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HYBRID MIXED VENTILATION SYSTEM AIDED WITH PERSONALIZED VENTILATION TO ATTAIN COMFORT AND SAVE ENERGY

by
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AN ABSTRACT OF THE THESIS OF

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This study examined the effect of using a new control strategy for a hybrid mixed ventilation system aided with personalized ventilation (PV) units on thermal comfort and energy consumption. The proposed system integrated natural ventilation (NV) with mechanical air conditioning (AC) to reduce the AC usage. Meanwhile, PV units were operated to maintain the thermal comfort of occupants when NV room temperature was lower than a set threshold value. Building performance simulations were performed using Integrated Environmental Solutions-Virtual Environment for an office floor of a building in Beirut in which the cooling mode operation was based on the proposed cooling control strategy. The case study was calibrated using measured energy consumption. Simulation results showed that it was feasible to operate the AC system for less hours. The adopted cooling strategy resulted in 61% energy savings compared to the base case AC as the only means of cooling and ventilation.

CONTENTS

NOMENCLATURE

AC	Air conditioning
EIA	Energy Information Administration
HVAC	Heating Ventilation and Air Conditioning
IES-VE	Integrated Environmental Solutions-Virtual Environment
MV	Mixed ventilation
NE	North East
NW	North West
n_{hours}	Total number of operation hours of the PV units per working day
n_{occ}	Total number of present occupants
PMV	Predictive Mean Vote
PV	Personalized ventilation
P_{AC}	Power of the mechanical AC system
$P_{cooling}$	Power of cooling of the PV unit
P_{fan}	Power of the fan of the PV unit
P_{PV}	Total power of the PV unit
SE	South East
SW	South West
TMY	Typical Meteorological Year
T_{min}	Minimum acceptable temperature indoor
T_{max}	Maximum acceptable temperature indoors
T_{out}	Outside ambient temperature
T_{space}	Indoor space temperature
T_{PV}	PV air supply temperature

ILLUSTRATIONS

TABLES

Table Page

CHAPTER I

CONTROLLED HYBRID MIXED MODE VENTILATION SYSTEM AIDED WITH PERSONALIZED VENTILATION

A. Introduction

According to the Energy Information Administration (EIA), the energy consumption of buildings is growing over the past few decades including both residential and commercial buildings [26]. A study done on 12 countries reported that people are spending less time outdoors, compared to the long time spent indoors to attain better thermal comfort [18]. This explains the increase in building's energy consumption, especially that of office buildings, which account for more than 50% of the total energy consumption within the commercial sector worldwide [3, 26]. Heating, ventilation and air conditioning (HVAC) sector constitutes 48 % of the offices' energy consumption in USA, compared to 55% in UK and 52% in Spain [26]. This means that designing a strategy to drop the HVAC energy consumption in office buildings is important to save energy. As for Lebanon, which is considered a moderate climate area, HVAC energy consumption comprises 40-44% of the total buildings' energy consumption, out of which office buildings manifest excessive amount of energy consumption due to the use of HVAC [2]. This leads to the conclusion that targeting more efficient HVAC systems in office buildings would result in significant impact on reducing overall energy consumption in Lebanon.

