Chapter 2

QGreen Low-Carbon Technology: Cooling Greenhouses and Barns Using Geothermal Energy and Seawater Bittern Desiccant

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Additional information is available at the end of the chapter

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Abstract

In hot-humid climates, cooling greenhouses and barns are needed to protect crops from extremely high temperature and to ensure high-yielding dairy cows. In Qatar, outside air temperature exceeds 46°C during summer, and the wet-bulb temperature can exceed 30°C which makes greenhouses and barns unworkable during this season. This study provides theoretical and experimental data for cooling greenhouses and barns using highly efficient and low-carbon technology (QGreen). QGreen uses groundwater (geothermal) for indirect-direct evaporative cooling coupled with desiccant dehumidification. The desiccant used is seawater bittern which is a by-product of the desalination process. A desiccant indirect-direct evaporative cooling panel system is designed and analyzed. The results show that the use of groundwater will enhance the efficiency and reduce the wet-bulb temperature dramatically. As a result, the efficiency of the overall cooling system is enhanced by more than 50% compared to the direct evaporative cooling efficiency that was recorded.

Keywords: desiccant cooling, greenhouse, barns, seawater, CO_2 emissions, brine

1. Introduction

The Gulf Region can be characterized by an extreme set of climatic conditions which are identified in the literature [1]. Extreme climatic conditions impose a heavy reliance on cooling, mostly electricity-based, and thus a strong and structural dependency of a high-energy resource. In addition to the dry-bulb temperature and solar radiation, the humidity is high in summer which raises the cooling challenges. The average hourly outdoor web-bulb temperature for Doha city is shown in **Figure 1**. Consequently, greenhouses in arid conditions suffer to produce crops during summer months, and dairy cow milk production is also impacted. Maintaining reasonable temperature and humidity levels for both greenhouses and barns became a vital challenge that meets these industries in the region. Plant dehydration and loss occurs during the hot and dry summer months and winter heating months. Serious problems occur when the humidity in the greenhouse and propagation environments is low. Plants will suffer and typically slow or halt the growing process.

Greenhouses and barns are important for food security in the region. However, they require temperature and humidity control to ensure sustainable crop and milk production. Therefore, energy-efficient cooling solutions are more urgent today.

In hot-dry climates, evaporative cooling is one of the least expensive techniques and most effective active cooling technologies available in favor of greenhouses to lower the supply of air temperature and provide desired indoor climate [2]. Also, convective combined with an evaporative cooling system of the barn microenvironment is normally used when cattle suffer from severe heat stress in hot-dry climates, functioning by the simple physics of transferring surrounding air heat to evaporating water [3].

Evaporative cooling pads made of fibrous material woven together with large gaps in the grooves are added to the air inlets of tunnel-ventilated barns. In this way, the incoming air is pulled through a saturated medium where the conversion of water from a liquid to a vapor phase removes heat energy from the incoming air, which lowers its temperature but increases its relative humidity. Cooling efficiency is about 55–75% for most evaporative cooling pads, but these water-based systems are prone to plugging and algae growth [4].

The fan-pad systems, which are direct evaporative coolers, in greenhouses have been available several decades ago [5], and various aspects are available in the literature studies continuously

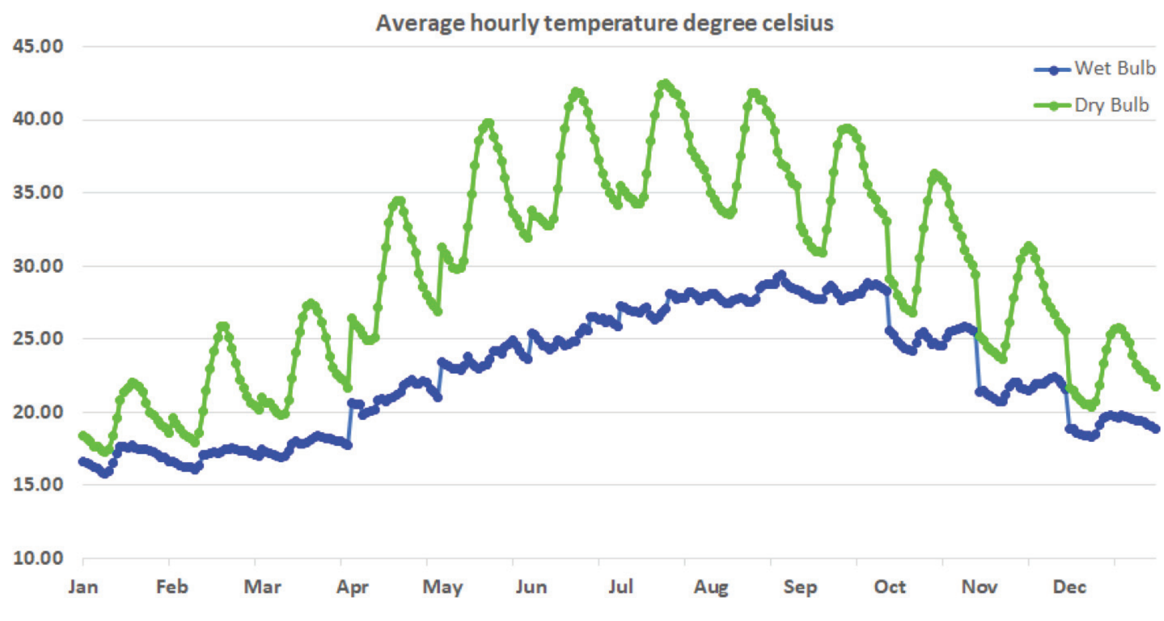

Figure 1. Average hourly temperature (Doha, Qatar).

being conducted to upgrade the performance of these systems. Several adjustments to the fan-pad system were present always to obtain better performance.

Some researchers have changed the traditional fan-pad setup in the greenhouse with mounted evaporative cooling boxes. They compared the performance of the later system with the original one but with four different pad types. They concluded that a better performance for the new system would be obtained in case of non-hermetic greenhouses [6]. Other researchers combined indirect evaporative cooling heat exchanger with cooling pads in one experimental setup while using groundwater as a cooling agent, and the results showed an enhanced cooling efficiency compared with the mere direct evaporative cooling system [7]. For greenhouse applications, an experimental study showed a reasonable performance of evaporative cooling pads operating under humid subtropical climate [8].

