



Effects of Window Films in Thermo-Solar Properties of Office Buildings in Hot-Arid Climates

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OPEN ACCESS

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Specialty section:

This article was submitted to
Sustainable Energy Systems
and Policies,
a section of the journal
Frontiers in Energy Research

Received: 09 February 2021

Accepted: 07 April 2021

Published: 20 May 2021

Citation:

Sedaghat A, Abbas Oloomi SA,
Malayer MA, Alkhatib F, Sabri F,
Sabati M, Salem H, Zafar WJ,
Mostafaeipour A, Issakhov A,
Jahangiri M, Techato K and
Chowdhury S (2021) Effects
of Window Films in Thermo-Solar
Properties of Office Buildings
in Hot-Arid Climates.
Front. Energy Res. 9:665978.
doi: 10.3389/fenrg.2021.665978

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The electricity consumption in residential/office buildings corresponded to 45% of the total annual electricity demand in hot-arid climates. This accounted for 27.2 TWh of electricity consumption with 14.2 MWh/capita/year in Kuwait. In this research, four offices in an educational building were equipped with a meteorological data logging system using temperature, humidity, and illuminance sensors. All four offices had double-glazed windows. Moreover, two offices were equipped with two types of commercially available window films. Two million data were stored in iCloud using Wi-Fi and an Internet of Things (IoT) system for the 3 months of June, July, and August 2019. Here, histograms and the kernel density estimation (KDE) of temperature/humidity were analyzed and compared for the two offices with/without 3M Neutral 20 window films. Two floors of the same building consisting of 31 offices were also modeled and simulated to study energy saving and CO₂ footprint reduction using various window films. The results of simulations for the month of July 2019 using SOL 101 and SOL 102 window films, respectively, showed that about 250 kg and 255 kg of production of CO₂ could be reduced and energy saving counted for 416 and 422 kWh. Measurements from offices with 3M Neutral 20% and 3M Neutral 70% window films for the month of July 2019 indicated that the carbon footprint could be reduced by about 82 kg and 0.43 kg and energy saving counted for 147.11 and 0.71 kWh, respectively. It was observed that an annual energy saving and CO₂ footprint reduction of 2.76% could be achieved using window films in a hot-arid climate.

Keywords: CO₂ footprint, energy saving, illuminance, kernel density estimation, office building, solar window film

INTRODUCTION

There are different sources of renewables that can be harnessed, but solar is the most popular since it is available in most areas (Ahmadi et al., 2020). The energy consumption of buildings is almost 40% of the demand in the world and also contributes 43% of the global greenhouse gas emission (Al Doury et al., 2020). Due to the increasing population, demand for electricity will grow in the near future (Ahmadi et al., 2018). Energy consumption optimization is an important goal to achieve sustainable development for buildings all over the world (Esbati et al., 2019). With increasing temperature of our planet due to greenhouse effects of using fossil fuels, tremendous efforts were devoted to decrease CO₂ footprints, increase energy efficiency, use renewable and other resources, replace carbon fuels with hydrogen, and more (Peel et al., 2007; King et al., 2015). It seems we are arriving in an era where energy security and oil prices are being brought down from the top, and environment protection and electricity production from renewable resources are becoming of prime importance (Lund, 2009). According to Kuwait energy outlook 2019, the electricity demand for AC systems was about 70% and the annual electricity use was over 45% in residential buildings in Kuwait (KISR, 2019).

In Europe, nearly the same amount of energy is consumed for heating buildings (Bordass, 2004) which has led European countries to set legislation to reduce energy use of buildings by 20% before 2020 and 50% by 2050 (Recast, 2010). Windows are responsible for a large portion of the energy loss/gain of buildings. There are both passive and active methods to reduce energy loss. KGBC (Kuwait Green Building Council) has implemented the use of insulation materials and improved air-conditioning ducts (Sayegh, 2012; AlSanad, 2015; Alsulaili et al., 2020). Building efficiency is directly correlated to windows size and aspect ratio on architecture of buildings (Huang et al., 2014; Cuce and Riffat, 2015; Hee et al., 2015; Wang and Greenberg, 2015). Windows allow entry of sunlight into buildings and provide visual and escape access to the outside in the case of fire, and also allow air entry and temperature moderation using outside air (Huang et al., 2014; Hee et al., 2015). Modern cities utilize windows as the main architecture of high-rise buildings due to visual access to surroundings and for the artistic look of buildings in the urban environment (Hee et al., 2015). However, above 60% of energy loss from buildings are correlated to windows and window frames in hot-arid climates (Jelle et al., 2012; Ürges-Vorsatz et al., 2015) and about 40% of cooling load is due to solar radiation and heat absorption through windows (Lee et al., 2013). Window films are cost-effective methods that prevent passive heat gain from radiation through windows and are commercially available. Window films can easily be installed to the inside/outside surface of windows using liquid glues. These films are made from many layers of metallic-polyester nanofilm materials with thermo-radiation properties to reflect and reject heating waves from the solar radiation spectrum (Plummer, 2015). Other useful aspects of window films are to prevent UV waves from entering the building and considerably reduce solar light intensity and illuminance. Window films are also featured in securing indoor privacy and increasing the life cycle of interior

fabrics and furniture from deterioration (Plummer, 2015; Wang and Greenberg, 2015).

Nanolayers in window films are usually made from metals/polymers where the metallic layer conducts and reflects solar heat, and the polymers are transparent oxides. Metallic nanolayers of about 10 nm are made from copper, silver, and gold and their job is to absorb very short wavelengths of the order of 0.5 μm or lower (Granqvist, 2007); but polymer nanolayers are made from dielectric materials which are optical oxides such as tin, titanium, zinc, and other similar materials with a 40-nm or lower thickness to allow visible light to pass through (Mohelnikova, 2009; Meszaros et al., 2012). Window films that are used for the outside surface of the window should withstand harsh outdoor environments, whereas the windows films for the inside surface of the window are cheaper due to less resistant materials.

The application of window films was investigated in a humid and warm climate by Li et al. (2015) where they found that clear glazing performed better than tinted windows for energy saving. In another study, it was found that exterior window films saved energy by 44% whilst interior window films merely saved 22% (Yousif, 2012). Window films reported energy saving in summer but increased energy use in winter in a hot climate (Yin et al., 2012).

The use of smart window blinds was found to be an effective yet expensive exercise (Dussault et al., 2012). Five completely different climate conditions were investigated in China by Chen et al. (2012) who found that flexible blinds of an opaque type were the most successful in energy saving.

Size, aspect ratio, and position of windows were studied in several studies on heat loss of buildings through windows (Vanhoutteghem et al., 2015; Yang et al., 2015). Yang et al. (2015) showed that low aspect ratio windows with low-emissivity could enhance building efficiency. Effects of orientation and size were investigated in a zero-energy building for cold climates (Vanhoutteghem et al., 2015). Some studies reported an energy increase using double-glazed windows combined with window films (Hee et al., 2015), whilst other studies through simulation proved the opposite (Yang et al., 2015). Their simulations also reported 17% to 47% cooling load reduction in a hot climate and other climate conditions. Human habits play an important role in the energy loss of buildings and some studies suggested that an automatic ventilation system had better energy savings (Cuce and Riffat, 2015). Window films can last between 10 to 20 years; therefore, they are economical (Glass and Glazing Federation, 1978).

The main aim of this study was to evaluate the effects of window films in thermo-solar properties of office buildings in hot-arid climates. In order to assess the effects of solar window films in thermo-solar properties and investigate the energy usage and CO₂ emissions performance of office buildings, a model for an Australian College of Kuwait (ACK) building was developed using Design Builder and Energy Plus software, then calibrated with experimental data. In this study, analysis of data was done using the kernel density estimation (KDE), also histograms/KDE probability distribution function (PDF) of the thermo-solar properties was presented. The results of this study are used as

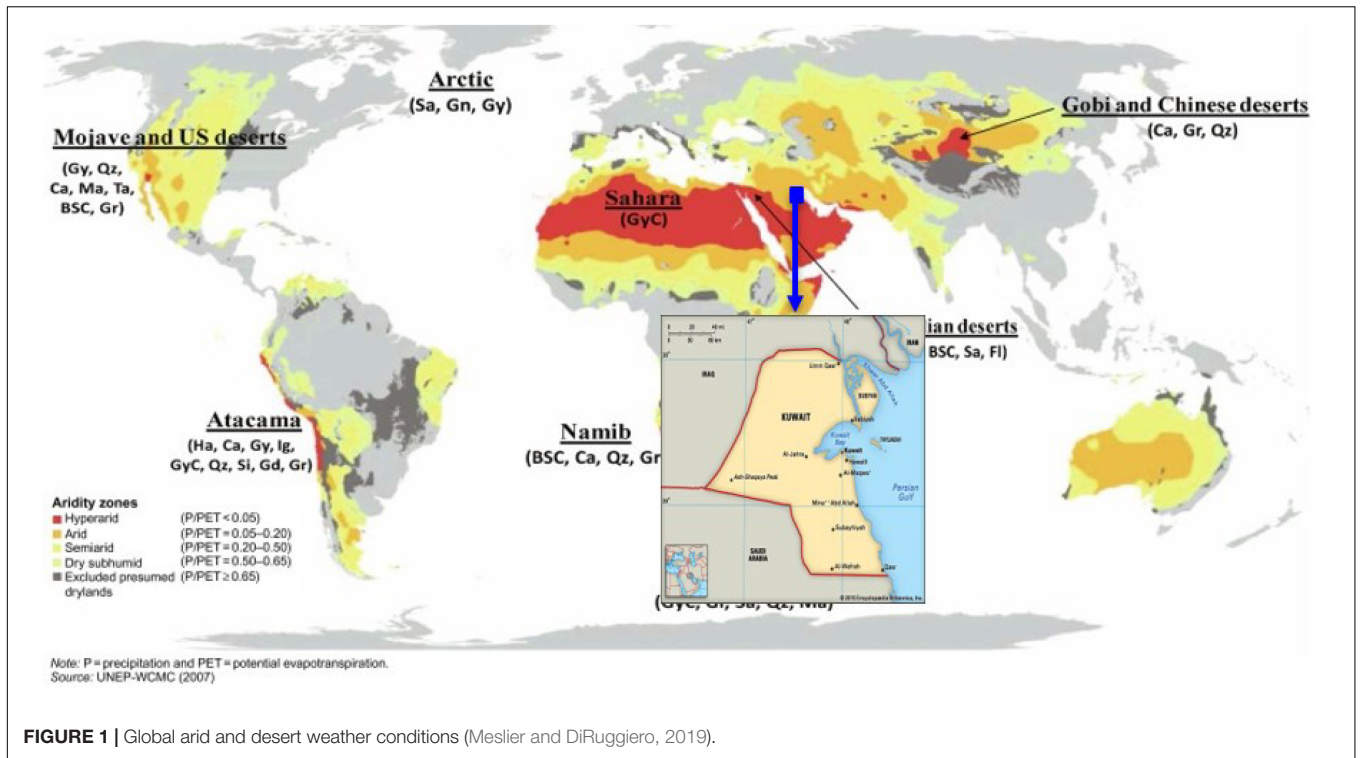


FIGURE 1 | Global arid and desert weather conditions (Meslier and DiRuggiero, 2019).