Different kinds of HVAC systems are used for providing the needed thermal comfort level in buildings. Among these systems is the mixed-mode air conditioning system, which combines natural ventilation with mechanical air conditioning depending on the outdoor conditions and is typical for use in moderate climate regions [6, 25]. This system can be manipulated to draw in fresh air when the outdoor conditions are favorable, depending on the time of the year [6, 16, 30]. In the study of Daaboul et al. [6], natural ventilation was used as the default option as long as it was maintaining thermal comfort and proper air quality. Otherwise, the mechanical cooling system became active to stabilize the internal macroclimate temperature and re-attain thermal comfort and air quality when external loads (temperature, humidity, insolation…) or internal loads (occupancy, equipment…) elevated. Mixed-mode ventilation may comprise window opening simultaneously with AC operation in some cases when poor air quality was detected indoors. Similarly, Ezzeldin and Rees [10] conducted a study on four different representative regions of the arid climate, assessing the effect of applying mixed mode ventilation and other additional cooling strategies on energy saving. Their study was applied to a prototypical office building as a thermal model simulated with four sets of climatic weather data. The performance in the mixed-mode system was evaluated by calculating the thermal comfort according to the ASHRAE adaptive model and was found to save up to 50% of the energy that would be consumed upon fully using the active mechanical conditioning system [10]. Although it saved energy, mixed mode ventilation posed a complexity regarding the adaptive comfort model which comprised occupants trying to accommodate to their surrounding climate by different means for the sake of improving customized thermal comfort [14, 29], the fact which renders this model controversial. In some office buildings, the adaptive comfort model is not applicable since the occupants may not have direct control over windows' openings or the possibility of changing their clothing type. This implies that using the mixed mode ventilation with the adaptive model is debatable regarding its practicality and ability to attain thermal comfort and may need to be replaced by a different method to assess comfort [8]. Another drawback of mixed ventilation is that it regulates only the macroclimate temperature of the occupied space and applies total volume ventilation. Melikov [22] reported that the adaptive model of ASHRAE 55 is based on average values of a large group of people. However the personal comfort needs of each human candidate differ, where occupants' perception and body response to temperature changes and air flow vary as well as their clothing, activities and preferences [22]. This brings the need for a more customized mode of ventilation and comfort evaluation [9].

An alternative solution would be to apply a special mixed ventilation system only to maintain the macroclimate internal temperature at a stable higher level. As for thermal comfort and air quality, some alteration would be needed to compensate for the deficiencies of the original mixed ventilation system. Personalized ventilation (PV) can be employed for this purpose, in which a jet of air with reduced cool temperature and comfortable air flow rate is directed to the occupant' face to drop the microclimate temperature in their vicinity and meet the customized comfort needs [22]. However, choosing the temperature of the PV air supply should avoid causing draft problems which may arouse due to high differences between micro and macroclimate air temperatures, while maintaining the needed thermal comfort [20]. Such PV system is typical for use in offices since the occupants are almost fixed in their locations most of the time. In addition, PV draws in fresh air from the outside to ensure acceptable air quality at the level of each occupant [5]. This means that opening windows simultaneously while turning on the AC system would not be required since the PV is already supplying the occupants with a fresh breeze of air, reflecting a more realistic behavior of occupants in offices [36]. The mechanism of fresh and cool air supply at the face and trunk of the occupants renders non-homogeneity of temperature in the occupant's microenvironment, which is the close vicinity of the different body parts. This means that the conventional predictive mean vote (PMV) model for estimating thermal comfort is not applicable, which inflicts the need to use the bio-heat model that accounts for non-homogeneity in the surroundings (microenvironment) of the different human body segments [17]. Then, the thermal comfort is estimated according to the model of Zhang et al. [35] which takes into consideration local and non-uniform environments using a scale of -4 (very uncomfortable) to +4 (very comfortable).

This work aims to study the effect of operating a special mixed mode ventilation and air conditioning system combined with PV on the occupants' thermal comfort, breathable air quality and the resultant savings in total energy consumption as a substitute for the original mixed mode ventilation accompanied with the controversial adaptive model. The control strategy of the AC system targets the stabilization of the macroclimate space temperature at a relatively higher value, while ensuring occupants' thermal comfort and air quality through PV usage. A comfort model is then employed to evaluate the resultant thermal comfort upon applying this proposed special ventilation system. A simulation study is performed on a space of an office building in the city of Beirut, which is a location exhibiting moderate weather conditions. This study targets the estimation of the energy saving when using the suggested mixed ventilation system, compared to the case where a conventional mechanical AC system is employed to attain similar level of thermal comfort.

