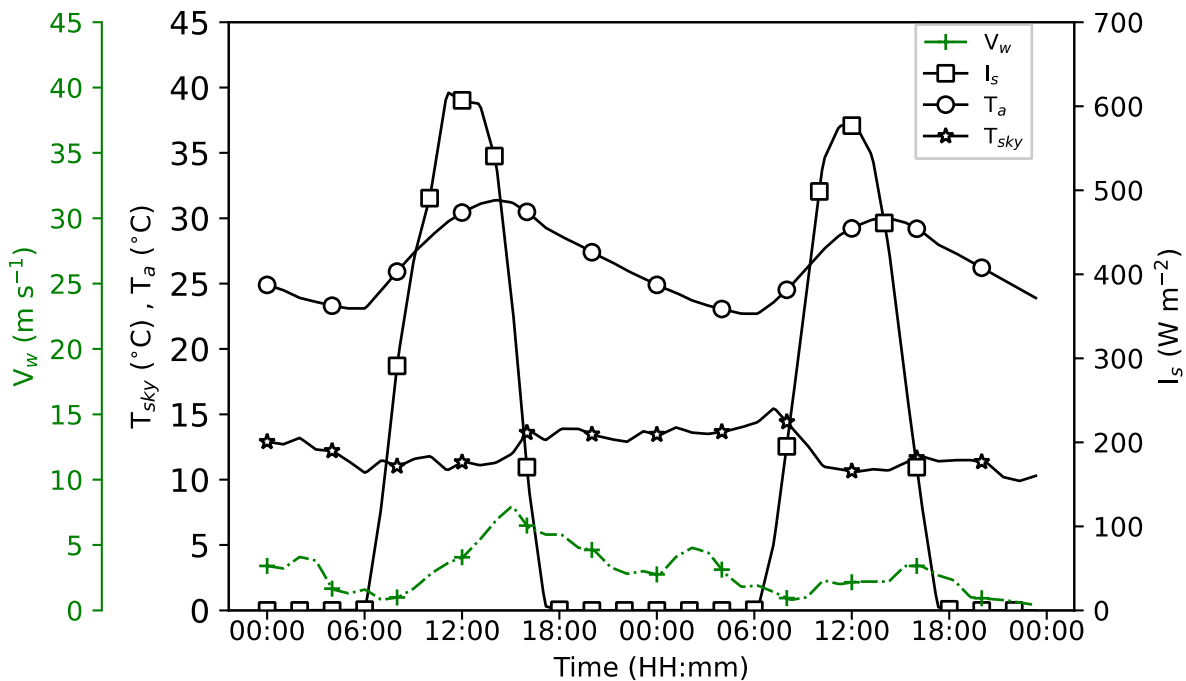
295 It is clear that the three configurations of 2, 4 and 8 circuits allow total pressure on the circuit  
296 to be less than 2 bars for a flow rate of  $172.5 \text{ L h}^{-1}$ . We ultimately chose the arrangement of 4  
297 circuits with 4 RSC panels in series.

## 298 **4.2 Volume storage choice**

299 In order to choose the volume of the storage tank, a simulation was carried out in Dubai  
300 climatic conditions during two typical days in winter (from 13 to 15 November). Figure 6  
301 shows the solar radiation, wind velocity, effective sky temperature and ambient temperature  
302 used as input for the numerical model of the RSC system with storage (effective sky  
303 temperature classically referring to an equivalent temperature based on a blackbody radiation  
304 hypothesis for the canopy). In the absence of solar radiation, the wind favors convective