An interesting widely used second option of evaporative cooling for greenhouses is the fogging system, which use high-pressure nozzles and water pumps to generate fog droplets. This system has proven to be an effective cooling method for greenhouses in many areas in the world [9]. It provides a spatial distribution of the temperature which creates a high range of desired temperature and humidity in the greenhouse during most months of the year [10].

However, a portion of water does not evaporate or simply fall on the floor making a determination of evaporated fraction essential for evaluating the system performance and cooling efficiency. Investigators have extended the research perimeter of fogging system effectiveness by studying its effect on eggplant crop. They found that its stomatal conductance increased by about 73%, 31% decrease in crop transpiration, did not affect the fruit quality, and enhanced the mean fruit weight and marketable fruits and total fruit number per plant reduced though [11].

Foggers use atomizing nozzles to evaporate water. High-pressure (>200 psi) fogging systems integrating a ring of fogging nozzles to circulation fans disperse very fine droplets of water into the surrounding air. As fog droplets are emitted, they are immediately spread into the fan's air stream where they soon evaporate. Cattle are immediately cooled down as cooled air is blown over their bodies, and they inspire it [4].

A comparison study between fan sprinkler and fogging cooling systems was conducted on ten Holstein cows in Brazil. It was found that there was almost no difference in response of cows to the two systems [12]. An experimental study compared two commercially available systems (Korral Kool and FlipFan) used to cool Holstein dairy cows located in the Kingdom of Saudi Arabia. Both cooling systems were found effective in mitigating the heat, with a preference for the FlipFan system as it consumed less water and electricity and did not require the use of curtains on the shade structure [13].

The common research trend of nurturing the literature with better and more precise results always continues when investigators correlate the ambient temperature with the physiological variables of Holstein cows (with and without cooling) monitored during morning and afternoon milking under five different weather patterns throughout the year by the convective evaporative cooling system. The outcomes showed the usual positive relationship between the variables and the temperature, and the cooled cows exhibited higher milk production [14]. Different heat-load management strategies were compared to obtain the best configuration with the highest milk yield in the subtropical environment [15]. The treatment of open-sided iron-roofed day pen adjacent to dairy plus sprinklers gave the highest milk yield (23.9 L per cow per day).

Misting systems generate larger droplets (15 and 50 μm in diameter) than fogging systems but cool the air by the same principle. A study was designed to investigate the effects of wallowing and misting against no cooling in physiological responses of lactating Murrah buffalo during summer months in Mathura, India. The authors concluded that misting and wallowing were equally effective in a hot and dry period of summer, whereas wallowing was more effective during the hot and humid period of summer. As expected, the results showed higher milk yield in cooled buffaloes compared to the uncooled group during the experimental period [16].

Tunnel ventilation system has air inlets at one end of the barn and exhaust fans at the other. This technology works to enhance convective heat loss by removing excess heat and humidity from the immediate surroundings of animals.

It has been found that using sprinkling in combination with supplemental airflow results in a rapid change in cow body temperature and respiration rate and is superior to either a fan or sprinkling alone [17]. The simplest implementation of this cooling practice, which has been used, is wetting the cattle with manual sprinklers while increasing air velocity with fans directed towards the cows to increase the rate of water evaporation from the skin, and that leads to cooling effect [18].

Low-profile, cross ventilated barns were developed to move air parallel to the body of the cows when they are lying in stalls, while traditional tunnel ventilation moves air parallel to the ridge of the building. A ceiling could be used to limit the size of the cross-sectional area. However, most often, vertical baffles are used to accelerate the air at the cow body level to the desired velocity. Researchers experimentally investigated the effectiveness of tunnel ventilation cooling. They reported a dramatic reduction in heat stress and comfort of lactating dairy cows when compared with traditional cooling technologies under the climatic conditions present in the Southeastern United States [19].

In hot-humid climate, humidity control is essential to achieve sufficient cooling levels for dairy and crop production. Desiccant evaporative cooling systems can provide such needs. There are two types of desiccant systems: liquid and dry. Liquid desiccant systems commonly use two chambers with air/liquid contact surfaces. In the conditioning chamber, the process air is dehumidified as the concentrated desiccant absorbs moisture from the air. In the regeneration chamber, the air is humidified as moisture is transferred from the dilute desiccant to the scavenging air. The desiccant or exhaust air is usually heated to promote desiccant regeneration. A desiccant pump, level controls and heat exchanger are typically included in the system. The heat required for regenerating the desiccant can be supplied by fossil fuel, waste heat and solar energy.

Several liquid desiccants, including aqueous solutions of the organic compounds (e.g. triethylene glycol) and aqueous solutions of inorganic salts (e.g. lithium chloride), have been employed to remove water vapor from the air. The process equipment utilized for liquid–gas contacting is falling film, spray or packed towers.

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	conventional		seawater derived	
	LiBr	LiCl	$CaCl_2$	$MgCl_2$
Equilibrium RH% (← More hygroscopic)	6	11	29	33
Abundance litres desiccant per m³ of seawater (More abundant →)	0.004	0.003	2.3	13
Toxicity (Less toxic →)	Medium	Medium	Low	Low

Figure 2. Comparison between conventional salts and seawater bittern.

Several researchers addressed the possibility of using desiccant dehumidification and solar energy [20–24] in conjunction with evaporative cooling systems to be more adaptive with the humid. Their target is to lower the average daily maximum greenhouse temperatures by about 4–6°C compared with the normal evaporative system.

This chapter discusses and analyzes an efficient system to cool greenhouses and barns. The system utilizes desalinated groundwater and seawater bittern to cool and dehumidify the air in a compact panel. The concept applied is the so-called green panel due to its low impact on the environment regarding recycling the desalination brine and also using waste heat or renewables to provide sufficient environmental and control for both plants and cattle.

Figure 2 summarizes the difference between the magnesium-based desiccant and conventional desiccants regarding toxicity, availability, cost and equilibrium humidity.

2. Desiccant dehumidification and regeneration effectiveness

Although today's computers are much faster than a few years ago, some researchers and designers have found the time-consuming finite difference model when predicting the performance of complicated systems over a long period. However, for desiccant cooling, the finite difference model requires the heat and mass transfer coefficients to be experimentally determined. The quick alternative method that can be used to predict the outlet conditions from the dehumidifier and regenerator is the effectiveness method. But this requires effectiveness correlations to be developed [25, 26].