B. System Description

The proposed cooling system is comprised of two complementary subsystems: a special mixed ventilation system along with the personalized ventilation units as shown in Figure 1. The suggested special mixed ventilation system is comprised of natural ventilation maintained through controlled window opening and active mechanical AC system (see Figure 1a). The latter operates when natural ventilation is not sufficient to stabilize the indoor air temperature of the occupied office space [17]. The PV units operate in order to draw in fresh air into the breathing zone of the occupant and attain thermal comfort through improving the microclimate air temperature; the air temperature in the close vicinity of the occupant's body parts [31]. (see Figure 1b).

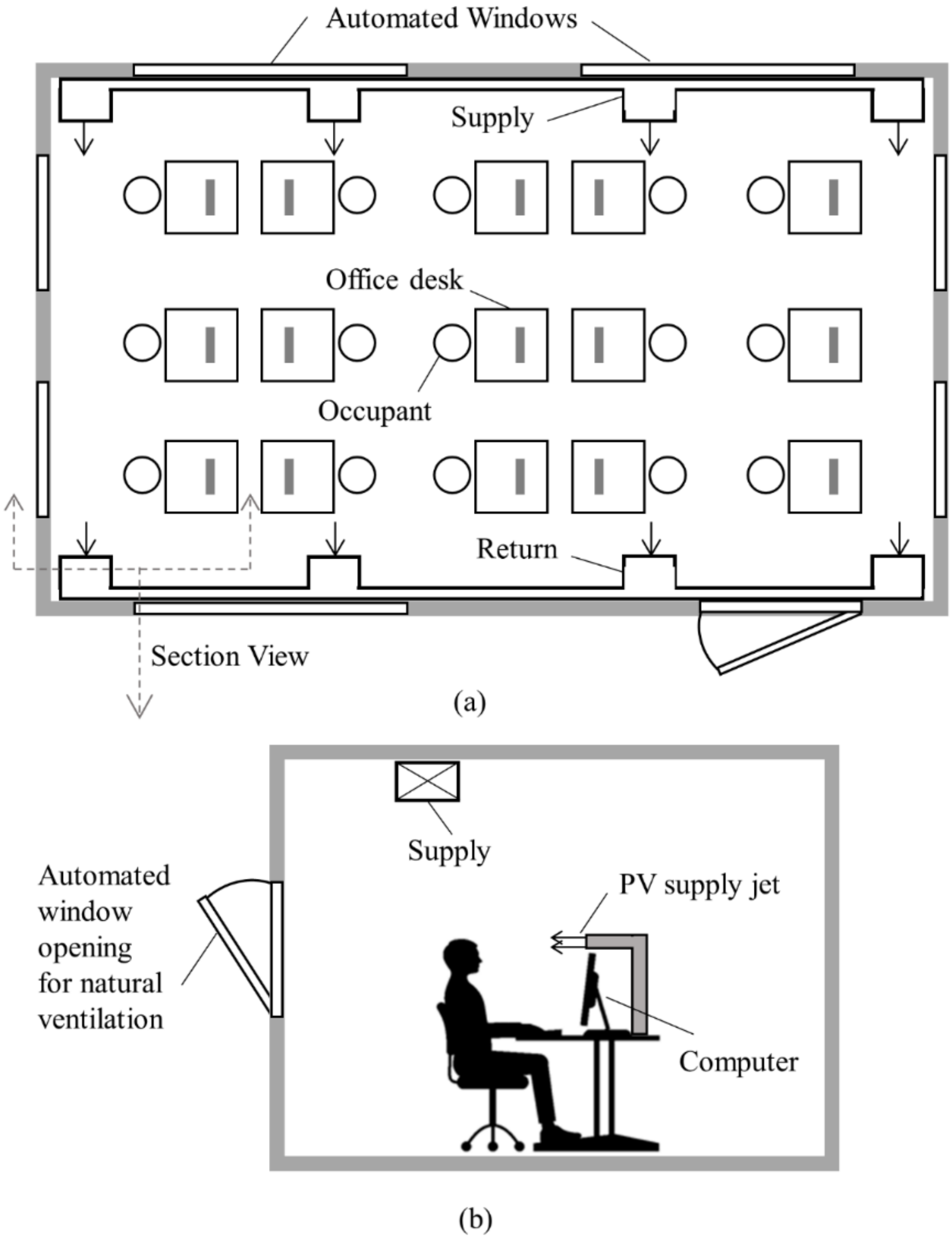

Figure 1. Schematic showing (a) the subsystems of the proposed cooling system and (b) a section view focusing on a single occupant with a PV unit