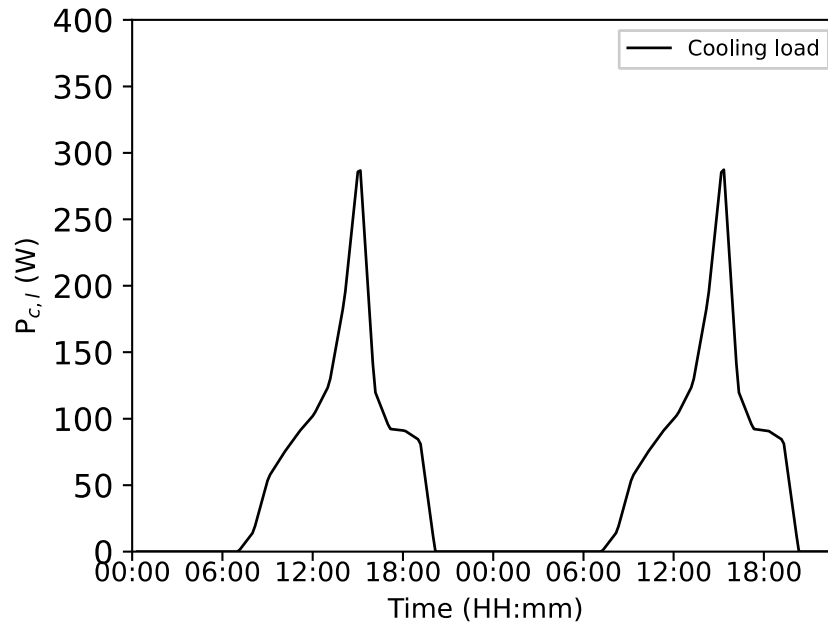
305 contributions that are not beneficial to nocturnal cold production, especially when the  
 306 temperature of the panels is below ambient temperature ( $T_{al} < T_a$ , convective heating [12]). On  
 307 the other hand, the wind is beneficial when the panel temperature is higher than the ambient  
 308 temperature ( $T_{al} > T_a$ , convective cooling [44]).

309 Furthermore, a daily cooling load profile was used to represent the cooling load in one  
 310 of the BaityKool rooms (Room-kitchen-area=10.5 m<sup>2</sup>). During this period, external ambient  
 311 air temperature ranges from 22.7°C to 31.4°C. In addition, the effective sky temperature  
 312 varies between 9.9°C and 15.4°C. Solar irradiance peaked at 616.1 W m<sup>-2</sup> on November 13.  
 313 The cooling load represented in Figure 7 was estimated considering thermal gains through the  
 314 walls, solar gains through the window, and thermal gains of the occupants in the room for a  
 315 typical day in Dubai during the winter. The energy required to maintain the room temperature  
 316 at 26°C is 1.4 kWh day<sup>-1</sup>. In this section on sizing, the pipes of the RSC system are assumed  
 317 to be well insulated so that heat losses (gains) are negligible.



318  
 319 **Figure 6 Meteorological conditions on 13 and 14 November in Dubai: black line with round markers represents**  
 320 **ambient air temperature ( $T_a$ ) (°C). Black continuous line with star markers represents effective sky temperature ( $T_{sky}$ )**

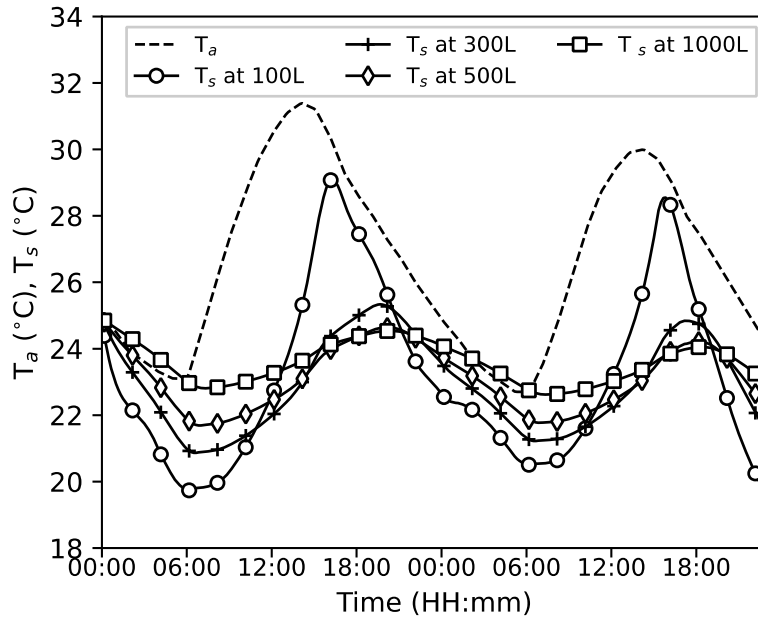
321 (°C). Green dash-dotted line with cross markers represents wind velocity ( $V_w$ ) ( $\text{m s}^{-1}$ ). Black line with square markers  
322 represents solar irradiance ( $I_s$ ) ( $\text{W m}^{-2}$ ).