2.1. The dehumidifier effectiveness

The dehumidifier undergoes simultaneous heat and mass transfer. The mass transfer effectiveness can be defined as the ratio of actual change in air humidity ratio across the absorber divided by the maximum possible change [23]:

$$\varepsilon_m = \frac{\omega_{a,i} - \omega_{a,o}}{\omega_{a,i} - \omega_e} \tag{1}$$

The maximum outlet achievable difference in the air is obtained when the air is in equilibrium with the inlet desiccant solution (Pv,o = Ps,i).

In such a case, the air leaves the absorber with the equilibrium humidity ratio ^{e} that would be obtained when the partial pressure of water in the air is equal to the vapor pressure of the inlet desiccant solution, that is, when the driving force is zero [23].

The heat transfer effectiveness can be defined as the ratio the total heat transfer between the air and the solution to the maximum possible heat:

$$\varepsilon_h = \frac{h_{a,i} - h_{a,o}}{h_{a,i} - h_e} \tag{2}$$

where:

$$h_a = C_{P,a}(T_a - T_0) + \omega[C_{P,v}(T_a - T_0) + \lambda] \tag{3}$$

$$h_e = C_{P,a}(T_{s,i} - T_0) + \omega_e[C_{P,v}(T_{s,i} - T_0) + \lambda] \tag{4}$$

The outlet conditions from the dehumidifier can be predicted if both the heat and mass transfer effectiveness are known. It can be done easily by rearranging Eq. (1) and Eq. (2) to calculate $\omega_{a,o}$ and $h_{a,o}$.

$$\omega_{a,o} = \omega_{a,i} - \varepsilon_m(\omega_{a,i} - \omega_e) \tag{5}$$

$$h_{a,o} = h_{a,i} - \varepsilon_h(h_{a,i} - h_e) \tag{6}$$

The two values can be represented in the psychrometric chart to obtain the dehumidified air conditions. But this requires effectiveness correlations for simultaneous heat and mass transfer. A simplified empirical effectiveness correlation can be used. The correlation assumes that the moisture effectiveness changes greatly with air and desiccant flow rates and negligible impact of other inlet parameters [27]:

$$\varepsilon_d = 0.67 \times (m_L)^{0.403} \times (m_a)^{-0.352} \tag{7}$$

However, the enthalpy effectiveness is influenced by both the air and desiccant inlet parameters. The following correlation for enthalpy effectiveness can be used for predictions [27]:

$$\varepsilon_h = 0.015 \times (\Delta h_{ai})^{0.831} \times (m_L)^{0.712} \times (\Delta\omega_{ai})^{-0.537} \times (m_{ai})^{-0.352} \tag{8}$$

2.2. The regenerator effectiveness

The effectiveness of the regenerator is defined as the actual change in the solution vapor pressure across the packed regenerator divided by the maximum possible change [Elsarrag 2008]. The maximum outlet achievable difference is obtained when the outlet desiccant solution is in equilibrium with the inlet air (Pso = Pai). The following definition is used to evaluate the effectiveness of packed bed regenerators [26]:

$$\varepsilon = \frac{P_{si} - P_{so}}{P_{si} - P_{ai}} \tag{9}$$

where

$$P_{si} = f(X_i, T_{si});$$

$$P_{so} = f(X_o, T_{so});$$

$$P_{ai} = f(\omega_{ai}) = f(T_{dbi}, T_{wbi})$$

Accordingly, a simplified correlation obtained by using the results from the present study is [26]

$$\varepsilon_r = 79.12 + 1.21 \times \left(1 - \frac{P_{ai}}{P_{si}}\right) + 4.37 \times \frac{m_a}{m_L} \tag{10}$$

where

$$P_{ai} = \frac{\omega_{ai} P}{(622 + \omega_{ai})} \tag{11}$$

The outlet desiccant temperature can be calculated from the temperature difference ratio [26]:

$$\pi = \frac{T_{si} - T_{so}}{T_{si} - T_{ai}}$$

$$T_{so} = (1 - \pi) T_{si} + \pi T_{ai} \tag{12}$$

Where π can be calculated by the following equation:

$$\pi = 0.5723 - 0.1179 \frac{m_L}{m_a} \tag{13}$$

Another effectiveness correlation including the effect of the solution temperature, flow rate and concentration was found in the literature [28]:

$$\varepsilon_r = 67.4 \times (m_a)^{-0.703} \times (m_L)^{0.762} \times (t_{si})^{-0.909} \times (X)^{2.001} \tag{14}$$

3. Groundwater and ground temperature

Barns and greenhouses require fresh water for domestic use, irrigation and cooling purposes. Groundwater is one of the available options in the region which is considered as brackish water. Most of barns and greenhouses treat the groundwater for such applications. The table below shows a typical test of a borehole water in the North of Qatar.

The ground temperature in the North of Qatar is predicted using the following formula [29]:

$$T_g = T_m - A_s e^{-z\sqrt{\frac{\pi}{365\alpha}}} \cos\left\{\frac{2\pi}{365\left[t - t_o - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right]}\right\} \quad (15)$$

where;

T_m is the mean annual ground temperature at z = 0m in °C

A_s is the annual amplitude at z = 0m in °C

Z is the ground depth in m

t is year in days

t_0 is the phase constant –day of the year when the lowest ambient air temperature occurs