The operation of these systems is controlled by the macroclimate space temperature (T_{space}), which is the air temperature of the whole occupied space. This temperature has a lower limit T_{min} (minimum acceptable macroclimate temperature) and an upper limit T_{max} (maximum acceptable macroclimate temperature) that control the window opening profile and the mechanical AC operation. Windows' openings are controlled by the values of macroclimate indoor air temperature (T_{space}) and the outdoor air temperature (T_{out}), according to a control strategy detailed in the following section. The mechanical AC only operates when T_{space} exceeds T_{max}. The PV air temperature (T_{PV}) is specified in a way to attain thermal comfort, without causing thermal draft or asymmetry in temperature distribution over the different body parts of the occupant.

C. Cooling System Control Strategy (Special Mixed Ventilation with PV)

The proposed system operation is controlled by a strategy which manages how and when each sub-system should operate. Sensors are used to measure the indoor and outdoor temperatures, while actuators control the operation of the suggested mixed mode system. Figure 2 summarizes the control strategy of the proposed system.

The indoor air temperature is bounded by lower and upper limits, T_{min} and T_{max}, respectively. The limiting temperature T_{min} is defined by the minimum acceptable indoor air temperature at which PMV thermal comfort index of Fanger [11] is within the acceptable range, without the need of any means of macroclimate cooling. For typical office workers, an indoor air speed of 0.15 m/s, relative humidity of 55% and indoor air temperature of 23°C gives an estimated PMV value of -0.53. This implies that T_{min} of 23°C is considered acceptable to be adopted in this study. On the other hand, the indoor air temperature above which thermal comfort is no more attained, while windows are fully opened and PV units are operating is considered to be the maximum allowable indoor air temperature (T_{max}). Once the indoor air temperature exceeds T_{max}, the active mechanical AC system should be employed to control the macroclimate air at a temperature around T_{max}, and maintain the thermal comfort of occupants. In studies where PV was used, the maximum macroclimate temperature above which thermal comfort was hard to be attained ranged between 28°C and 30°C [19, 20, 21, 32]. A macroclimate air temperature of 29°C is considered acceptable for use in this study.

The cooling mode operation targets PMV values ranging between -0.5 and +0.5, indicating thermal comfort of the occupants when PV units are not operating. If PV units are turned on, the non-homogeneous temperature distribution over the different body parts due to local cooling of the face and trunk necessitates the use of a different comfort model that incorporates the effect of local cooling for evaluation of comfort. In this case, the model of Zhang et al. [35] is adopted which has a comfort scale which ranges between -4 (very uncomfortable) to +4 (very comfortable). Zhang et al. [35] model require the knowledge of core and segmental skin temperatures which can be found using a bio-heat model that can predict human segmental thermal responses [17]. In current proposed strategy, occupants are considered comfortable for when Zhang et al. comfort scale is between 1 and 2.

During the working hours of the day and when the office is occupied, the cooling mode is specified according to the values of T_{space} and T_{out} as shown in Figure 2. The following strategy is applied:

- If T_{space} is less than T_{min}, then the window opening and PV operation are controlled as follows:

  If $T_{space} < T_{out}$, then windows are opened and PV units are turned off.

  If $T_{space} > T_{out}$, then windows are closed and PV units are turned on to supply fresh air.

- When T_{space} exceeds T_{min} but is still less than T_{max} while occupants are uncomfortable, then:

If $T_{space} < T_{out}$, then windows are closed and PV units are turned on.

If $T_{space} > T_{out}$, then windows are opened gradually and PV units are turned off.

The above continues until windows are fully opened. At this point, if occupants are still uncomfortable, then PV units should be operated to re-attain thermal comfort.