323

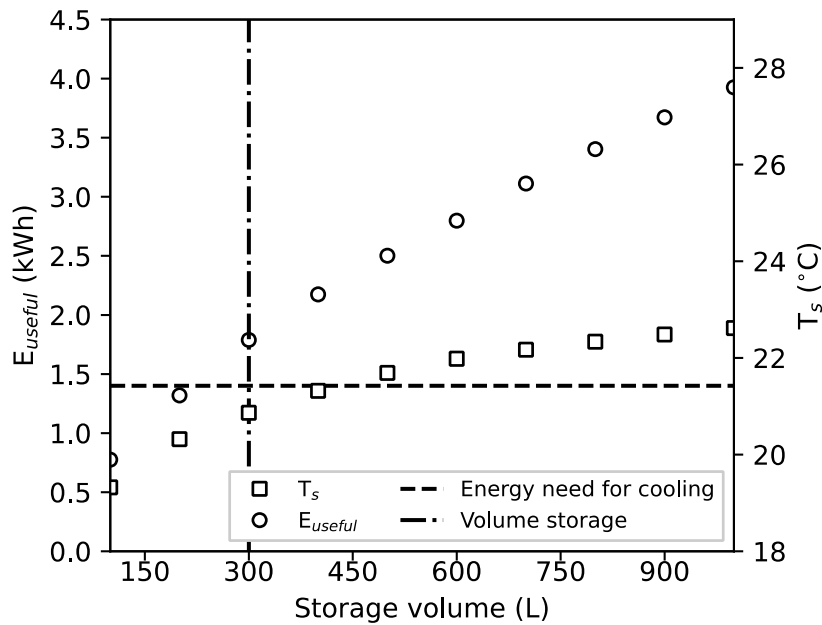
324 **Figure 7 Cooling load ( $P_{c,l}$ ) (W) of the room in BaityKool between 13 and 14 November in Dubai.**

325 Figure 8 shows the water storage temperature for different values of the water volume  
326 tank. Regardless of the storage volume, the RSC cold production contributes to the decrease  
327 in the water storage temperature during the night to below the ambient temperature, due to the  
328 radiative heat exchange of the RSC panels with the sky (canopy). This water storage  
329 temperature follows the variation in the cooling load with a phase shift and damping that  
330 depends on the storage volume. By increasing the storage volume from 100 L to 1000 L, the  
331 maximum value of the water storage temperature decreases from 29.1 to 24.8°C while the  
332 phase shift increases from 1 hour and 20 minutes to 5 hours and 20 minutes, and the minimum  
333 water storage temperature increases from 19.7 to 22.8°C.



334  
 335 **Figure 8 Ambient air temperature ( $T_a$ ) ( $^{\circ}\text{C}$ ) (black dashed line) and water storage temperature ( $T_s$ ) ( $^{\circ}\text{C}$ ) for different**  
 336 **storage volumes: 100 L (black continuous line with round markers), 300 L (black continuous line with cross markers),**  
 337 **500 L (black continuous line with diamond markers) and 1000 L (black continuous line with square markers),**  
 338 **between 13 and 14 November in Dubai.**

339 Figure 9 represents both the *minimum* value of the water storage temperature and the  
 340 useful energy stored in the tank, versus the storage volume. As mentioned before, this  
 341 minimal value increases by about  $3.3^{\circ}\text{C}$  ( $19.3$  to  $22.6^{\circ}\text{C}$ ) as the tank volume increases from  
 342 100 L to 1000 L, and remains below the desired value for the internal air temperature ( $26^{\circ}\text{C}$ ).  
 343 In terms of useful energy, Figure 9 shows that it increases (from 0.7 kWh to 3.9 kWh) with  
 344 the storage volume. Note also that the storage volume that corresponds to the energy needed  
 345 for cooling the room (1.4 kWh) is 217 L. To ensure this cooling load during the SMDE 2018  
 346 competition we chose to oversize this storage and installed a 300-liter storage tank in the  
 347 BaityKool house.



348

349 **Figure 9** Minimal storage temperature ( $T_s$ ) (°C) (black square markers) and useful energy stored ( $E_{useful}$ ) (kWh)  
 350 (black round markers) versus storage volume. Horizontal black dashed line represents the energy needed to cool the  
 351 room (1.4 kWh) corresponding to the storage volume (300 L) (vertical black dash-dotted line).