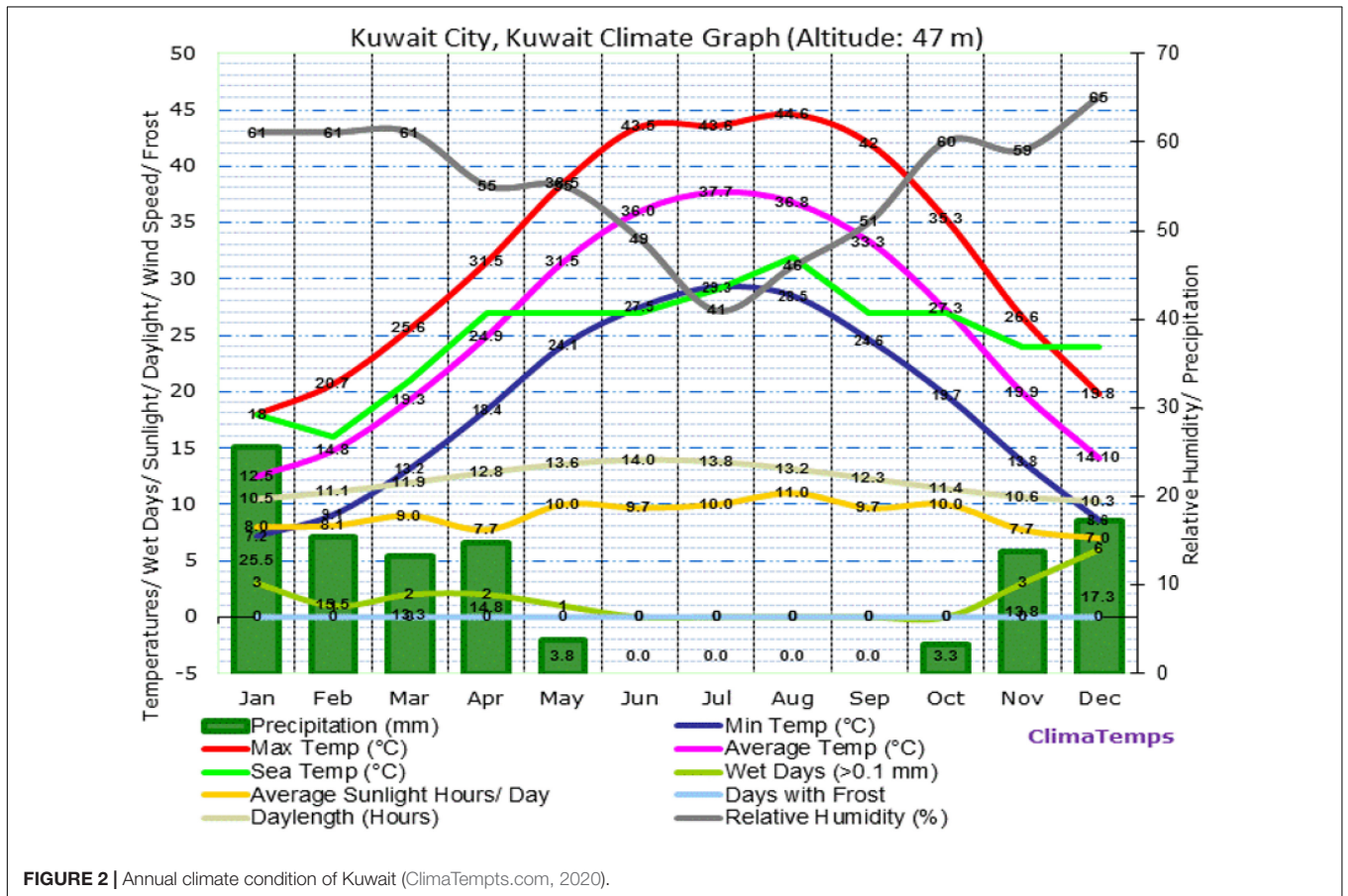


FIGURE 2 | Annual climate condition of Kuwait (ClimaTempts.com, 2020).

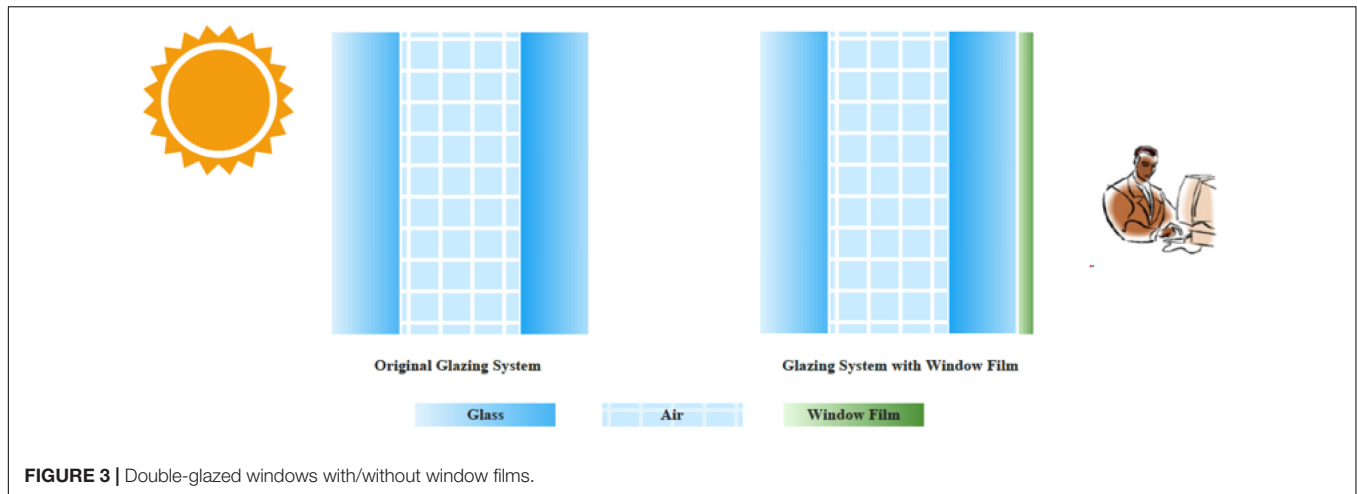


FIGURE 3 | Double-glazed windows with/without window films.

TABLE 1 | Window film products of the Reflective company (Reflectiv, 2019).

Film type	Visible light transmitted (%)	Light rejected (%)	Light reflected (%)	UV light transmitted (%)
SOL 101	16	78	55	5
SOL 102	16	78	65	1
SOL 148	58	77	28	10
SOL 150	47	80	27	3

TABLE 2 | Window film products of the 3M company.

Film type	Visible light transmitted (%)	Light rejected (%)	G value	U value (W/m ² .K)	UV light rejected (%)
Neutral 20	15	62	0.38	5.6	99
Neutral 35	36	56	0.44	5.6	99
Neutral 50	52	44	0.56	5.8	98
Neutral 70	69	32	0.68	5.8	98

TABLE 3 | Window film products of the LLumar company (LLumar, 2019).

Film type	Visible light transmitted (%)	Light rejected (%)	U value (W/m ² .K)	UV light rejected (%)
R15B SR CDF (Bronze)	8	78	0.89	99
R15BL SR PS (Blue)	9	78	0.93	99
R15G SR CDF (Gray)	6	77	0.92	99
R15GO SR PS (Gold)	13	80	0.92	99

the benchmark for assessing energy saving and CO₂ footprints reduction of solar window films in hot-arid climates.

The novelties of this research are summarized as follows:

- ✓ Providing an easy solution to reduce energy consumption in hot-arid climate buildings.
- ✓ Thermal modeling and analysis of the ACK building, calibrating with an experimental work.
- ✓ Analysis of data by using the kernel density estimation (KDE).
- ✓ Providing histograms/KDE probability distribution function (PDF) of the thermo-solar properties.
- ✓ Investigating the performance of four types of commercial solar control window films in energy usage and CO₂ emissions reduction in hot-arid climates.

THE CASE STUDY

The case study considered here was Kuwait located at the northern edge of Eastern Arabia at the top corner of the Persian Gulf (see Figure 1). Kuwait’s population was reported to be 4,270,571 on November 8, 2020 (worldometer, 2020). Kuwait has one of the most hostile, extremely hot, and arid climate conditions with major desert-type weather conditions and a maximum average temperature exceeding 50°C in summer time (see Figure 2). Kuwait’s precipitation is annually between 25 and 200 mm on an approximately 17,818 km² land area.

Figure 2 shows the annual climate condition of Kuwait at a 47 m elevation from sea level. The temperature in Kuwait exceeds 50°C at ground level in June, July, and August, with

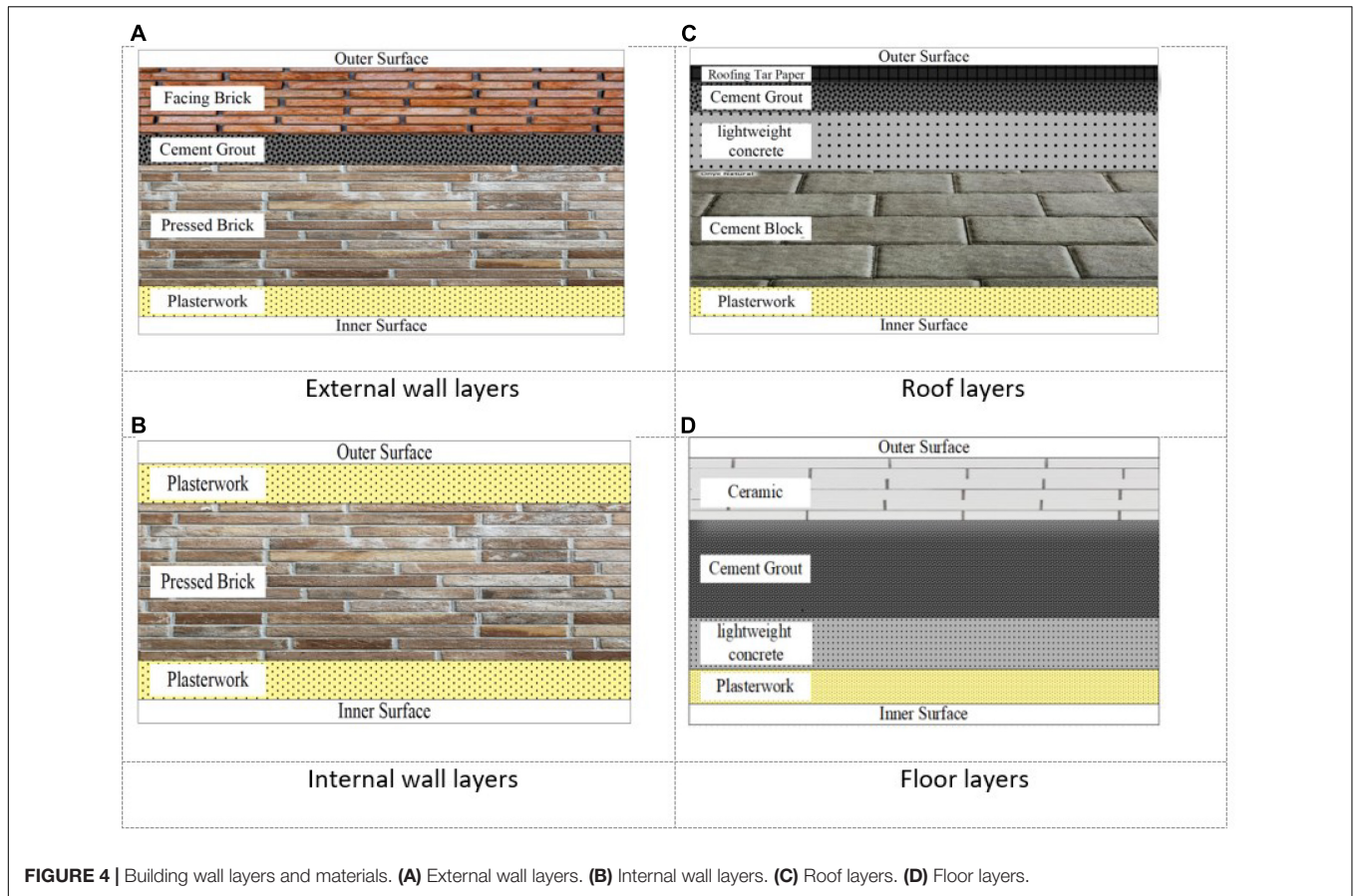


TABLE 4 | Thermal and physical properties of outer wall materials.