- When T_{space} exceeds T_{max}, the active mechanical AC system will be operated to stabilize T_{space} around T_{max}, PV units are turned on, while the windows are kept closed.
- After working hours and when the space is unoccupied, then thermal comfort and air quality are no longer important and only night-time natural ventilation will be employed to avoid heat buildup within the space.

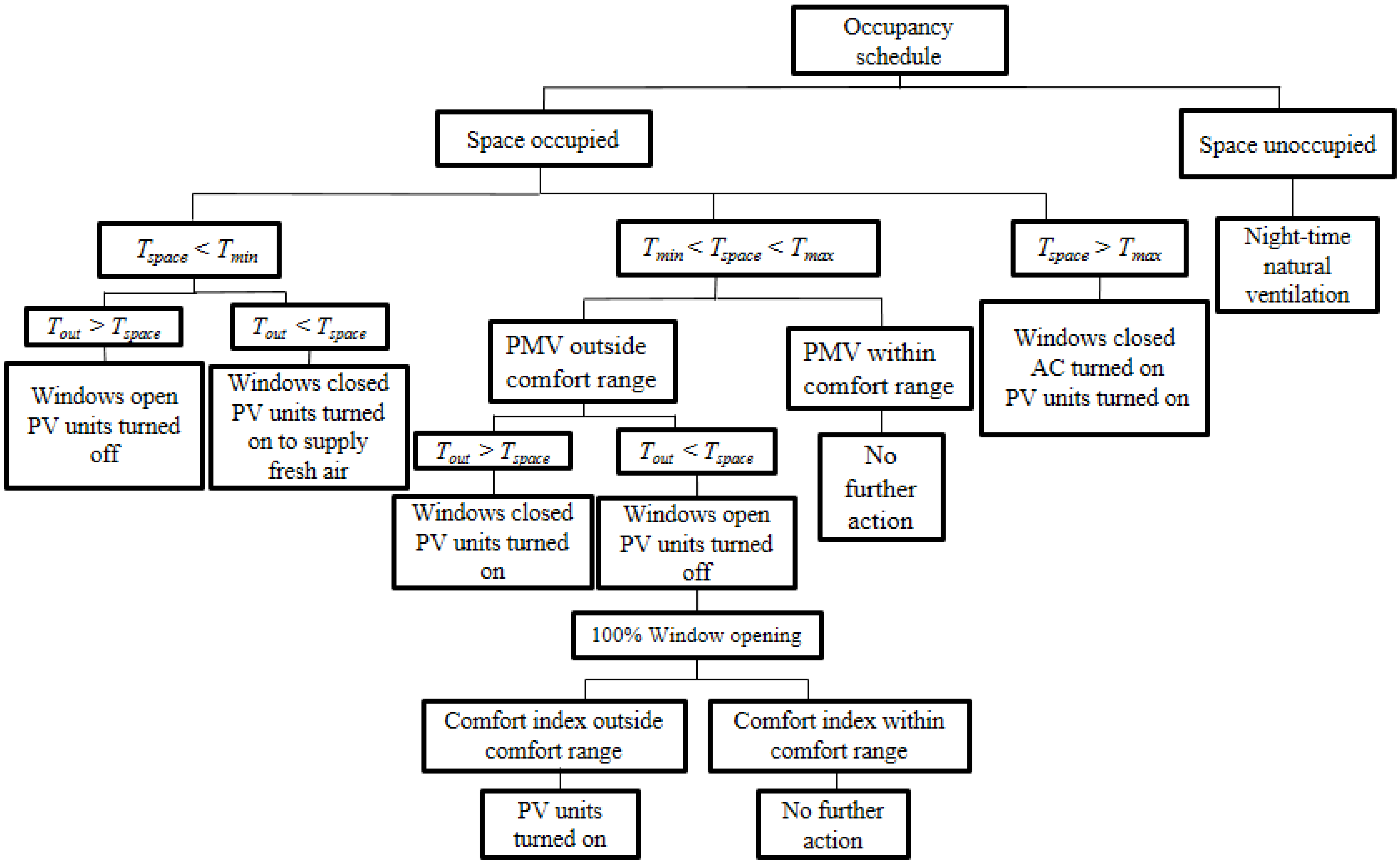

Figure 2. Control strategy for the overall AC system

CHAPTER II

METHODOLOGY AND SYSTEM MODELS

A. Methodology

In order to test the effectiveness of the proposed system, a set of models are adopted that will help in implementing the system and estimating the indoor temperature, thermal comfort, and energy consumptions. Figure 3 shows the integration of the three mentioned systems along with their inputs and outputs. A reference base case is analyzed as well, where only the conventional mechanical AC system is employed to attain similar levels of thermal comfort as that of the case study proposed system. This base case is used for comparison purposes, to estimate the resultant energy consumption saving upon applying the suggested cooling system as shown in

Figure 3. In addition, the predicted energy consumptions are compared with the collected actual data in order to calibrate the base case and prove the reliability of the simulation case.

These models are as follows:

I. The energy simulation software (IES-VE) used for predicting internal space temperature, electrical energy consumption, and testing the suggested implementation of cooling control strategy

II. PV model integrated with special mixed ventilation system, having a fixed air flow rate and temperature, used for attaining acceptable thermal comfort and fresh air quality [23]

III. The bio-heat model [17] used to estimate the different body-segments' core and skin temperatures for the known surrounding and microclimate temperatures. These temperatures are used as inputs for Zhang et al. [35] thermal comfort model to calculate the resultant thermal comfort index which has a range from -4 (very uncomfortable) to +4 (very comfortable).

B. Simulation software model (IES-VE) and weather data

The simulation software used in this study is IES-VE [15], which refers to heat equations and the outdoor surrounding conditions of the building under study to estimate the resultant indoor conditions along with energy consumption of the HVAC system involved. It takes as an input the layout of the space under study, along with the construction material, the internal loads in the space with their operation schedule (equipment, lighting, occupancy...), and the weather data. Then IES-VE integrates the natural ventilation process with the conventional mechanical AC, to attain acceptable and comfortable conditions in the occupied space. The schedule of operation of the overall ventilation and conditioning system is defined by a control strategy utilized to regulate the performance accordingly. The IES-VE software proved its reliability and was used by a number of studies tackling energy consumption of buildings which involve natural ventilation [2].