## 352 5 Experimental platform and instrumentation

353 Sixteen RSC panels are installed on the roof of BaityKool, arranged in 4 circuits in  
 354 parallel (4 panels in series in each circuit) with a total area of 11.5 m<sup>2</sup>. The pipes are insulated  
 355 with 19 mm of black rubber insulation pipe. The outlet water temperature of the RSC panels  
 356 is measured using a PT100 temperature sensor (Produal TEP NTC 100,  $\pm 0.5^\circ\text{C}$  accuracy).  
 357 This is installed on one circuit and mounted on the pipe by means of an adjustable tie. For the  
 358 storage tank, a commercial Solerio H300 from Atlantic is used (Volume of water 300 L,  
 359  $U \cdot A = 2.75 \text{ W K}^{-1}$ ). The storage temperature is measured using a PT100 (TEY4 NTC 10,  
 360  $\pm 0.5^\circ\text{C}$  accuracy) placed half-way up the water tank in a position specified by the  
 361 manufacturer. Total flow rate is measured by an ultrasonic flow sensor (Belimo FM015R-SZ,  
 362  $\pm 6\%$  accuracy). Temperature and flow rate data are monitored and stored using a building  
 363 automation system from Distech Controls.

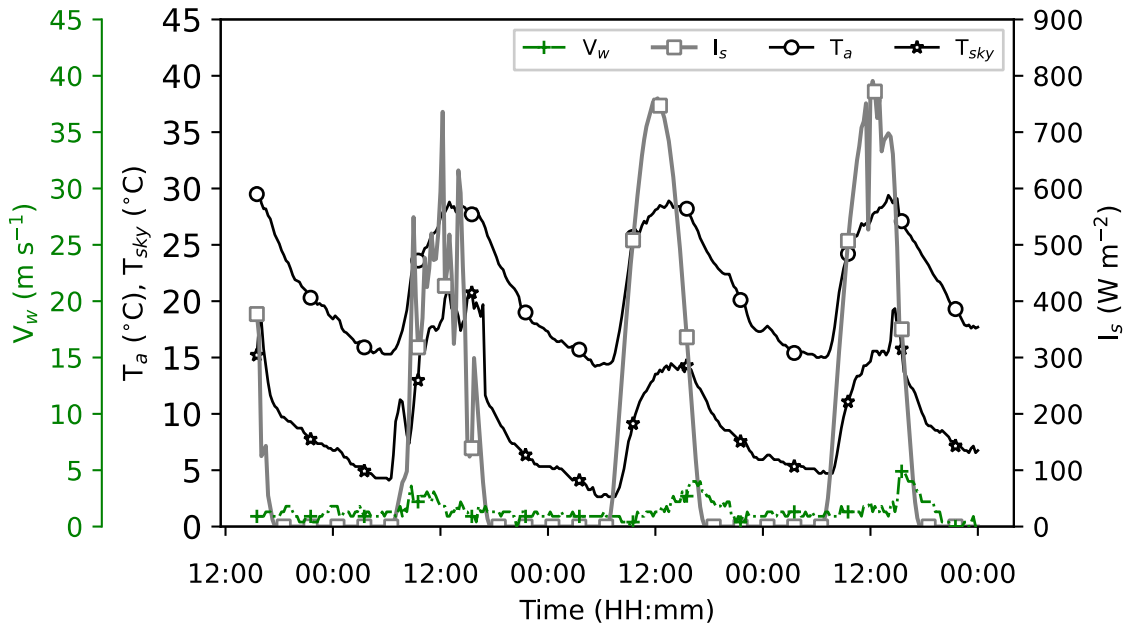
364 The effective sky temperature ( $T_{sky}$ ) is measured using a pyrgeometer SGR3-V (Kipp &  
365 Zonen, <5% accuracy). Data are stored on the computer using Smart Explorer software from  
366 Kipp & Zonen. For the weather conditions, a weather station (Vintage pro2 plus from Davis  
367 instruments) is installed on the roof of BaityKool. It measures and stores data for ambient  
368 temperature ( $\pm 0.5$  K accuracy), air relative humidity ( $\pm 2\%$  accuracy), solar irradiance ( $\pm 5\%$   
369 accuracy), wind direction ( $\pm 3^\circ$  accuracy) and wind velocity ( $\pm 3$  km h<sup>-1</sup> accuracy).

## 370 **6 Experimental evaluation of the energy performance in Dubai**

371 In order to evaluate the thermal performance of the installed RSC system with storage,  
372 we carried out an experimental test consisting of three successive nights' cooling without  
373 daily cold diffusion (only cold production by RSC panels and cold storage in the tank).