α is the thermal diffusivity of soil m^2/day

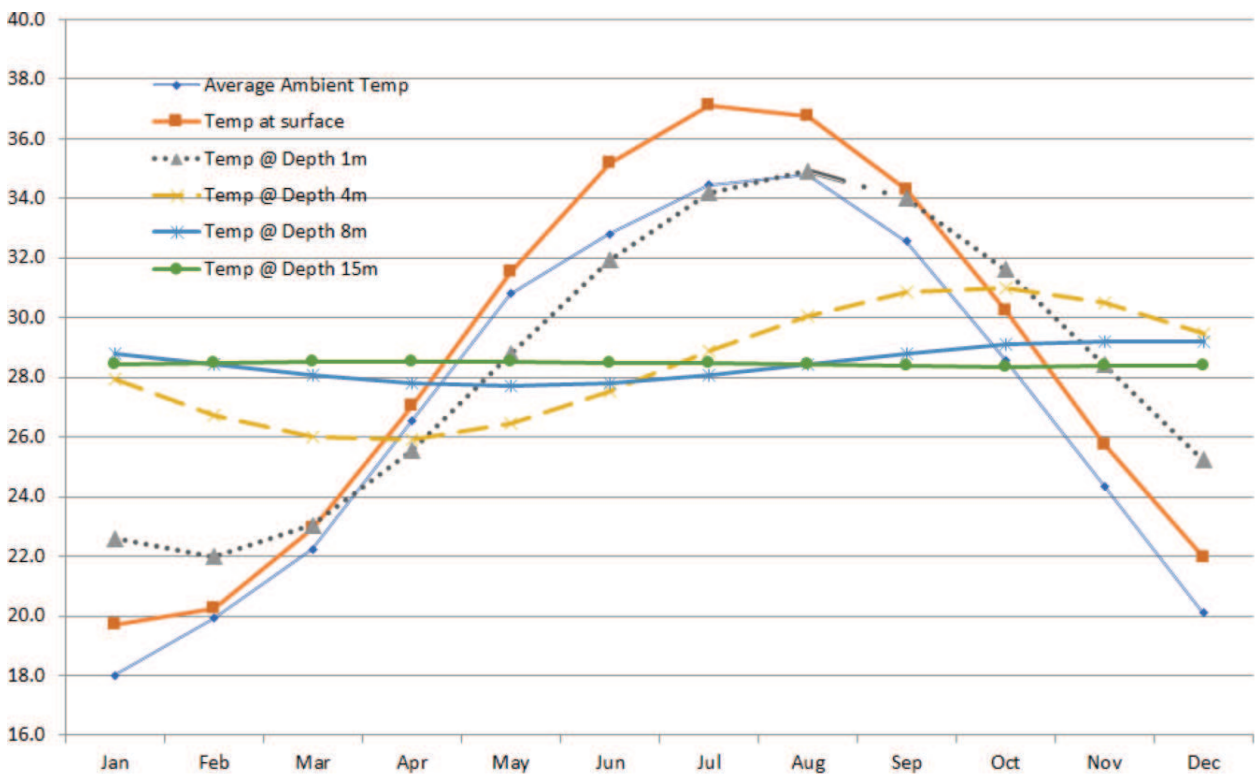

Figure 3. Ground temperature at different depths in Qatar.

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Qatar weather data were inserted into Eq. 15 to produce the predicted annual ground temperature profile at different depths as shown in **Figure 3**.

It can be seen that at the surface (z = 0 m) the temperature profile is sinusoidal, but the soil temperature profile becomes more flat when the depth increase. At 15 m depth, the soil temperature is approximately constant, 28.5°C in Qatar, and its value is close to the annual average ambient air temperature.

The above results are very encouraging and provide clear guidelines about the water quality and thermal energy to utilize the groundwater for irrigation and cooling applications.

As mentioned above, maintaining a wet-bulb temperature 24–27°C can support the corp and dairy industry. The wet-bulb temperature of the ambient air can be controlled by recovering the geothermal energy by indirect evaporative cooling. In a humid climate, more control can be achieved by using desiccant dehumidification (**Table 1**).

Tests performed	Results obtained	WHO/EPA/EU Guidelines
pH Value @25°C	7.86	6.5–8.5*
Electrical conductivity @25°C (μS/cm)	8620	Max 1000*
Total dissolved solids (TDS) (mg/l)	4469	Max 500
Total suspended solids (TSS) (mg/l)	78	No guideline
Total alkalinity ($CaCO_3$) (mg/l)	202	No guideline
Carbonate (CO_3) (mg/l)	<1	No guideline
Bicarbonate (HCO3) (mg/l)	246	Max 30*
Total hardness ($CaCO_3$) (mg/l)	2435	Max 500
Calcium (Ca) (mg/l)	559	Max 100
Magnesium (Mg) (mg/l)	252	Max 50
Sulfate (SO_4) (mg/l)	3073	Max 250
Chloride (Cl) (mg/l)	2274	Max 250
Nitrate (NO_4.N) (mg/l)	0.21	Max 10
Iron (Fe) (mg/l)	<0.03	Max 0.3
Residual chlorine (mg/l)	0.03	Max 0.3
Turbidity (NIU)	5.02	Max 4
Appearance	SL cloudy	—
Odor	Acceptable	Acceptable
Taste	N/A	Acceptable
Color	10	Max 15
Bacteria (*E. coli*) (counts/100 ml)	0	Absent
Bacteria (total coliform) (counts/100 ml)	0	Absent

Table 1. Groundwater test analysis in the north of Qatar.

4. System description

Figure 4 shows the complete system setup. The main advantages of the proposed system are the utilization of the geothermal energy, the use of low-toxic desiccant extracted from desalination process (rejected brine) and the compact wall-mounted cooling and dehumidification panel.

The QGreen panel consists of a bundle of thin polymer tubes and cellulose pads. The pressure drop across the panel is shown in **Figure 5**.

The QGreen polymer heat exchanger requires less maintenance and do not require any chemical water treatment. The scale does not adhere to the polymer tubes in the exchanger; therefore, scale inhibitors are not necessary, eliminating the cost of chemicals and labor necessary for water treatment. The panel utilizes indirect-direct evaporative cooling technology and desiccant dehumidification coupled with open- and closed-loop systems.

The system operation can be divided into process air, desiccant and water cycles. The process fresh air enters the QGreen cooling and dehumidification panel in a cross manner to the desiccant flow. The groundwater can consistently flow through the micro polymer tubes effectively removing heat from the seawater bittern desiccant and the air. The magnesium-based desiccant absorbs moisture from the air. As a result, the air is dehumidified, and its wet-bulb temperature decreased. The cooled and dehumidified air is then evaporatively cooled by either evaporative pads, misting or fog system. The cooled air is then supplied to the greenhouse or barn. The circulated desiccant is stored in a tank. The regenerator maintains the desiccant concentration within the required levels. The desiccant temperature is raised via flat