As for the weather data used, TMY (Typical Meteorological Year) weather data for the location of interest is collected, using Meteonorm (V7.3) database [24]. The TMY data is considered well representative of the weather conditions, since it offers data of the highest occurrence for a given period of time according to statistics done for a certain number of years. For Meteonorm, the TMY data is estimated based on a period of 10 years extending from 2000 till 2009 and is used for the simulation case of the suggested cooling system.

C. PV system

The PV unit has two main functions: 1) to deliver fresh air and 2) to offset the discomfort that results from allowing high macroclimate temperatures. Its operation is controlled by the supply air flow rate and temperature [31]. In this study, the flow rate will be fixed at 10 l/s, which was used in a number of previous studies [21, 32]. and was found to reach the breathing zone and penetrate the occupant thermal plume. As for the PV air temperature, it should be lower than the macroclimate one but with a difference that does not cause thermal draft [12, 13, 20]. Since the macroclimate temperature would range between 23°C and 29°C, the PV will be operated at a fixed temperature of 22°C; achieving the desired cooling effect while avoiding thermal draft.

D. Bio-heat and comfort models

When the PV unit is operated, the microclimate conditions in the vicinity of the human body become non-homogenous and hence the PMV index is no longer applicable. The appropriate comfort model of Zhang et al. [35], which accounts for the non-uniformity in environment surrounding the occupant, can be used instead. The selected comfort model utilizes the occupant core and segmental skin temperatures as input to evaluate the state of overall comfort [35]. These temperatures can be predicted using the bio-heat model of Karaki et al. [17], which divides the human body into 17 segments and takes as an input the ambient temperature and the convective heat transfer coefficients in the vicinity of each segment. This way, the bio-heat model accounts for the temperature non-homogeneity between the upper (face and trunk) and other body parts and predicts segmental temperatures of face and trunk that have a higher weight in comfort compared to the other parts of the body [35]. Occupants are considered comfortable in this study with a target value ranging between 1 and 2 using Zhang et al.'s comfort scale.