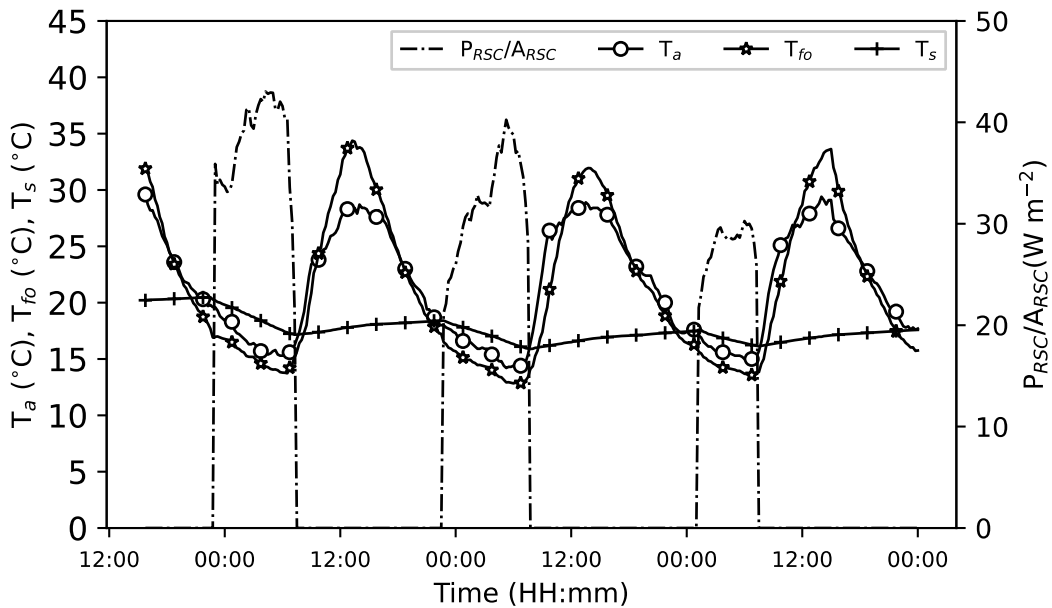
374 Figure 10 shows the weather conditions during the test phase from 2 to 5  
375 December 2019. The ambient temperature varies between 29°C during daytime and 14°C  
376 during night-time. The maximal effective sky temperature is reached during the first day with  
377 a value of  $T_{sky}=21^\circ\text{C}$  while the minimal temperature is reached during the second night with a  
378 value of  $T_{sky}=2.5^\circ\text{C}$ . During this period, solar irradiance reaches its maximum value (800  
379 W m<sup>-2</sup>) on December 5.





380

381 **Figure 10** Weather conditions in Dubai from 2 to 5 December 2019. Black solid line with round markers represents  
 382 ambient air temperature ( $T_a$ ) (°C). Black solid line with star markers represents effective sky temperature ( $T_{sky}$ ) (°C).  
 383 Green dash-dotted line with cross markers represents wind velocity ( $V_w$ ) (m s<sup>-1</sup>). Grey line with square markers  
 384 represents solar irradiance ( $I_s$ ) (W m<sup>-2</sup>).



385

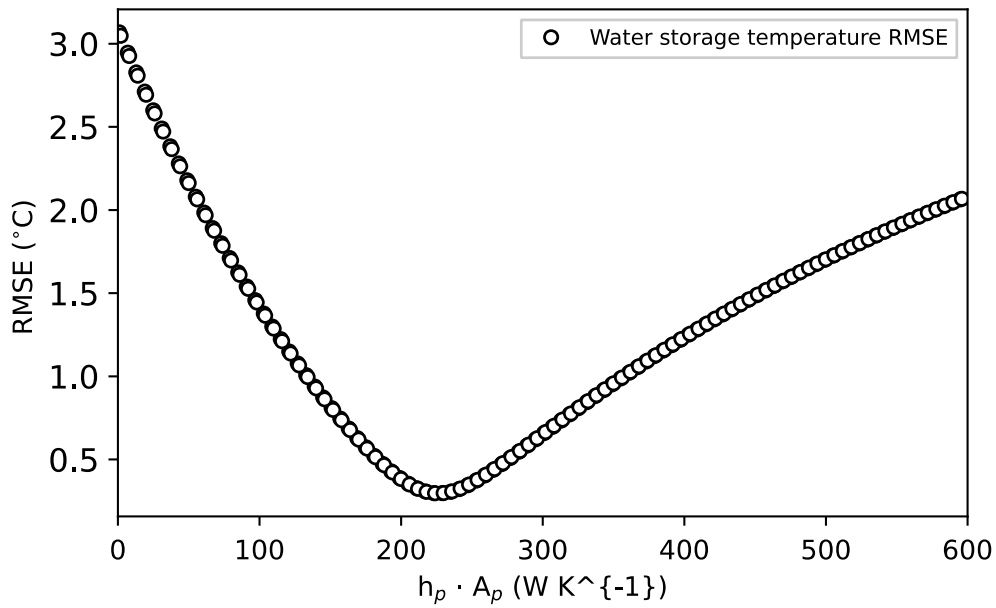
386 **Figure 11** Radiative Sky Cooling (RSC) panels outlet temperature ( $T_{fo}$ ) (°C) (black dash-dotted line with star  
 387 markers), storage tank temperature ( $T_s$ ) (°C) (black continuous line with cross markers), ambient air temperature  
 388 ( $T_a$ ) (°C) (black continuous line with round markers), and cooling power density ( $P_{RSC}/A_{RSC}$ ) (W m<sup>-2</sup>) (black solid line  
 389 with star markers) (right y-axis) (when the pump between the panels and the storage tank is in operation). From 2 to  
 390 5 December 2019 in Dubai.