Layer	Outer layer material	$k (\frac{W}{m.K})$	$C (\frac{J}{kg.K})$	$\rho (\frac{kg}{m^3})$	Thickness (cm)
1	Facing brick	2.2	840	3000	7
2	Cement grout	0.72	780	1860	3
3	Pressed brick	1	840	1850	22
4	Plasterwork	0.72	780	1860	3
Layer	Inner layer material	$k (\frac{W}{m.K})$	$C (\frac{J}{kg.K})$	$\rho (\frac{kg}{m^3})$	Thickness (cm)
1	Plasterwork	0.72	780	1860	3
2	Pressed brick	1	840	1850	22
3	Plasterwork	0.72	780	1860	3
Layer	Roof layer material	$k (\frac{W}{m.K})$	$C (\frac{J}{kg.K})$	$\rho (\frac{kg}{m^3})$	Thickness (cm)
1	Roofing tar paper	0.062	920	2115	2
2	Cement grout	0.72	780	1860	3
3	Light weight concrete	1.4	880	2500	7
4	Cement block	0.3	840	12	20
5	Plasterwork	0.72	780	1860	3
Layer	Floor layer material	$k (\frac{W}{m.K})$	$C (\frac{J}{kg.K})$	$\rho (\frac{kg}{m^3})$	Thickness (cm)
1	Ceramic	2.9	745	2150	4
2	Cement grout	0.72	780	1860	10
3	Lightweight concrete	1.4	880	2300	4
4	Plasterwork	0.72	780	1860	6

long average sunlight hours of 10–11 h. Relative humidity levels at ground level hardly reach 30% in the summer months and precipitation is absolutely zero. Summer in Kuwait is one the hottest places on our planet. A maximum temperature of 54°C (129 °F) was reported on July 21, 2016 in Kuwait (Alahmad et al., 2020); although we measured 55.2°C on June 11, 2019.

MATERIALS AND METHODS

Building Windows

The size and type of windows in the ACK building which are double glazed with an approximate 1 cm air gap was defined in the software tools. The heat transfer coefficient for double-glazed windows is $2.785 \text{ W/m}^2.K$ and the UV light rejection is 0.497 W.h/m^2 . All window frames are considered as aluminum metals. **Figure 3** shows the type of glazing system with/without window films.

Window Films

In the first part of this project, a number of markets with readily available window films designed for buildings were investigated. Three major companies were identified and their products are listed in **Tables 1–3** for the Reflective, the 3M, and the LLumar companies, respectively.

The 3M company has a branch in Kuwait; therefore, we decided to select two types of 3M window films; i.e., Neutral 20 and Neutral 70. The window films that were purchased from the 3M company were installed by the company’s skilled workers in two offices on the second floor of the ACK building (see **Figure 3**). The process included cleaning the windows to remove any dust or particles, applying the glue to the films, sticking to the windows, and cutting edges. The window films were allowed to dry for 72 h untouched and the installation was quality checked after this time. The installation of sensors was conducted after 2 weeks to ensure the window films were firmly dried and stuck to the windows.

Building Materials

Detailed specifications of building components such as type of materials used in the external walls, inner walls, roof, and floor of a building are needed. The following common materials used in the building are discussed.

External Wall Properties

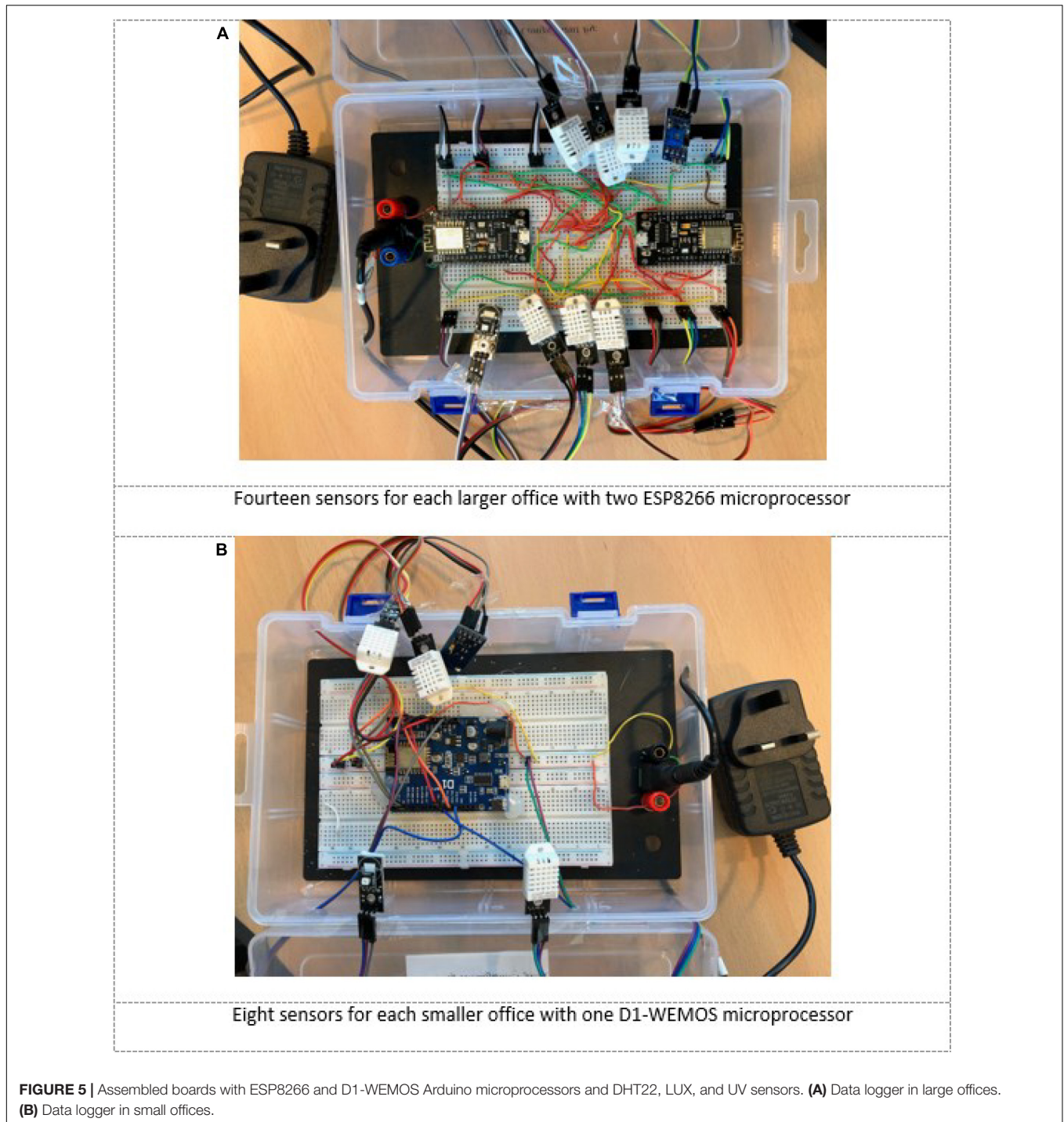
An example of external wall materials is shown in **Figure 4**. From the inner surface toward the outer surface of the wall may be composed of a 30 mm thick inner decoration layer, 220 mm compressed bricks, 30 mm concrete, and 70 mm of outside decorating bricks or stones. The density, heat capacity, heat conductivity, and thickness of each layer is provided in **Table 4**.

Internal Wall Properties

An example of the inner building walls is shown in **Figure 4**. This may be composed of a 30 mm thick inner decoration layer, 220 mm compressed bricks, and another 30 mm thick outer

TABLE 5 | Specifications of the sensors and microprocessors.

Device	Measured parameter	Model	Number	Operating range	Precision	Installed location
Digital output relative humidity and temperature sensor/module	Temperature and humidity	DHT22 (or AM2302)	12	Humidity 0–100% RH; temperature 40~80 Celsius	Humidity 2%RH (Max 5%RH); temperature < 0.5 Celsius	Interior glass surface, indoor/outdoor wall surface
Digital ambient light sensor	Illuminance lux	BH1750	2	Calibrated to measure illuminance (lux 0–10,000)	0.5 lux	Interior glass surface
LM393 optical photosensitive LDR light sensor module for Arduino shield DC 3-5V - ML026	Detecting ambient brightness and light intensity	LDR	2	Wi-Fi operating microprocessor	100 lux	Interior glass surface
ESP8266 Arduino microprocessors	Data processor	ESP8266	4	Wi-Fi operating microprocessor	Very fast and reliable Arduino microprocessor	Assembled and programmed in a box
ESP8266 Wi-Fi-based board	Arduino type processor	WeMos D1	2	Wi-Fi operating microprocessor	Very robust and fast processor	Assembled on a breadboard in a controller box



decoration layer. The thermal and physical properties (thermal conductivity (k), specific heat coefficient (C), and density (ρ) of the inner wall materials are given in **Table 4**.