E. Energy Consumption Estimation

The energy saving achieved by the suggested system can be calculated by comparing the energy consumption of the system with that of a base case, where the mechanical AC system is the only means of cooling. The suggested system energy consumption for a given month of the cooling season is calculated as follows:

$$P_{total} = \sum_{i=1}^{n} (P_{PV} + P_{AC}) \tag{1}$$

where n is the total number of working days for a given month of the cooling season, and P_{AC} and P_{PV} are the total power consumption of the mechanical AC system and PV units respectively, for a single working day. P_{PV} is estimated according to the following formula:

$$P_{PV} = n_{hour} * n_{occ} (P_{fan} + P_{cooling}) \tag{2}$$

where n_{hour} is the total number of operation hours of the PV units per working day, n_{occ} is the total number of present occupants, P_{fan} denotes the power consumption of a single PV unit fan and $P_{cooling}$ denotes the cooling power of a single PV unit. P_{fan} is estimated to be 1.8 W per unit, for a steady PV air supply with a flow of 10 l/sec [1].

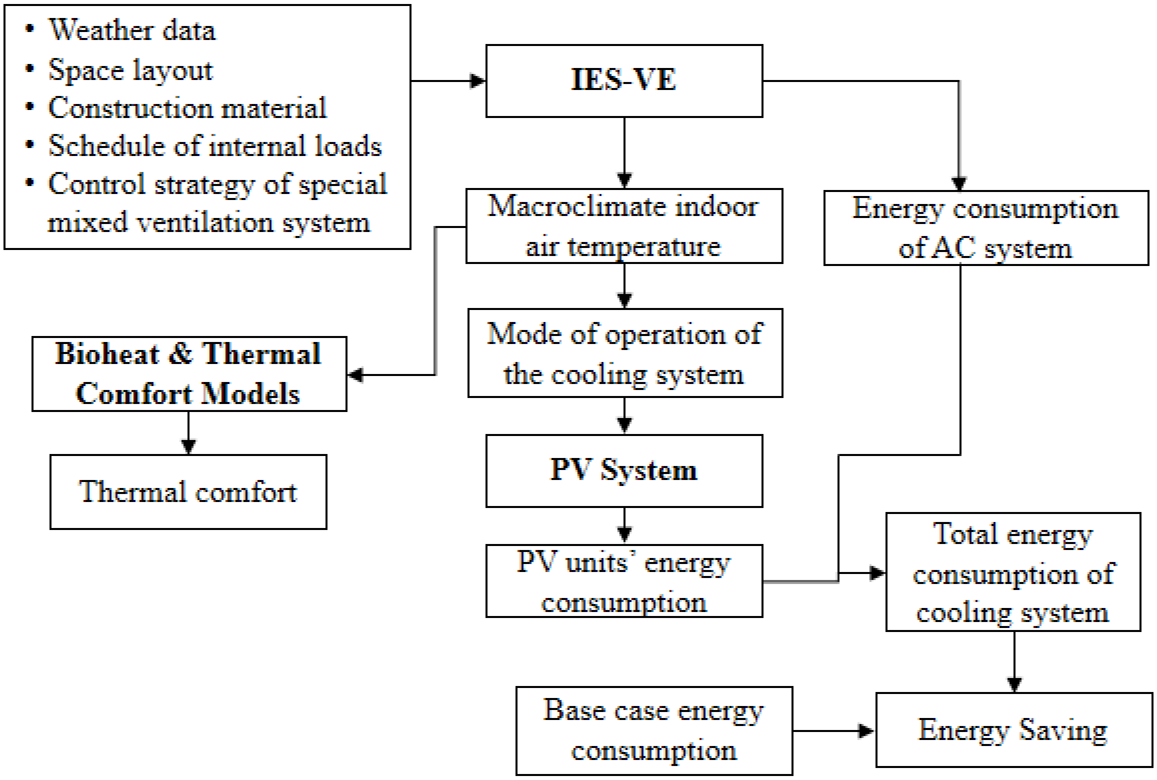

Figure 3. Methodology flow chart

CHAPTER III

CASE STUDY AND CALIBRATION

A. Case Study Description

The space considered in this study is a rectangular single-zone office of total area of 240 m^2. It is located at the ground floor level of a seven-story engineering office building in Beirut city with south-east (SE) to north-west (NW) building axis. This building exhibits the typical building features used in the country of Lebanon [33]. It is separated from the neighboring buildings by a distance ranging between 10 m to 20 m depending on the direction considered. The specifications of the construction material of the building are listed in Table 1. The glazing percentage is 12% in the SW and NE façades, and 20% in the SE and NW façades [6, 33].

Table 1. Specifications of the construction material of the space under study

Construction Element	**Construction Material (Internal to External)**		
	Material	Thickness (mm)	Overall U-value ($W/m^2.K$)
Window	Single layer glass	8	5.53
Door	Polywood-30 mm	50	1.80
External Wall	Plaster (Light Weight)	12	1.40
	Concrete block (Medium Weight)	200	
	Plaster (Light Weight)	12	
	Carpet	10	0.27

Internal Ceiling/ Floor	Reinforced Concrete	100	
	Insulation	100	
	Reinforced Concrete	100	

The considered office has a maximum possible occupancy of 15 people who are present during the working hours which range between 8:00 am and 6:00 pm for 5 days per week. The internal gain within the space of study is due to lighting, operating computers, present occupants, and other miscellaneous equipment. The fluorescent lighting power distributed all over the area is around 1250 W. In addition, there are fifteen computers in the space which might have different brands, thus, an average of 75 W/computer will be considered. A printer and a fax machine are also present and emit a summed total of 150W.