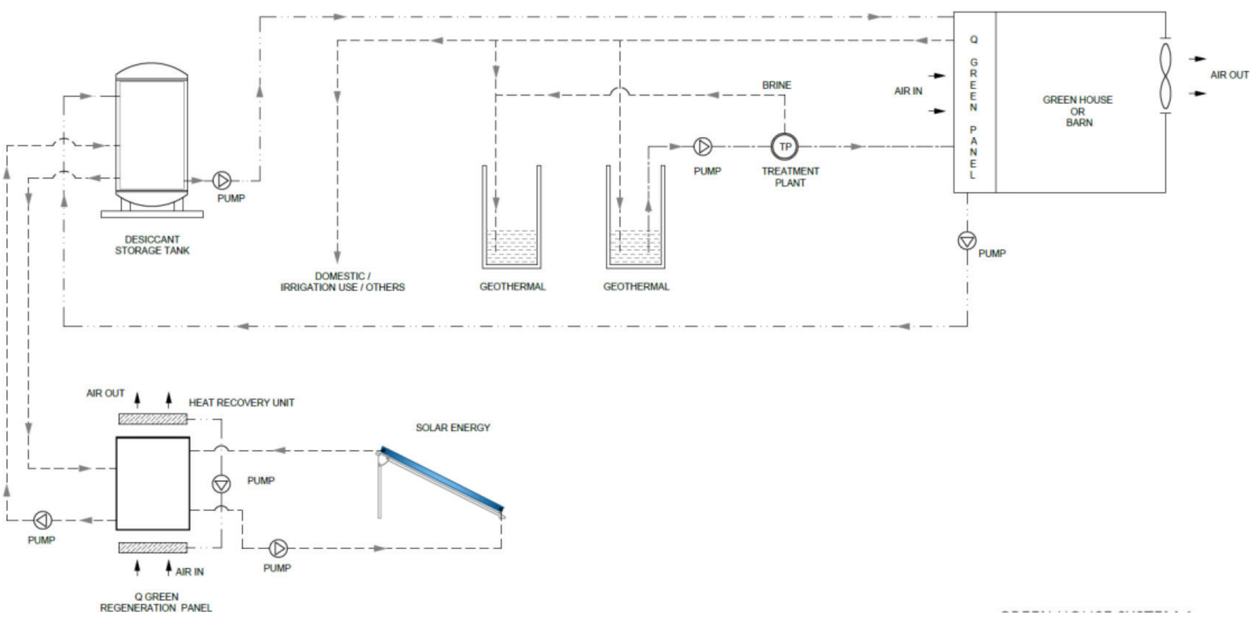

Figure 4. The proposed system schematics.

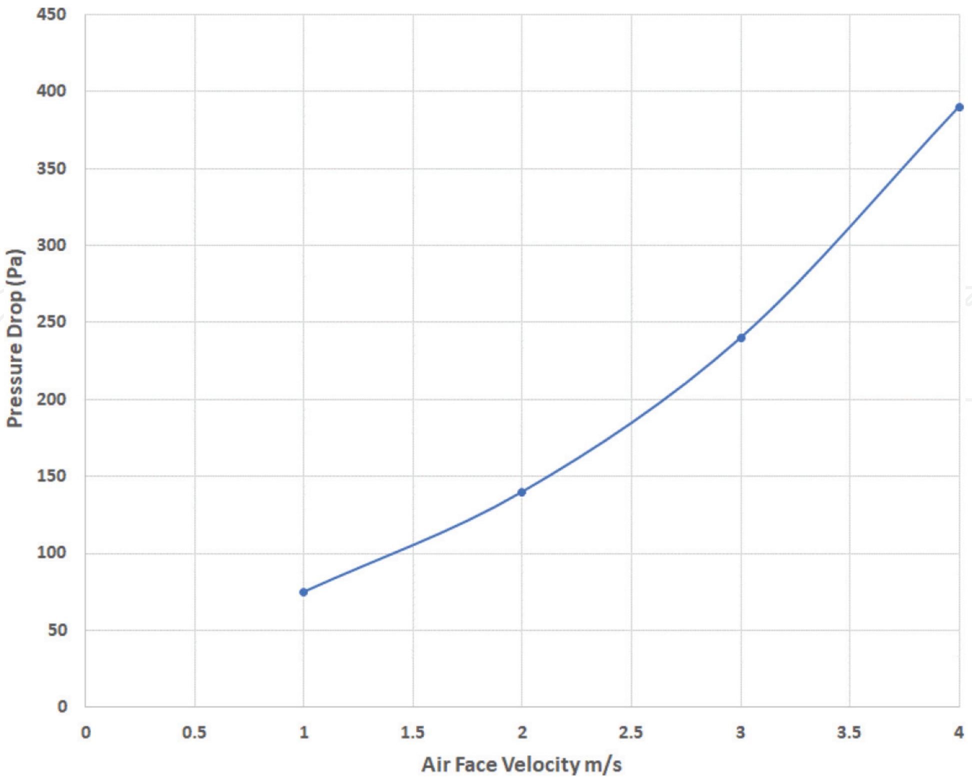

Figure 5. QGreen panel pressure drop (pa).

thermal collectors and hybrid photovoltaic thermal system. The average regeneration temperature is 50°C. The desiccant is sprayed over the QGreen packed regeneration panel. The scavenging air passes in a counter manner to the hot desiccant flow. As a result, the air is humidified, and the desiccant is concentrated.

5. Results and discussion

The rejected brine from the electricity water authority in Qatar is analyzed and enhanced by $MgCl_2$ to provide the sufficient concentration that will lower the process air wet-bulb temperature to the desired levels.

Figure 6 shows the relation between the equilibrium humidity and the minimum wet-bulb which can be obtained assuming that the effectiveness is 100% and the air temperature is equal to the solution temperature.

The QGreen polymer heat exchanger performance is vital. The relation between the geothermal water flow rate and the rate of heat transfer is depicted graphically in **Figure 7**. As shown, the heat transfer rate per panel is about 0.55 kW/(l/min).