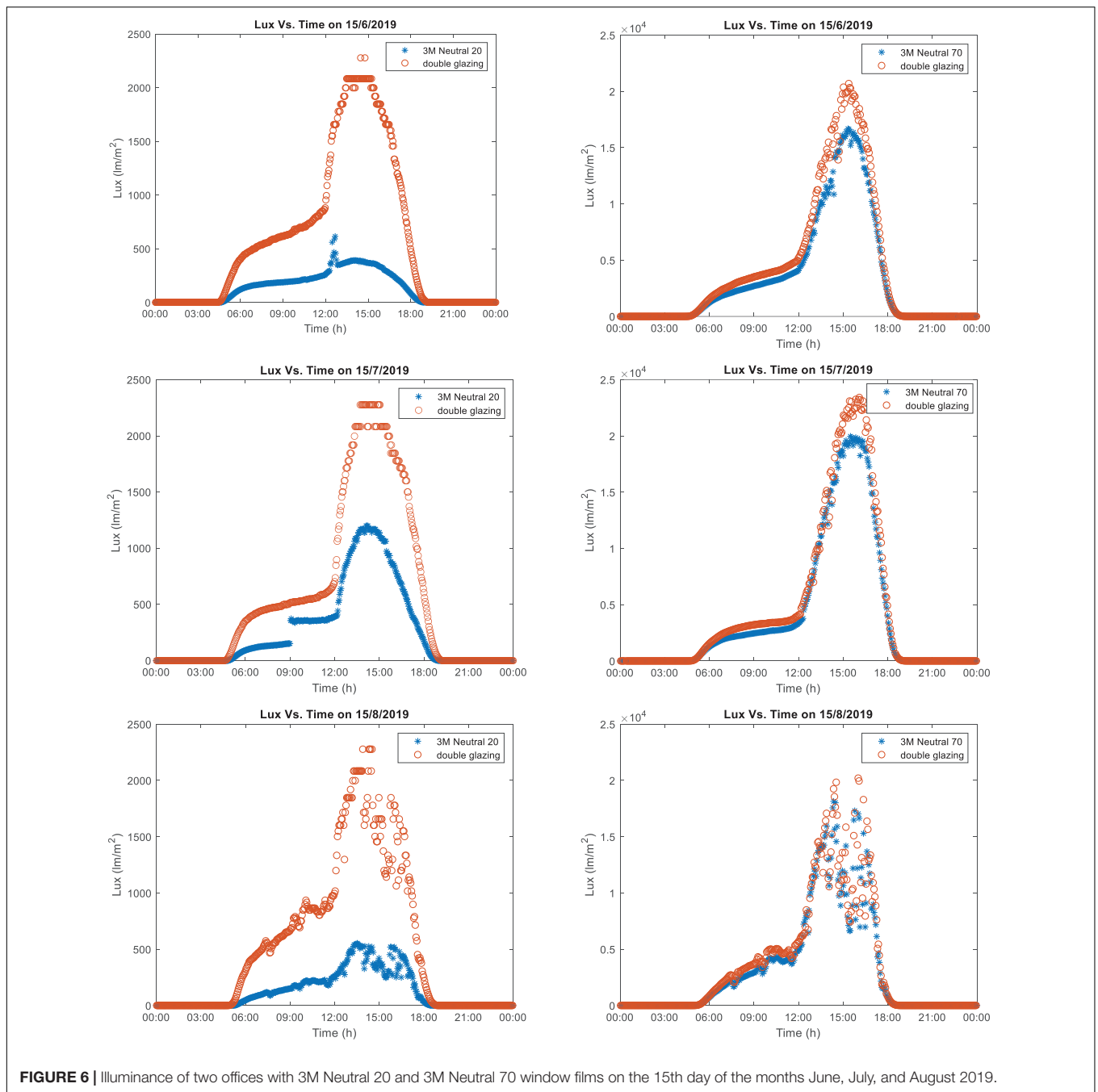
The Roof Properties

The roof of the building may utilize the layers shown in **Figure 4**. It may be composed of a 30 mm inner decoration layer, 200 mm concrete blocks, 70 mm light concrete, 30 mm of fine cement and sand, and a 20 mm roof-sealing layer. The 300 mm ceiling

was attached to the rooms so that the lighting system and AC channels could be connected. The thermal and physical properties (thermal conductivity (k), specific heat coefficient (C), and density (ρ) of each layer are shown in **Table 4**.

The Floor Properties

The floor of the building may utilize the layers shown in **Figure 4**. It may be composed of a 60 mm inner decoration layer, 40 mm light concrete, 100 mm of fine cement and sand,



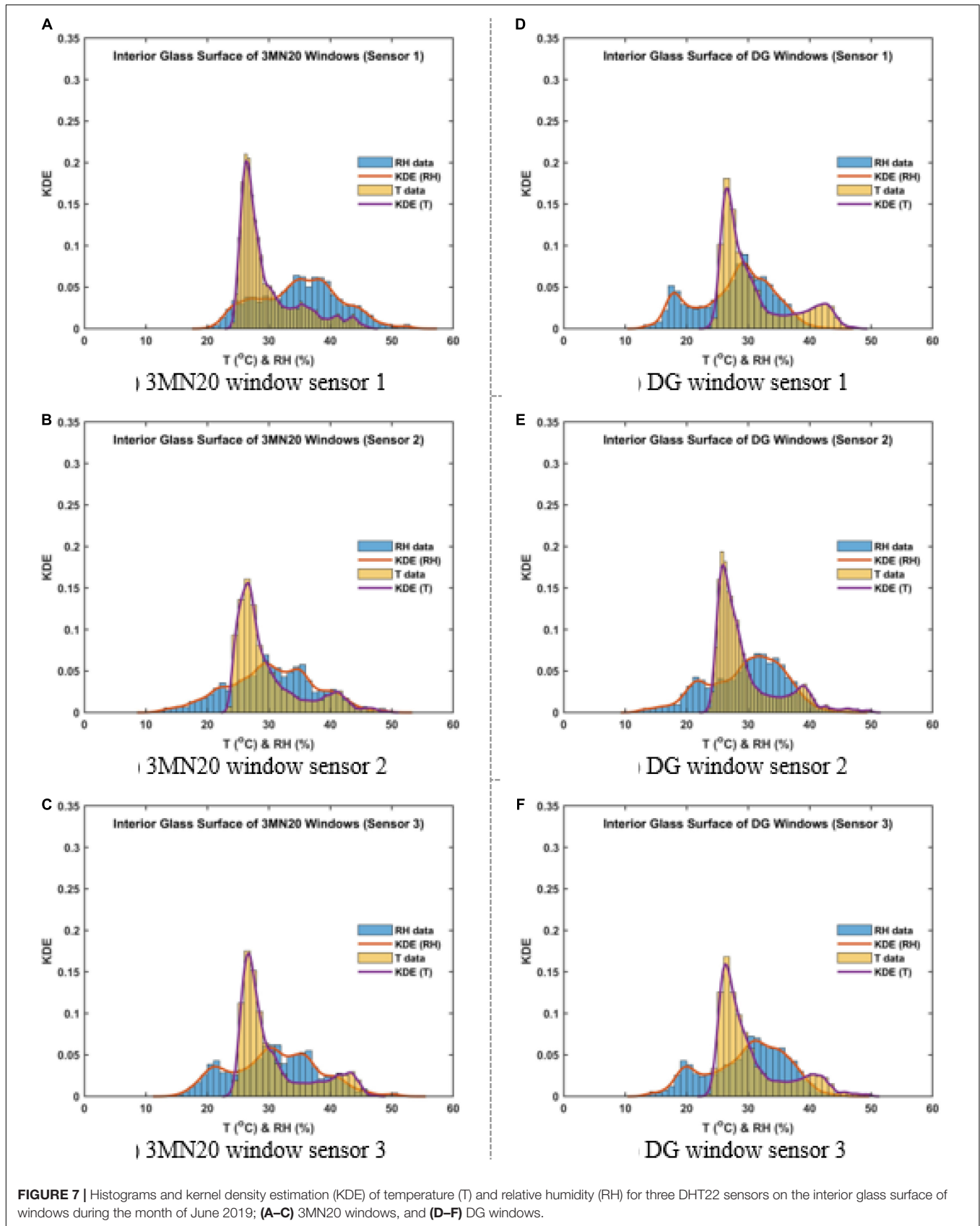
and a 40 mm layer of ceramic or similar flooring. The thermal and physical properties of each layer [thermal conductivity (k), specific heat coefficient (C), and density (ρ)] are shown in **Table 4**.

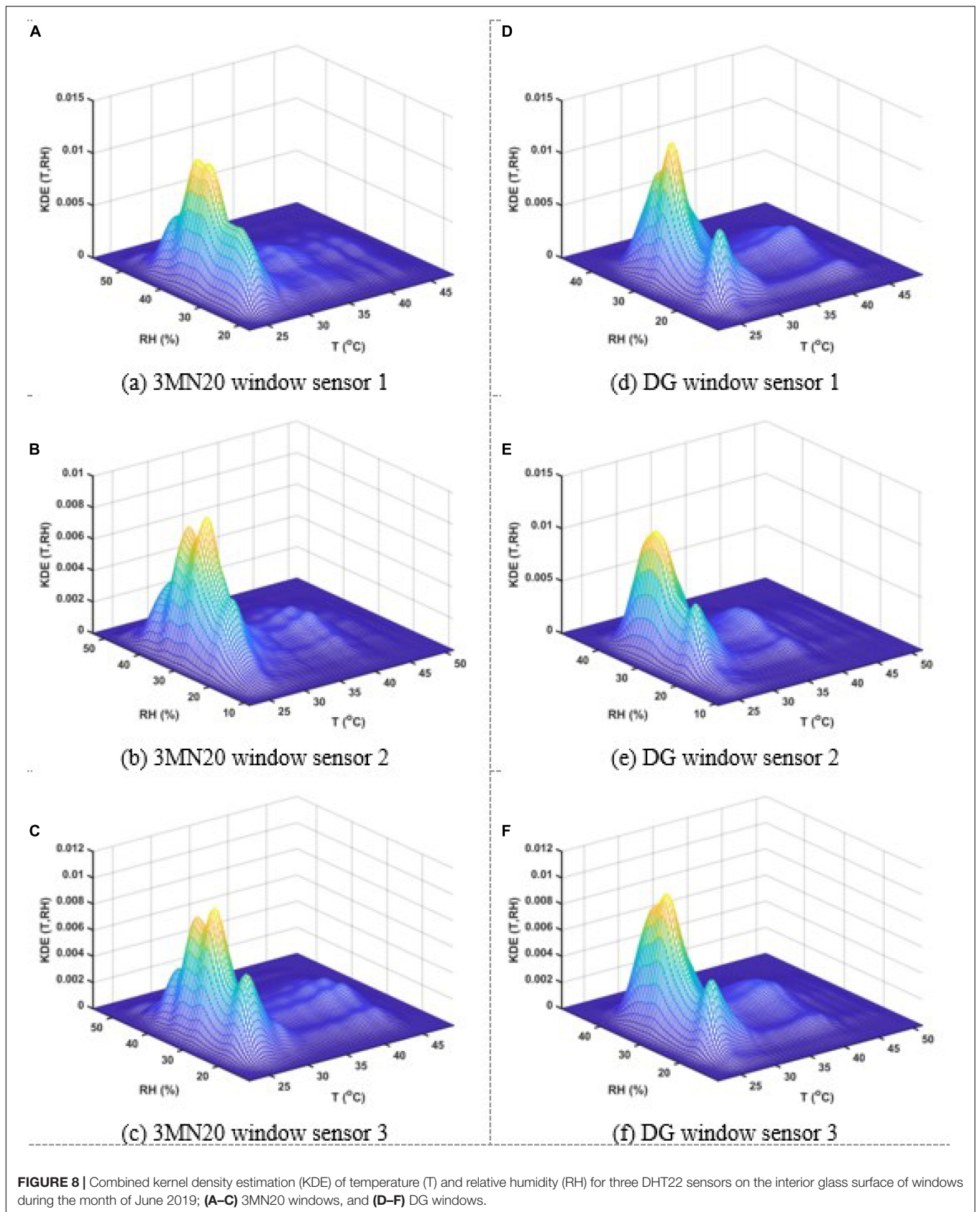
Sensors

In this work, we used DHT22 sensors to measure temperature and humidity, LDR and BH1750 sensors to measure light intensity and illuminance lux, respectively, and a UVM 30A sensor to measure UV radiation. The specification of sensors used are listed in **Table 5**. As shown in **Figure 5**,

the sensors were programmed in the Arduino environment using the microprocessors ESP8266 and D1-WEMOS with capability to connect through a Wi-Fi system into an Internet of Things (IoT) iCloud. With the small yet fast microprocessors selected, we found these worked efficiently for connecting and storing data from six to eight sensors. The sensors and the microprocessors were installed with a breadboard in a controller box as shown in **Figure 5**.