391 Figure 11 illustrates the thermal performance of the RSC system in terms of  
 392 temperature and cooling power density from 2 to 5 December 2019. The water mass flow rate  
 393 is  $110 \text{ L h}^{-1}$ , which is less than the sized value. This is mainly due to the choice of pump and  
 394 the excessive pressure drop in the RSC system hydraulic circuit (a consequence of some  
 395 unexpected pipe elbows which were added to the BaityKool hydraulic circuit during  
 396 assembly). Due to the radiative Sky Cooling phenomenon, the outlet water temperature of the  
 397 RSC panels is below the ambient temperature during the three successive nights by a  
 398 maximum of  $\Delta T_{sub-a} = 2.8^\circ\text{C}$ . Average cooling power density is between  $30 \text{ W m}^{-2}$  and  $45$   
 399  $\text{W m}^{-2}$ . This cold production resulted in a decrease in the storage tank temperature from  
 400  $20.2^\circ\text{C}$  to  $17.7^\circ\text{C}$  during the first night, from  $18.4^\circ\text{C}$  to  $15.9^\circ\text{C}$  during the second night, and  
 401 from  $17.6^\circ\text{C}$  to  $16.0^\circ\text{C}$  during the third night. We notice a slight increase in the storage  
 402 temperature during the day because of heat losses from the tank into the ambient air.

403 In order to identify the average heat loss coefficient in the pipe and hydraulic  
 404 accessories  $h_p$ , the model of the RSC system proposed in section 2.2 is considered, together  
 405 with the weather conditions from 2 to 6 December and the monitored flow rate value. The  
 406 following Root Mean Square Error (RMSE) is then computed (Eq. 11):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_{s,num,i} - T_{s,exp,i})^2} \quad \text{Eq. 11}$$