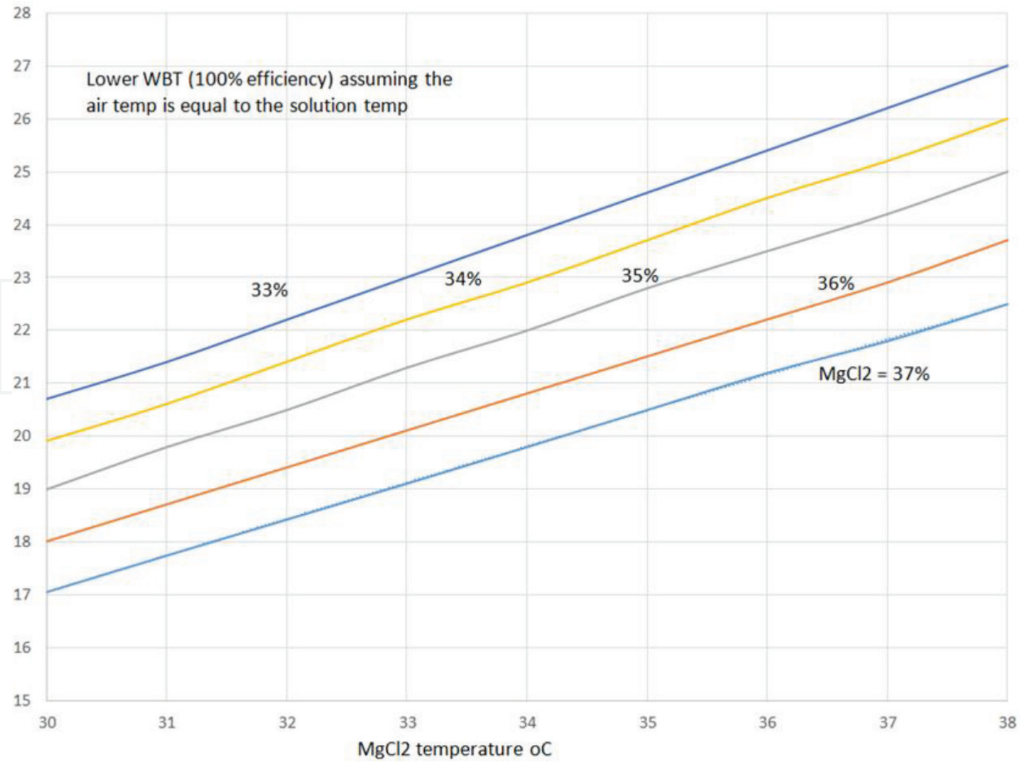

Figure 6. The lower wet-bulb temperature at different concentrations.

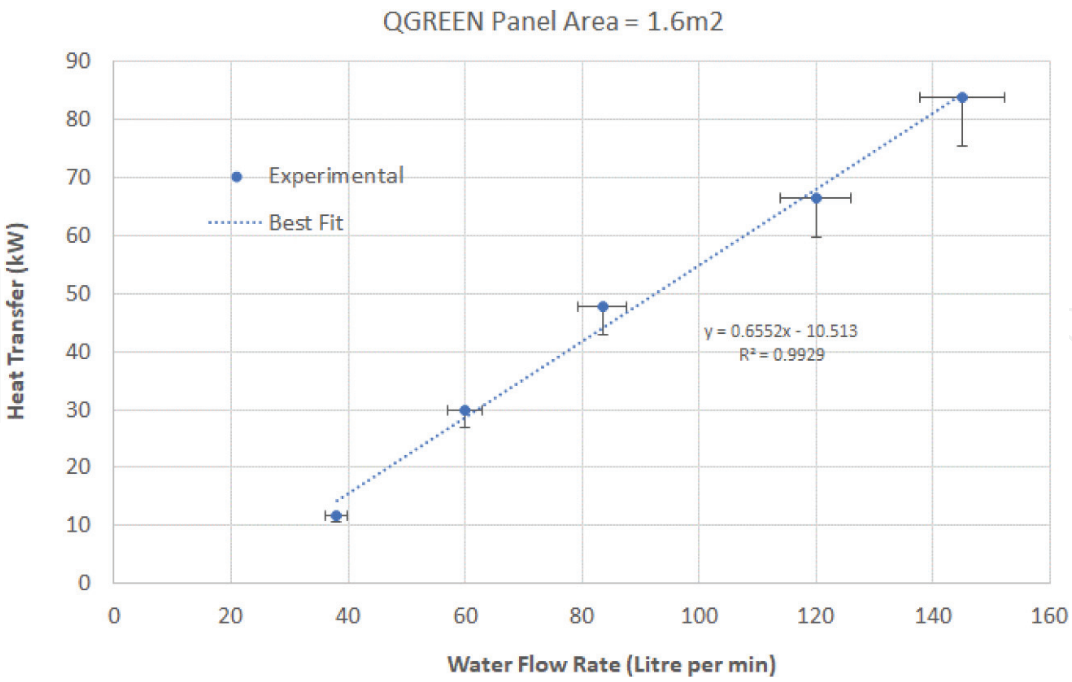

Figure 7. The QGreen geothermal polymer panel thermal performance.