The sensors were taped to the surfaces of windows or walls inside and outside of the offices we studied in ACK Kuwait. The





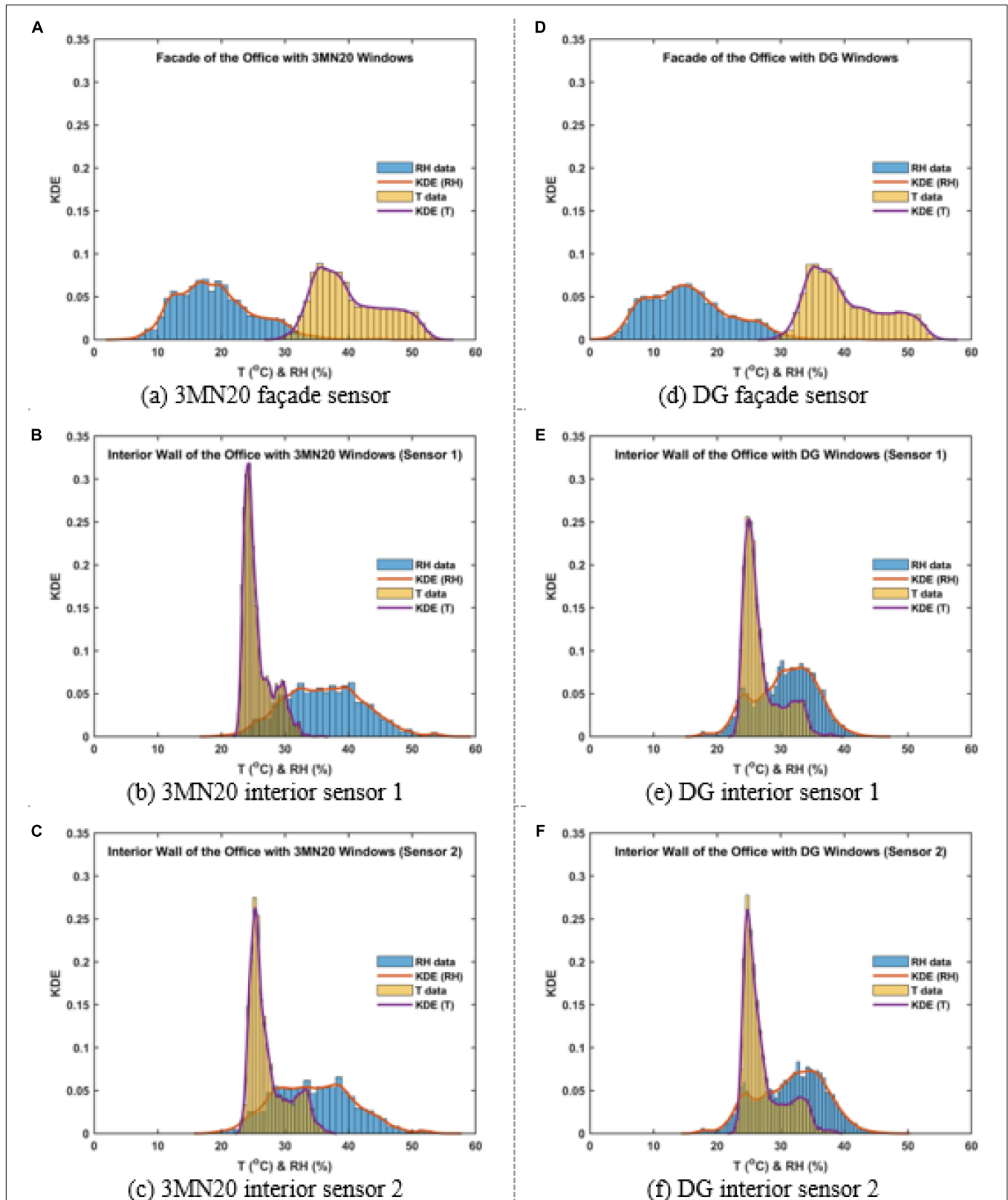
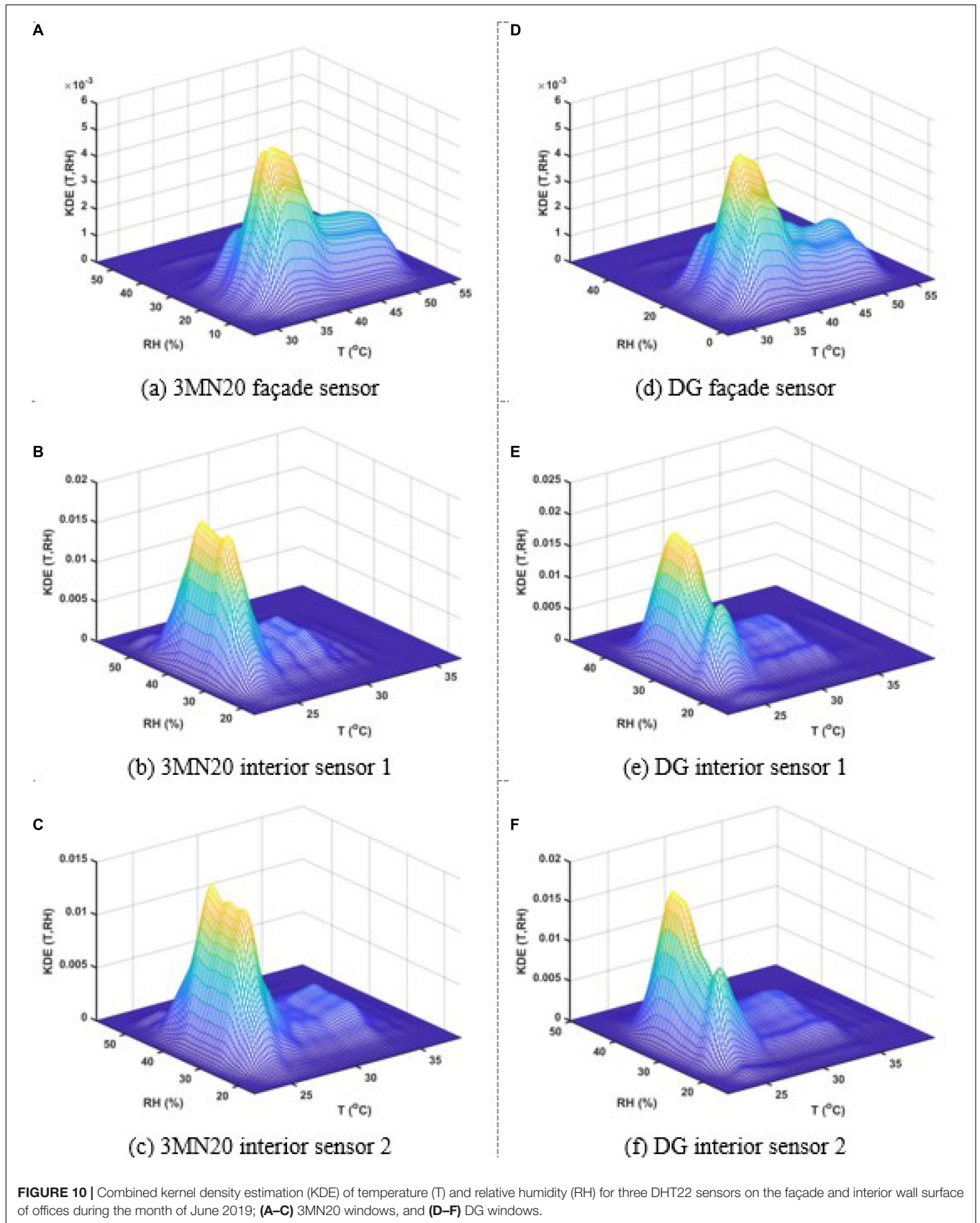


FIGURE 9 | Histograms and kernel density estimation (KDE) of temperature (T) and relative humidity (RH) for three DHT22 sensors on the façade and interior wall surface of offices during the month of June 2019; **(A–C)** 3MN20 windows, and **(D–F)** DG windows.



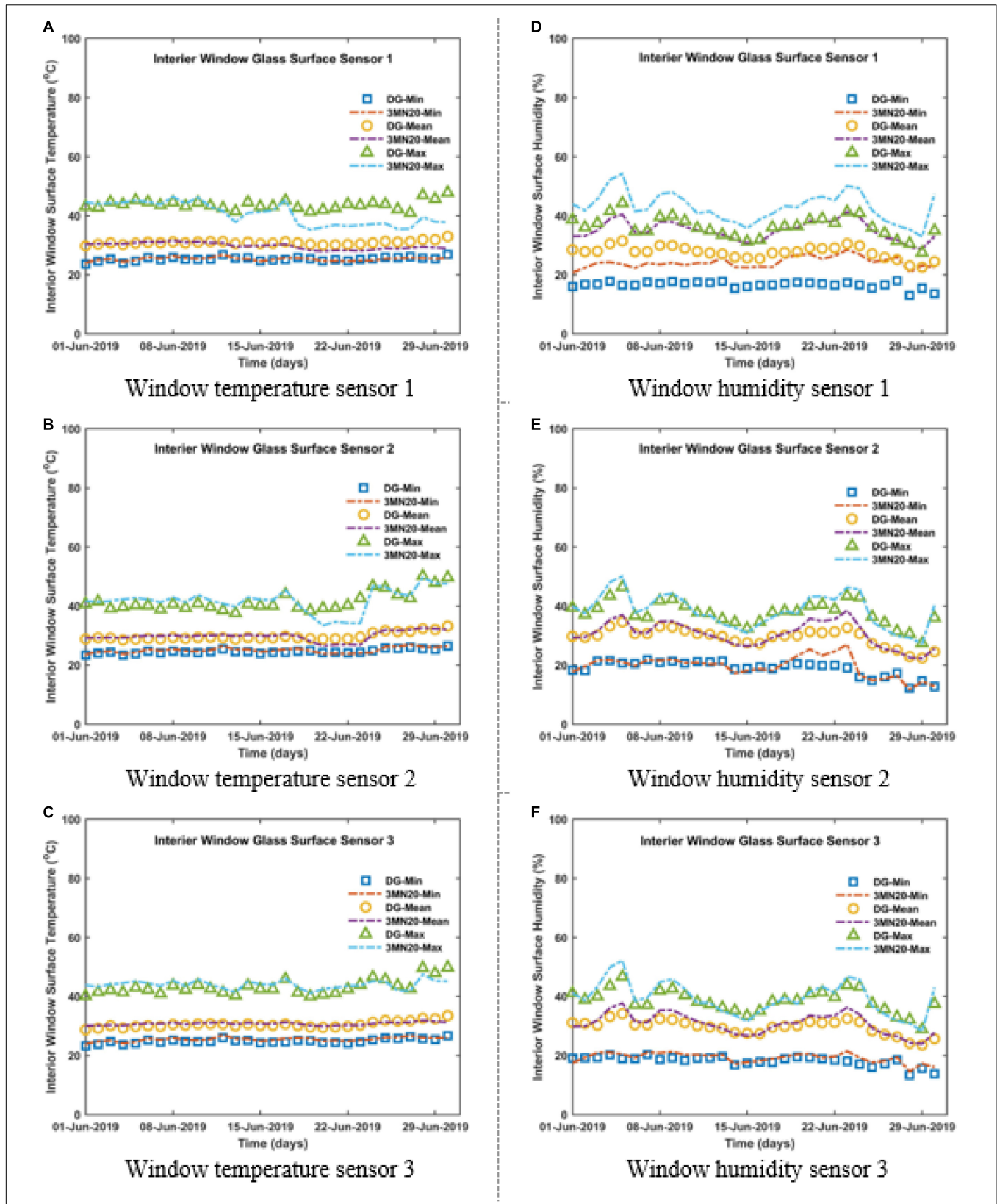


FIGURE 11 | Temperature and humidity (max-mean-min) for three DHT22 sensors on the interior glass surface of the offices with double glazing (DG) and 3M Neutral 20 (3MN20) windows during the month of June 2019; **(A–C)** temperatures, and **(D–F)** humidity variations.