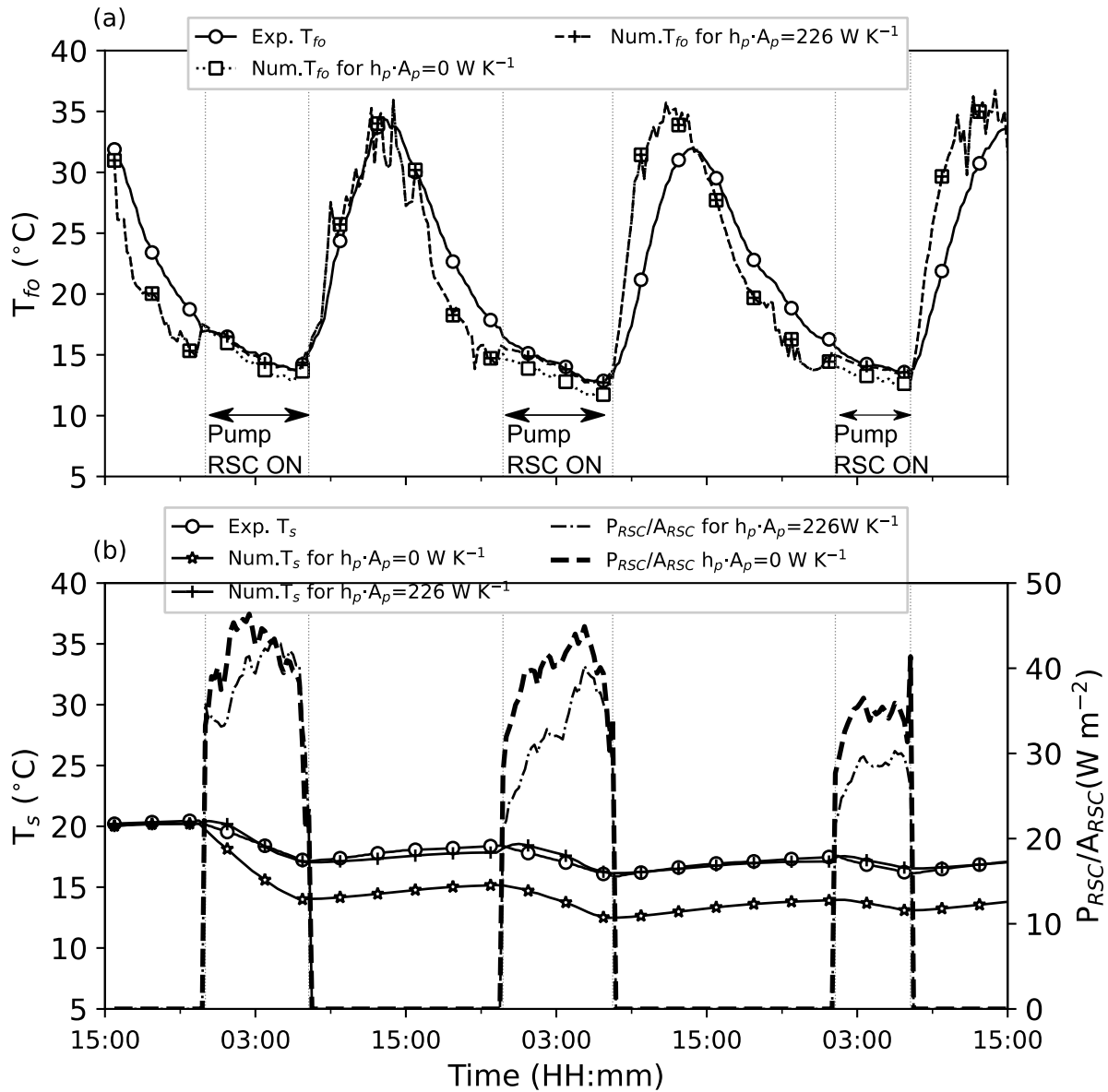
407 where  $T_{s,num,i}$  and  $T_{s,exp,i}$  are the modeled and measured water storage temperature (K)  
 408 respectively.



409

410 **Figure 12 Identification of heat loss in the hydraulic circuit of the RSC system: water storage temperature RSME (°C)**  
 411 **versus water-pipe heat exchange coefficient considering area of the pipe  $h_p \cdot A_p$  (W K<sup>-1</sup>).**

412 Figure 12 shows a *minimum* value of RMSE (0.29°C) for a value of the heat exchange  
 413 coefficient  $h_p \cdot A_p = 226$  W K<sup>-1</sup>. Corresponding numerical values in terms of water storage  
 414 temperature  $T_s$  and RSC outlet temperature  $T_{fo}$  are compared to experimental values in Figures  
 415 13(a) and 13(b) respectively, confirming good agreement between experimental and  
 416 simulation results for this  $h_p$  value. In Figures 13(a) and 13(b), simulation results for  $h_p \cdot A_p = 0$   
 417 W K<sup>-1</sup> are also proposed for  $T_s$ ,  $P_{RSC}/A_{RSC}$  and  $T_{fo}$ , in order to estimate the impact of insulating  
 418 pipes and hydraulic accessories on the RSC system performances: better insulation of the  
 419 pipes and hydraulic accessories will certainly reduce the heat gains and the stored water  
 420 storage temperature considerably.