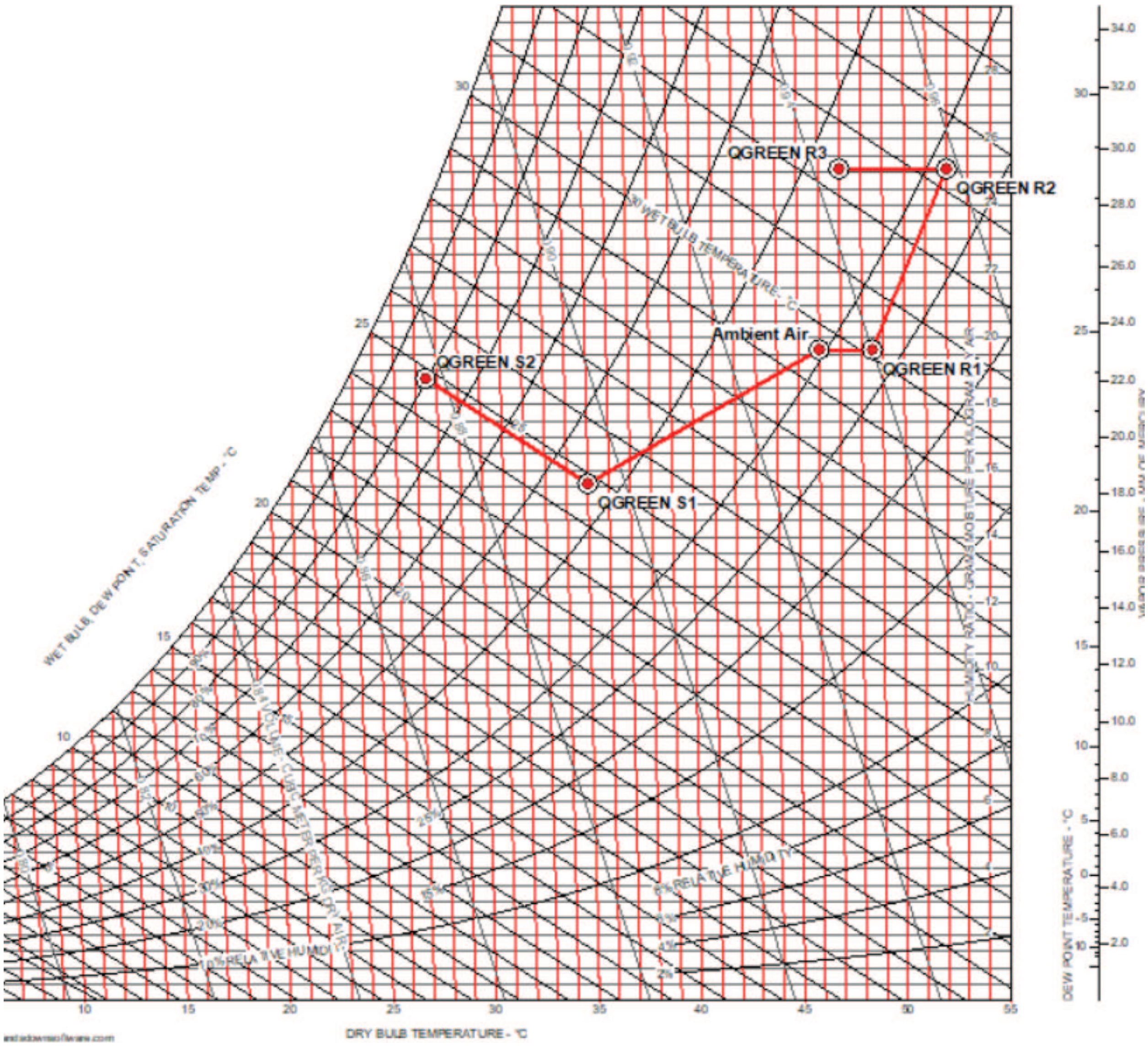

Figure 8. Cooling, dehumidification and regeneration cycle (case a).

Using the effectiveness method described above along with the psychometric model, the performance of the QGreen cooling and dehumidification panel can be predicted.

In order to design the system properly, three different weather conditions are used for analysis: (a) DB = 46°C, WB = 29.6°C; (b) DB = 35.5°C, WB = 31°C; and (c) DB = 35°C, WB = 24°C. The psychrometric cycle proposed by the authors is shown in **Figures 8–10**.

The ambient air passes the QGreen polymer heat and mass exchanger. As a result, the air is cooled and dehumidified. The wet-bulb temperature reduces; hence, the air will be evaporatively cooled in the second stage that integrated into the QGreen polymer panel.

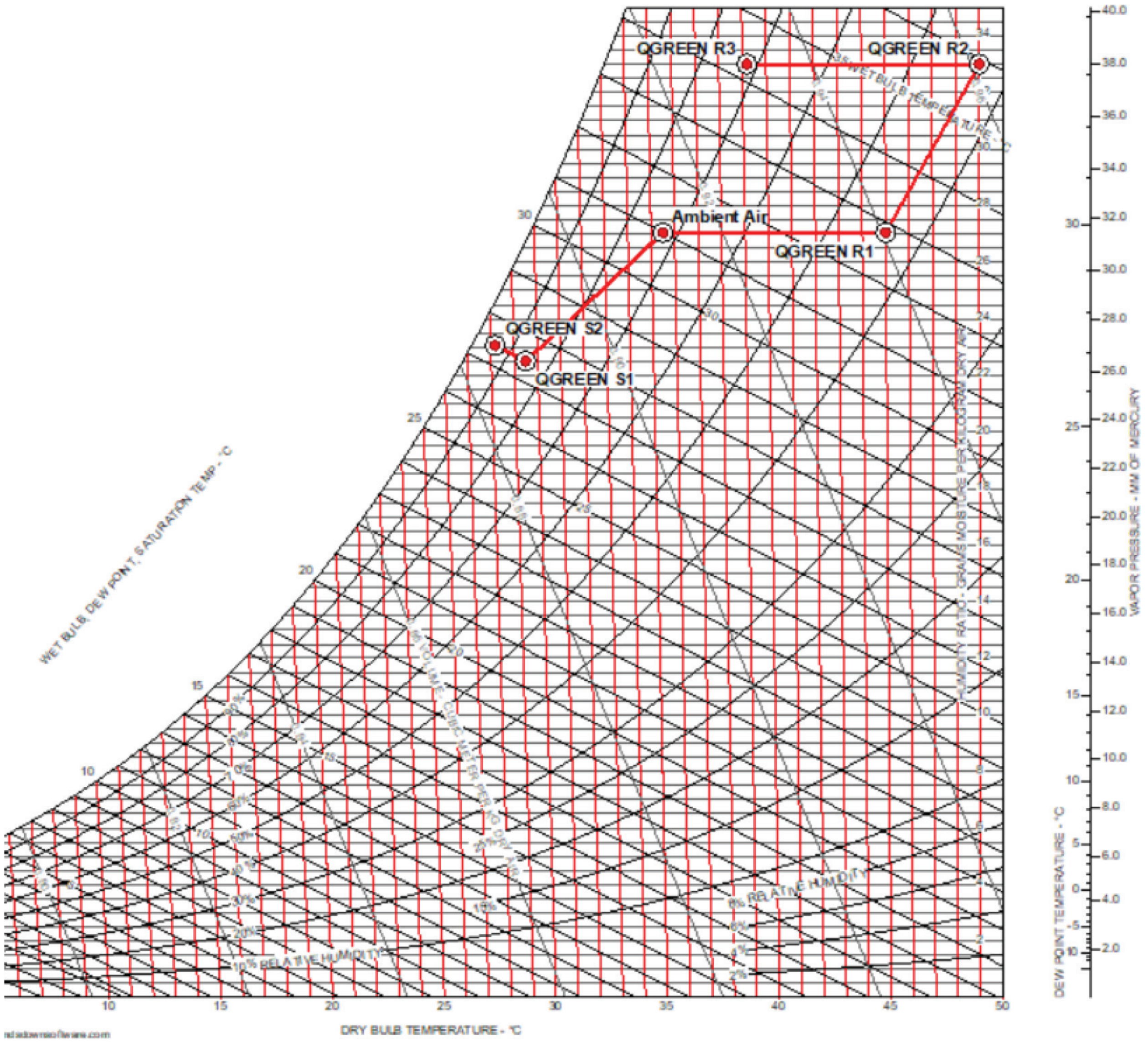

Figure 9. Cooling, dehumidification and regeneration cycle (case b).

The geothermal water could either be consumed or recirculated. The desiccant is regenerated by heating the desiccant to an average temperature of 55°C. Ambient air is initially preheated via a heat recovery system connected to the regenerator outlet and inlet. The hot air evaporates the absorbed water from the hot desiccant, and its temperature rises. The exhaust air is cooled via the sensible heat exchanger.