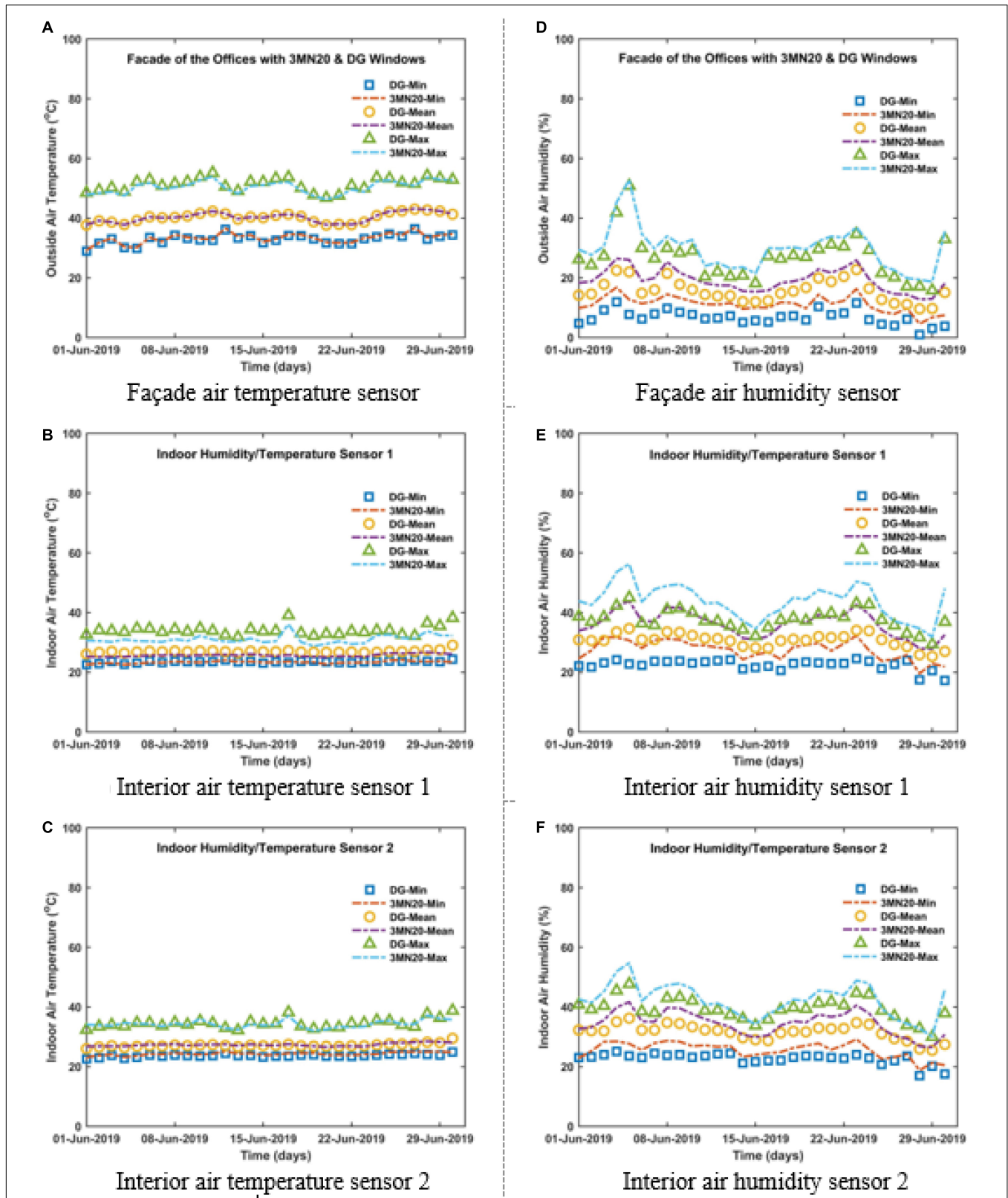


FIGURE 12 | Façade and interior air temperature and humidity for three DHT22 sensors for the offices with double glazing (DG) and 3M Neutral 20 (3MN20) windows during the month of June 2019; **(A–C)** temperatures, and **(D–F)** humidity variations.

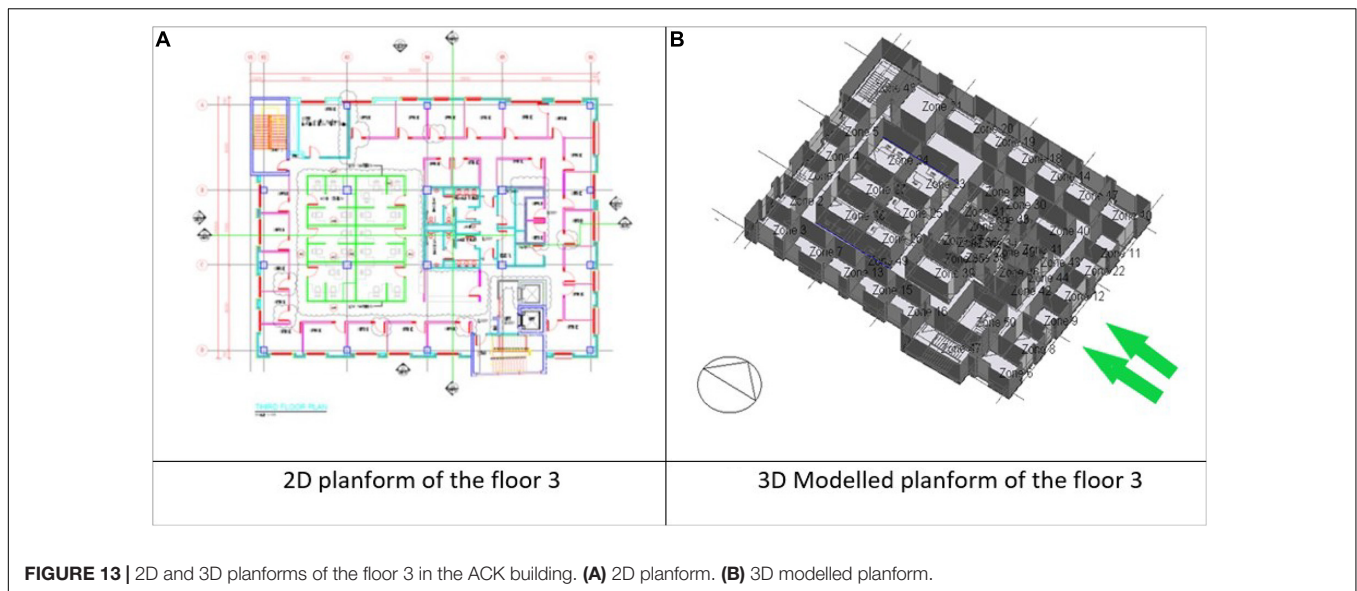


FIGURE 13 | 2D and 3D planforms of the floor 3 in the ACK building. **(A)** 2D planform. **(B)** 3D modelled planform.

building offices use double-glazed windows therefore window films were installed in the interior side of windows.

For offices with/without 3M Neutral 20 window films, we used 14 sensor readings using two ESP8266 microprocessors in each room. For smaller offices with/without 3M Neutral 70 window films, we used D1-WEMOS with eight sensor readings for each room (see **Figure 5**). Every 3 min sensor readings were stored through the Wi-Fi 33 systems into iCloud using an IoT website called Thing Speak. The IoT Thing Speak iCloud system allows four links per user and can store 10 readings simultaneously. This continued over 3 months in summer 2019 in Kuwait. Each sensor nearly reported 50,000 readings and in total a data bank of 2 million were recorded and stored using 40 sensors readings.

Kernel Density Estimation (KDE)

Kernel density estimation is a non-parametric probability density function (PDF) method to fit with any experimental data introduced in (Parzen, 1962; Davis et al., 2011)] as a univariate method which was later extended as a reliable and strong statistical tool for multivariate density estimation (Scott, 2015). For a sample of data, the KDE is estimated by Benseddik et al. (2018):

$$KDE(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x-x_i}{h}\right); x_1 \leq x_i \leq x_n \quad (1)$$

In which K is usually a symmetric and positive kernel function with bandwidth h and is centered around the origin as follows (Benseddik et al., 2018):

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \geq 0; \int_{-\infty}^{+\infty} K(x) dx = 1 \quad (2)$$

In this work, we used the MATLAB (version R2020b release, The MathWorks, United States) “KS density” function to obtain KDE based on a normal kernel function at equally spaced points for temperature, humidity, and illuminance. The MATLAB’s

KDE estimates the density at 100 points for the univariate data and 900 points for bivariate data. For the combined PDFs, we assumed that the variables of temperature and humidity are independent and the combined PDFs are obtained as follows:

$$KDE(x, y) = KDE(x) \cdot KDE(y) \quad (3)$$

The histograms of experimental data and KDE distributions functions of the experimental data PDFs are shown and discussed in the next section.

RESULTS AND DISCUSSION

Illuminance Results

Two offices were installed with 3M Neutral 20 and 3M Neutral 70 window films during summer 2019. The illuminance measurements for the 15th day of the months of June, July, and August 2019 are demonstrated in **Figure 6**. As observed in **Figure 6**, it was evident that 3M Neutral 70 window films had little effect and only reduced light intensity at peak high temperatures in the day. Temperature and humidity results also only marginally changed using this window film. Therefore, the results of this window film are not presented here.

TABLE 6 | Comparison of maximum error between experiment and simulation of window temperatures for the four cases on June 10, 2019.