421

422 **Figure 13 (a) Experimental results of Radiative Sky Cooling (RSC) outlet temperature ( $T_{fo}$ ) (black continuous line**  
 423 **with round markers) and numerical results of RSC  $T_{fo}$  for  $h_p \cdot A_p = 0 \text{ W K}^{-1}$  (black dotted line with square markers)**  
 424 **and  $h_p \cdot A_p = 226 \text{ W K}^{-1}$  (black dashed line with cross markers). (b) Experimental results and water Storage**  
 425 **temperature ( $T_s$ ) (°C) (black continuous line with round markers), numerical results of  $T_s$  for  $h_p \cdot A_p = 0 \text{ W K}^{-1}$  (black**  
 426 **continuous line with star markers) and  $h_p \cdot A_p = 226 \text{ W K}^{-1}$  (black continuous line with cross markers), cooling power**  
 427 **density ( $P_{RSC}/A_{RSC}$ ) ( $\text{W m}^{-2}$ ) for  $h_p \cdot A_p = 226 \text{ W/K}$  (tiny black dash-dotted line) and for  $h_p \cdot A_p = 0 \text{ W K}^{-1}$  (large black**  
 428 **dashed line) (right y-axis).**

429

430

431

Considering periods of pump operation in the case of  $h_p \cdot A_p = 0 \text{ W K}^{-1}$ , Figure 13b shows that the storage temperature varies on average between  $17.1 \pm 0.3^\circ\text{C}$  and  $18.8 \pm 1.2^\circ\text{C}$  while the effective sky temperature in Dubai varies from  $4.1 \pm 1.1$  to  $5.8 \pm 1.1^\circ\text{C}$  (see Figure

432 10). The corresponding  $P_{RSC}/A_{RSC}$  produced during pump activation is about  $37.9\pm 2.5 \text{ W m}^{-2}$   
433 (see Figure 13b). The temperature difference between the indoor set-point temperature ( $26^\circ\text{C}$   
434 in our case) and the sky ranges from approximately  $20.2$  and  $21.9^\circ\text{C}$ . This temperature  
435 difference provides important information for estimating the ability and the performance of  
436 the RSC system with cold storage to meet the cooling needs in a given place-location and  
437 time-period relying solely on knowledge of the average effective night-time sky temperature.  
438 With an appropriate indoor set-point temperature, knowing the average effective night-time  
439 sky temperature will allow rapid assessment of the cooling potential of such a system.  
440 According to our results, a temperature difference of  $20^\circ\text{C}$  indicates a significant potential  
441 (slightly less than  $40 \text{ W m}^{-2}$ ) that could be exploited for such a water RSC cooling production  
442 and storage system.

## 443 7 Conclusion

444 In the present study, we propose a sizing method for a night-time radiative sky cooling  
445 system that includes water storage, mostly for day-time cooling uses, based on four  
446 performance indicators (sub-ambient temperature, cooling power density, *minimum* storage  
447 temperature and useful stored energy). Using these indicators, it is possible to choose the  
448 operational water flow rate in cooling generation (for a fixed value of the area intended for the  
449 radiative sky cooling panels) and in the storage volume, in order to cover cooling needs. This  
450 method was applied to the BaityKool project, a house prototype built in the Dubai desert  
451 (United Arab Emirates, UAE) for the Solar Decathlon Middle East 2018 competition. A case  
452 study was conducted on part of the BaityKool prototype, a living zone with an area of  
453  $10.5 \text{ m}^2$ . Using a  $0.3 \text{ m}^3$  cold storage tank and a radiative sky cooling area of  $11.5 \text{ m}^2$ , the  
454 experimental campaign was carried out over 3 successive nights and noted an average cooling  
455 production of between  $30$  and  $45 \text{ W m}^{-2}$ . These results indicate that the insulation of the

456 hydraulic circuits is of crucial importance and has a considerable influence on the system  
457 performance in terms of production and storage.

458         It is expected that the proposed sizing method can be used as a design support tool for  
459 engineers and researchers to design successful and economically competitive radiative sky  
460 cooling systems under other weather conditions (e.g. northern Mediterranean or near-oceanic  
461 climates). An initial assessment should be based on the temperature difference ( $\Delta T$ ) between  
462 the desired indoor set-point temperature and the mean effective night-time sky temperature in  
463 the considered location. Once the cooling potential is proven ( $\Delta T > 20^\circ\text{C}$ ), the method  
464 proposed in this article can be applied to size the elements that make up the radiative sky  
465 cooling system with storage consistent with part or all of the building's the cooling needs and  
466 architectural considerations such as available roof area.

467         In order to improve the overall performance of the system, future work could assess  
468 systems integrating both the production of cold by radiative sky cooling (overnight) and a  
469 heat supply or domestic hot water production using solar energy (during the daytime), through  
470 the same panels. The hydraulic operations of the two production modes are very similar,  
471 although the production potential (power densities) differs significantly for these two  
472 renewable energy resources.

## 473 **Acknowledgments**

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477 acquisition system and the data.

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