As shown in **Figures 8–10**, the supply air temperature can always achieve 28°C or lower.

Therefore, the geothermal desiccant system fits well such applications.

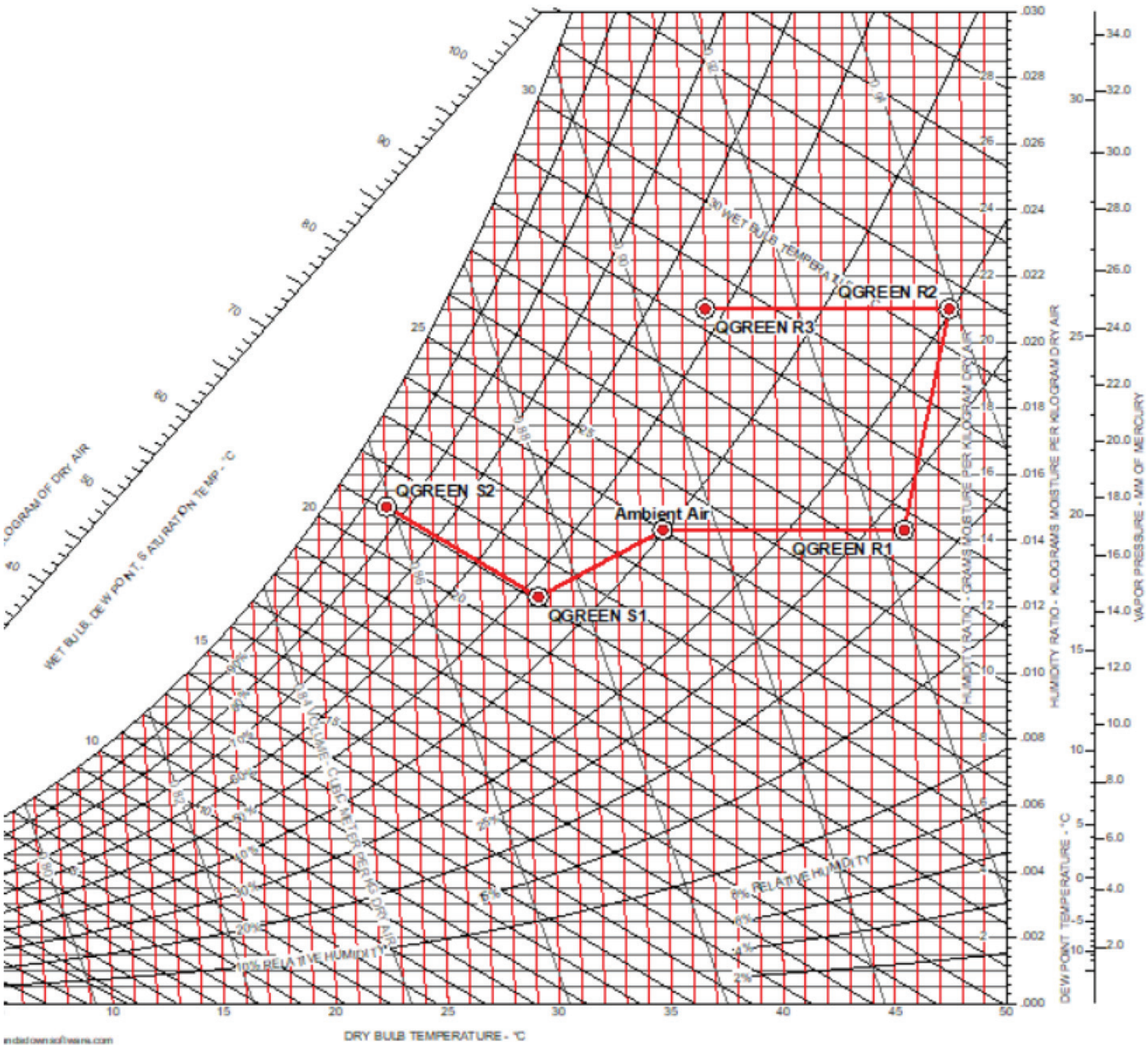

Figure 10. Cooling, dehumidification and regeneration cycle (case c).

6. Conclusions

With regard to food security, the Food and Agriculture Organization (FAO) requires all people to have access to sufficient, safe and nutritious food that meets their needs for an active and healthy life. However, in areas that have hot and humid climate and water scarcity, this remains a challenge. This chapter discussed one of the most interesting solutions that provide water source and climate control utilizing renewable energy. Qatar depends on desalination as a water source. The QGreen panel utilizes the rejected brine as a desiccant to dehumidify the air. The geothermal water cools the desiccant and air to the required temperature resulting in 2–4°C drop in the wet-bulb temperature. The thin polymer panel is corrosion and scale formation-free and can be installed within the greenhouse or barn boundaries. The results are promising and encouraging to be used in food security applications.

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Nomenclature

a	Area of heat and mass transfer, m^2/m^3
a_t	Specific interfacial area of packing, m^2/m^3
Cp	Specific heat, kJ/kg.K
D_v	Diffusion Coefficient, m^2/s
d_{eq}	Equivalent diameter for structured packing, m
F_G	Gas phase mass transfer coefficient, kmol/m^2.s
F_L	Liquid phase mass transfer coefficient, kmol/m^2.s
h_G	Heat transfer coefficient, kW/m^2.K
K	Mass transfer coefficient, kmol/m^2.s
k	Thermal conductivity, W/m.K
Le	Lewis Number
m	Flow rate, kg/s or kg/h
m'	Superficial flow rate (mass velocity), kg/m^2s
M	Molecular weight, kg/kmol
N_v	Molar vapor mass transfer flux kg/m^2s
Re	Reynolds number
Sc	Schmidt number
T	Temperature, °C
X	Desiccant concentration, kg desiccant/kg solution
y	Water mole fraction, kmol water/kmol air
Z	Tower height, m

Greek

λ	Latent heat of condensation/vaporization, kJ/kg
ϕ	Density, kg/m^3
ω	Humidity ratio, kg water/kg dry air

Subscripts

a	air
c	condensation
e	equilibrium
G	gas phase
h	heat transfer
i	inlet or interface
L	liquid
m	mass transfer, mean
o	outlet
s	solution
v	vapor
w	water

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