Case no.	Window temperature (°C)		Error (%)
	Simulation	Experiment	
Case 1	40.3064	38.4	4.7297
Case 2	44.8925	43.6	2.9646
Case 3	43.8356	43.8	0.0812
Case 4	45.0985	43.8	2.9646

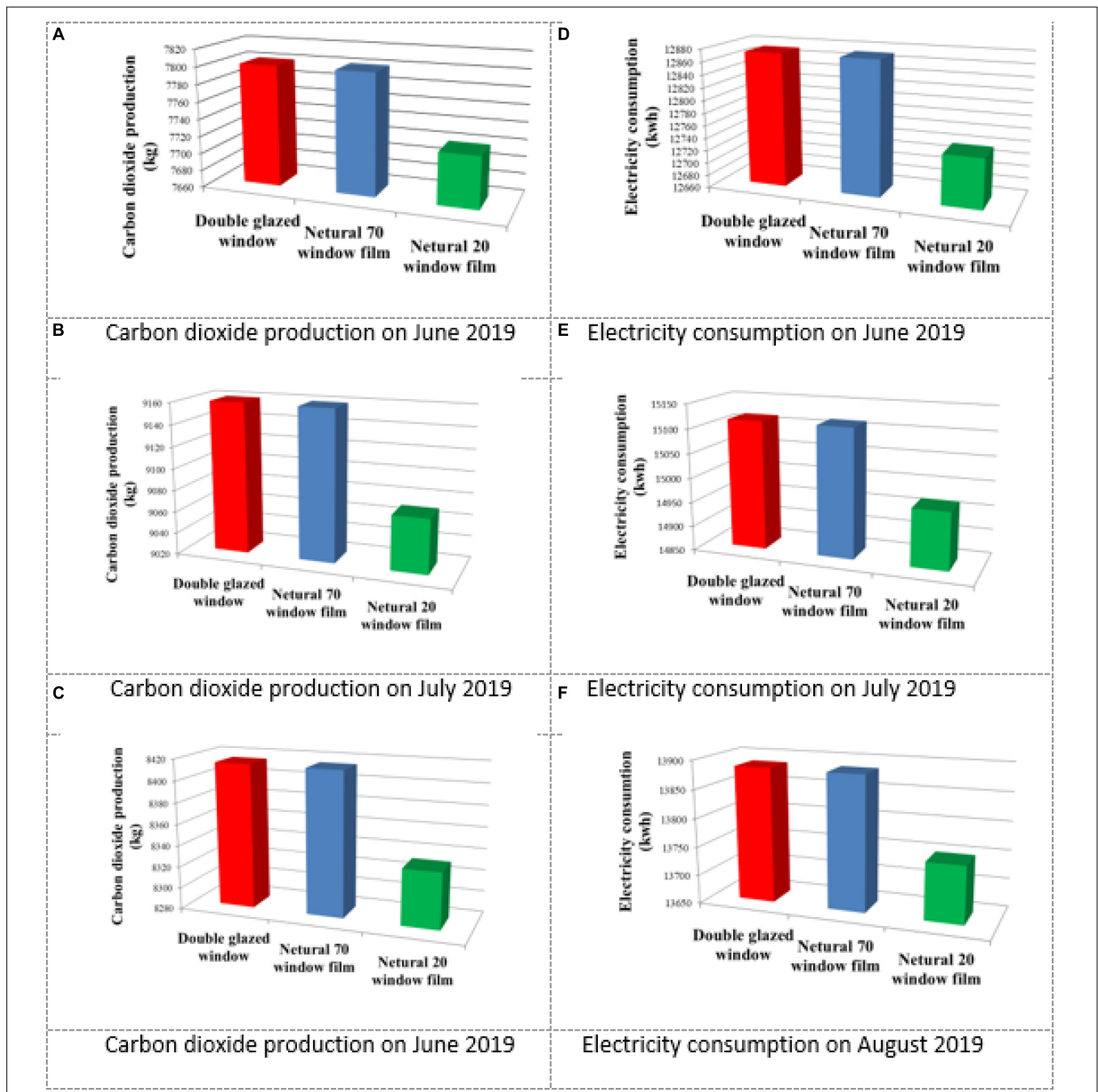


FIGURE 14 | Comparison of carbon dioxide production and electricity consumption of four offices in the ACK building using double-glazed windows with/without 3M Neutral 70 and 3M Neutral 20 window films in summer 2019 in Kuwait. **(A)** CO₂ production on June 2019. **(B)** CO₂ production on July 2019. **(C)** CO₂ production on August 2019. **(D)** Electricity consumption on June 2019. **(E)** Electricity consumption on July 2019. **(F)** Electricity consumption on August 2019.

Experimental Results

Daily experimental results for the month of June 2019 was reported by Sedaghat et al. (2020). In this paper, experimental data are only presented for two similar offices with/without 3M Neutral 20 window films. **Figure 7** compares histograms and KDE distributions for these two offices for window glass temperature and relative humidity in the month of June 2019 which exhibited nearly double peak curves. A more obvious effect

of the 3M Neutral 20 window film was on changing the double peaks structure of the relative humidity and increasing the upper band of temperature (except sensor 1).

Figure 8 compares the combined KDE distribution for the two offices. More peaks appeared in the results for 3M Neutral 20 windows which obviously indicate the effects of the window films. These changes can be engineered by altering the architecture of window film layers for a desirable effect.

TABLE 7 | Carbon dioxide (CO₂) footprints reduction using window films in summer 2019 in Kuwait.

Carbon dioxide production (kg)				
Month	Double-glazed	3M Neutral 20	CO ₂ footprint reduction (kg)	CO ₂ footprint reduction (%)
June	7800.437	7719.859	80.578	1.032
July	9159.38	9070.238	89.142	0.973
August	8414.78	8332.213	82.567	0.981
Summer	25374.597	25122.31	252.287	0.9942

Carbon dioxide production (kg)				
Month	Double-glazed	3M Neutral 70	CO ₂ footprint reduction (kg)	CO ₂ footprint reduction (%)
June	7800.437	7800.4	0.037	0.0004
July	9159.38	9158.95	0.43	0.004
August	8414.78	8414.43	0.35	0.006
Summer	25374.597	25373.78	0.817	0.0032

Carbon dioxide production (kg)				
Month	Double-glazed	SOL 101	CO ₂ footprint reduction (kg)	CO ₂ footprint reduction (%)
June	7800.437	7590.83	209.607	2.68
July	9159.38	8907.39	251.99	2.75
August	8414.78	8176.84	237.94	2.82
Summer	25374.597	24675.06	699.537	2.76

Carbon dioxide production (kg)				
Month	Double-glazed	SOL 102	CO ₂ footprint reduction (kg)	CO ₂ footprint reduction (%)
June	7800.437	7644.43	156.007	2
July	9159.38	8903.602	255.778	2.79
August	8414.78	8173.35	241.43	2.87
Summer	25374.597	24721.382	653.215	2.57

Figure 9 compares indoor/outdoor temperature/humidity of the two offices. The outdoor façade sensor predicted the same pattern for the two offices; but the indoor sensors clearly showed that relative humidity flattened and increased while interior temperature reduced in the office with 3M Neutral 20 window films.

Figure 10 compares the structure of indoor/outdoor combined KDE with a more flattened structure for the offices with the window films.

Figure 11 compares minimum-mean-maximum temperature and relative humidity of the two offices. No considerable changes were observed between measurements on the interior side of the glass for the two offices (except sensor 1) which indicated the safe operation of the window films.

Figure 12 compares the façade and interior air temperature and humidity of the two offices. Slightly higher humidity in the façade of the office with double glazing was mainly due to higher elevation (third floor). Interior temperature of the office with window films was 2°C to 5°C colder and humidity was usually 5% higher which indicated a positive effect of the window films.

The same results discussed here from **Figure 7** to **Figure 12** are presented for the month of July 2019 in appendix A (ures A1–A6)

and for the month of August 2019 in **Supplementary Appendix B (Supplementary Appendix Figures B1–B6)**.

Simulation Results

Two floors of the ACK building were fully modeled in the Design Builder software. **Figure 13** shows the image of the building and the modeled planform for the third floor.

Then, the selected floors were simulated using Energy Plus software. The location and operation times with human encounters should be included in the software. The materials of the walls, partitions, windows, window films, floors, and roofs have been specified in the Design Builder software. To communicate with Energy Plus software, the interior design, thermal properties, heating/cooling system, and lighting system must be specified.

Four cases were selected for validating the Design Builder software with experimental data for a 24 h period on the day of June 10, 2019. Case 1 corresponds to the office on the second floor where the 3M Neutral 20 window films were installed. Case 2 refers to the office on the second floor where the 3M Neutral 70 window films were installed. Case 3 refers to a similar office to Case 1 located on the third floor without window films (only double-glazed). Case 4 refers to a similar office to Case 2 located

TABLE 8 | Electrical energy saving (kWh) using window films in summer 2019 in Kuwait.

Electricity energy consumption (kWh)				
Month	Double-glazed	3M Neutral 20	Energy saving (kWh)	Energy saving (%)
June	12872.02	12739.05	132.97	1.033
July	15114.51	14967.4	147.11	0.973
August	13885.7	13749.54	136.16	0.980
Summer	41872.23	41455.99	416.24	0.994

Electricity energy consumption (kWh)				
Month	Double-glazed	3M Neutral 70	Energy saving (kWh)	Energy saving (%)
June	12872.02	12871.96	0.06	0.0004
July	15114.51	15113.8	0.71	0.004
August	13885.7	13884.74	0.96	0.006
Summer	41872.23	41870.5	1.73	0.004

Electricity energy consumption (kWh)				
Month	Double-glazed	SOL 101	Energy saving (kWh)	Energy saving (%)
June	12872.02	12526.13	345.89	2.68
July	15114.51	14698.68	415.83	2.75
August	13885.7	13493.14	392.56	2.82
Summer	41872.23	40717.95	1154.28	2.76

Electricity energy consumption (kWh)				
Month	Double-glazed	SOL 102	Energy saving (kWh)	Energy saving (%)
June	12872.02	12614.58	257.44	2
July	15114.51	14692.43	422.08	2.79
August	13885.7	13487.39	398.3	2.87
Summer	41872.23	40794.4	1077.82	2.57

on the third floor without window films with only double glazing. Experimental results presented in this article only correspond to the Cases 1 and 3 due to the large amount of data; however, simulation results are compared here.

Table 6 compares the maximum error between window temperatures of the four offices obtained from the simulation and experiment on June 10, 2019. It was observed that the maximum error was below 5% which is acceptable in engineering practices.

Once the Design Builder was calibrated and fine-tuned with experimental data then Energy Plus software was used to simulate floor 2 and floor 3 of the ACK building for electrical energy consumption and carbon dioxide production. Simulation results on electrical energy consumption and carbon dioxide production for the 3 months of June, July, and August 2019 are shown in **Figure 14**. For one floor of the ACK building in June 2019, detailed simulations on CO₂ footprint reduction and energy saving are listed in **Tables 7, 8**, respectively, using double glazing with/without 3M Neutral 20, 3M Neutral 70, SOL 101, and SOL 102 window films for the summer months in Kuwait. As observed in **Tables 7, 8**, the highest CO₂ footprint reduction and energy saving corresponded to the value of 2.76% for SOL 101.

Simulation results on minimum-mean-maximum temperature and humidity are compared with measured

values in **Figure 15** for the office with double-glazing in the month of June 2019. Simulation results for sensor 1 provide the closest match with experiments. Simulation results on minimum-mean-maximum temperature and humidity are also compared with measured values in **Figure 16** for the office with 3M Neutral window films in the month of June 2019. Simulation results for sensor 2 provide the closest match with experiments. Simulation results for the months of July and August 2019 are presented in **Supplementary Appendix C (Supplementary Appendix Figures C1–C4)**.

CONCLUSION

The electricity consumption of AC systems in hot-arid climates demands around 70% of peak load and above 40% of the annual production of electricity. Energy saving and CO₂ footprint reduction in residential/office buildings is becoming a national priority in many countries. Window films are passive and economic methods for obstructing more than 76% of solar heat rays and about 99% of UV rays particularly in hot summer months. In this paper, the energy saving and CO₂ footprint reduction of two types of window films, 3M Neutral 20 and 3M

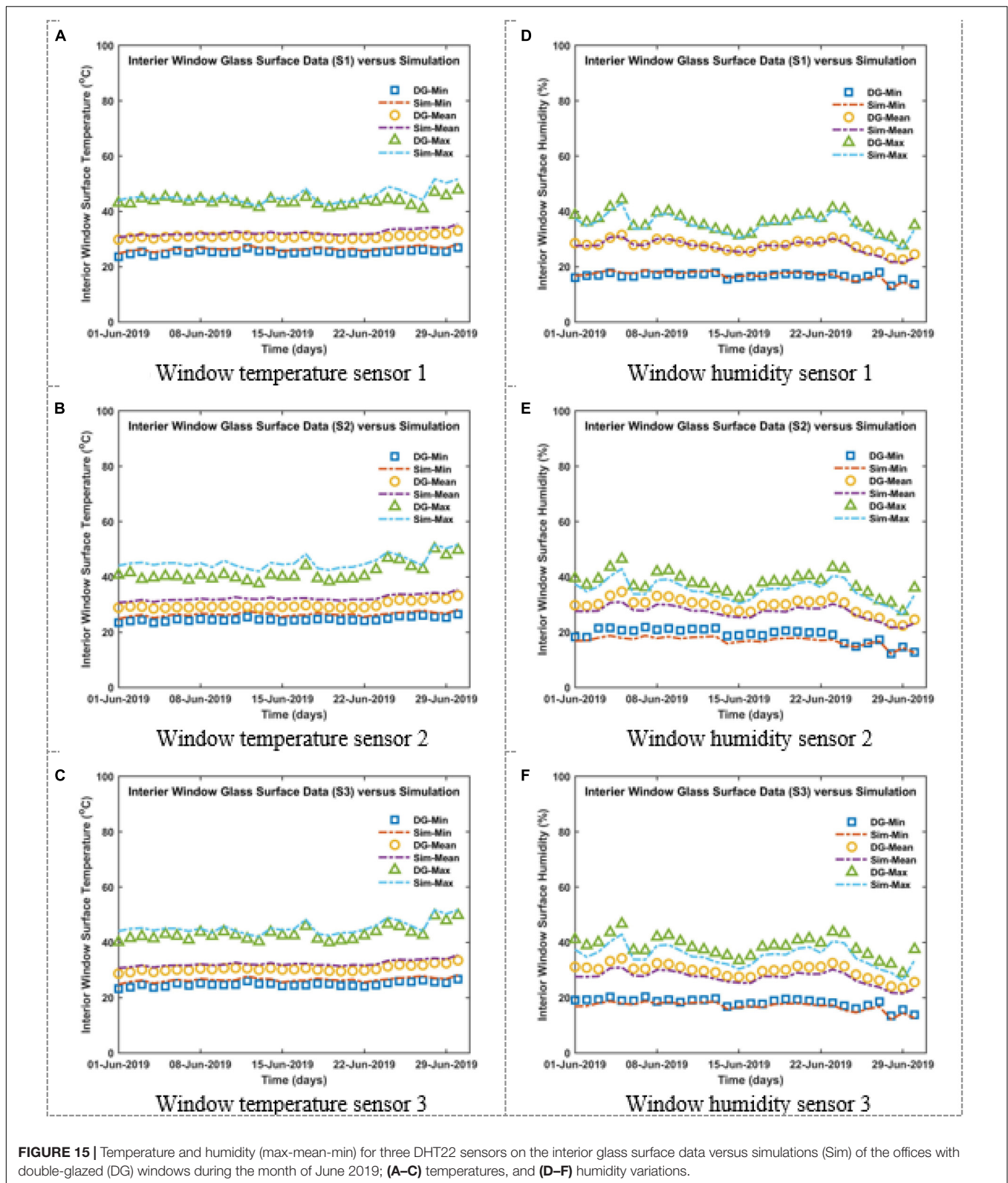


FIGURE 15 | Temperature and humidity (max-mean-min) for three DHT22 sensors on the interior glass surface data versus simulations (Sim) of the offices with double-glazed (DG) windows during the month of June 2019; **(A–C)** temperatures, and **(D–F)** humidity variations.

Neutral 70, were investigated experimentally in four offices in an extremely hot-arid climate. Two floors of the same building with 31 offices were simulated with/without four types of window

films including SOL 101 and SOL 102 window films. Two million of experimental data were created using an in-house-developed data logging system through a Wi-Fi system and stored in iCloud

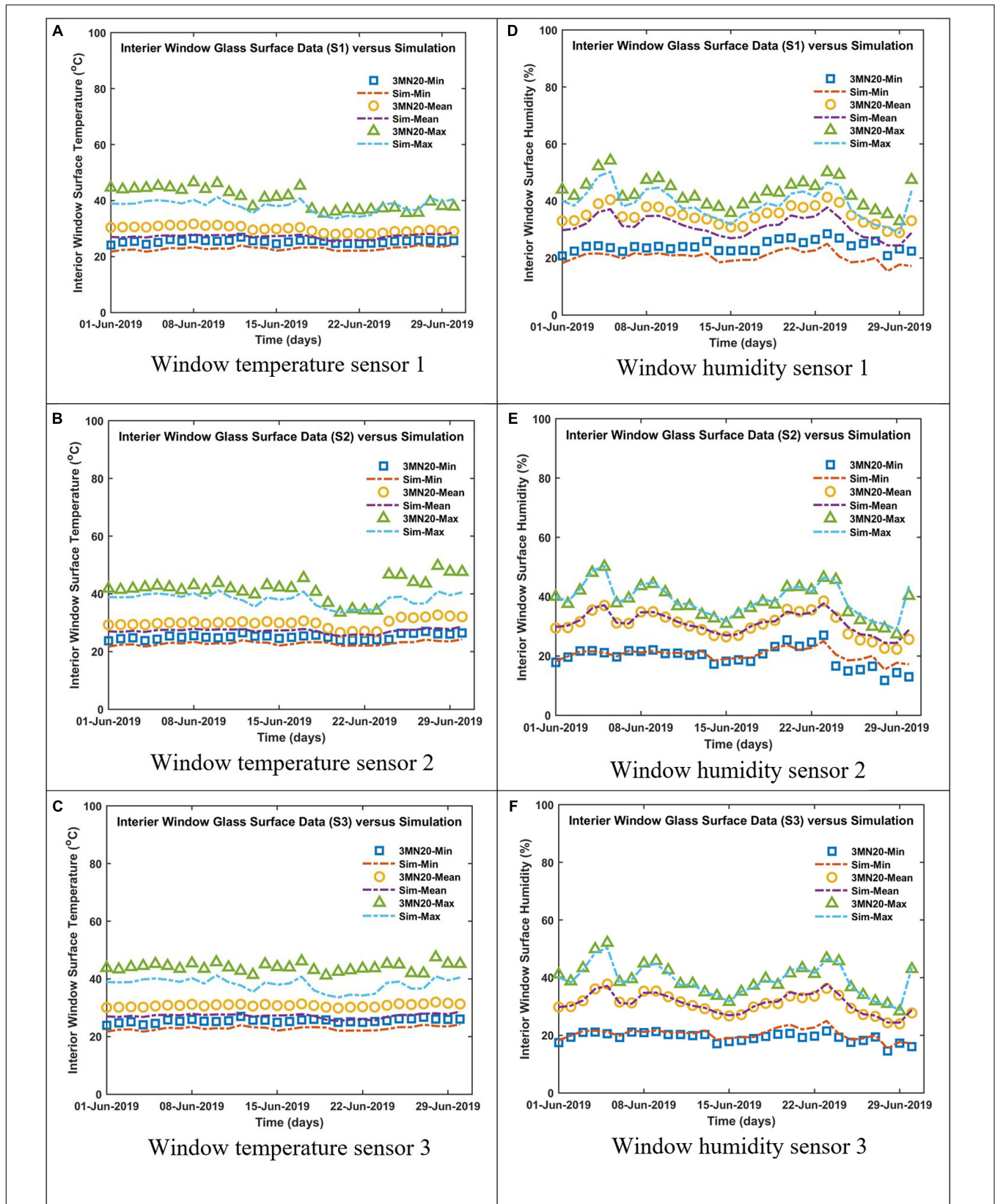


FIGURE 16 | Temperature and humidity (max-mean-min) for three DHT22 sensors on the interior glass surface data versus simulations (Sim) of the offices with 3M Neutral 20 (3MN20) windows during the month of June 2019; **(A–C)** temperatures, and **(D–F)** humidity variations.

using an IoT system. Temperature/humidity experimental data were analyzed and the histogram/PDF distribution structure of univariate and bivariate kernel density estimation (KDE) function were explored. A systematic method was presented to develop a monthly PDF (probability density function) indicator using a rational function for parameters of interest such as temperature, humidity, and illuminance. From experimental results, it was observed that the office with the 3M Neutral 20 window film performed better than its counterpart without a window film by increasing the relative humidity by 5 to 10% and decreasing temperatures between 2°C and 5°C during the months June, July, and August 2019 in Kuwait. Simulation results depicted that the SOL 101 window film could produce far better energy savings and a CO₂ footprint reduction of 2.76% annually compared with the other types of studied window films. The summary of conclusions are mentioned below:

- A systematic method was presented to develop a monthly PDF (probability density function) indicator using a rational function for parameters of interest such as temperature, humidity, and illuminance.
- The offices with window films always possessed 5 to 10% higher humidity compared with offices without windows films.
- The offices with window films always possessed lower temperatures between 2 degrees and 5 degrees Celsius compared with offices without window films.
- The lux intensity was reduced by applying window films particularly during the peak solar radiation of the day around 3 to 4 pm.
- For the 3M Neutral 20 window films in June 2019 in Kuwait, the electricity consumption and carbon dioxide production could be reduced by 3 %.
- For the 3M Neutral 70 window films in June 2019 in Kuwait, the electricity consumption and carbon dioxide production could be reduced by 0.009 %.
- The energy saving in the month of June 2019 by installation of 3M Neutral 20 window films was about 132.97 kWh.
- The energy saving in the month of June 2019 by installation of 3M Neutral 70 window films was about 0.06 kWh.
- Simulations for the SOL 101 window film indicated a 699.537 kg CO₂ footprint reduction and 1154.28 kWh energy saving in summer 2019 for one floor in the ACK building.
- Results for the SOL 102 window film showed a 653.215 kg CO₂ footprint reduction and 1077.83 kWh energy saving in summer 2019 for the same floor.

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Some of the challenges this project included communication between the sensors and Wi-Fi network, calibration of experimental data with software modeling, experimental data processing, and defining the properties of solar window films in Design Builder software, etc.

One of the best suggestions for future work is thermo-economic analysis of a big commercial building using solar control window films and estimating the amount of energy cost savings in different hot-arid climates.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KT and FS: reviewing, editing, writing, and methodology. AS: conceptualization, writing, methodology, and software. SA and FA: writing, methodology, and software data curation. MM: writing, methodology, software, reviewing, and editing. MS: reviewing, editing, and writing. HS: software, reviewing, and editing. AM: software, reviewing, editing, original draft preparation, and supervision. AI: data curation and visualization. MJ: conceptualization, writing methodology, and writing manuscript. SC: methodology and software data curation. All authors contributed to the article and approved the submitted version.

FUNDING

This study was fully funded by the Kuwait Foundation for the Advancement of Sciences (KFAS) under grant number PN18-15EE-04 which is greatly acknowledged. The corresponding author also wishes to acknowledge the support by grant number ENV6402012N from Prince of Songkla University.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2021.665978/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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