The office space is equipped with a conventional mixed AC system, which operates during the working hours as the main cooling system. This AC system has a 24^{o}C set-point temperature and 21.1 kWh total cooling capacity. The space is also equipped with windows that could be opened at some times during the day.

B. Case Calibration

A calibration of the case study will be done to minimize the difference between the simulated and the actual measured HVAC energy consumption [28]. The latter consumption was retrieved for the month of August, since during this month the AC system is the only means of cooling used throughout the working hours. A sensitivity analysis should be done for the most uncertain inputs to test the effectiveness of each in decreasing the error between the measured and simulated energy consumption. After performing the simulation using the weather data for

August, IES-VE predicted a total HVAC energy consumption of 1.98 MWh, implying 10.3% increase compared to that of the actual data which showed a value of 1.79 MWh. This difference between the simulated and measured data indicated the necessity of tuning the internal loads to attain closer results, as these were considered the inputs with the least certainty. As a first step, the occupancy schedule was modified to account for possible absences of employees. Instead of full daily occupancy, a schedule of 14 present occupants per day, and then 13 present occupants per day were considered, each in a separate simulation. However, this did not reduce the error significantly, and still induced a relatively high discrepancy error of 9.1% and 8.4% respectively. This was due to the small drop in total heat gain into the surrounding resulting from 1 or 2 missing occupants per day. The other trial was to modify another aspect of the internal load of the space. As mentioned before, the computers were estimated to emit an average of 75 W/computer into the space. However, differences in the computer brands along with possible occupants' absences would eventually drop the heat emissions into the space. Thus, a heat dissipation of 65 W/computer and 60 W/computer were considered, with a resultant average heat dissipation of 4 W/m^2 and 3.75 W/m^2 respectively. A simulation based on each dissipation was done, to reveal a total consumption of 1.93 MWh and 1.9 MWh respectively. Thus, the calibrated computer heat loss to the surrounding was 60 W/computer, resulting in an acceptable discrepancy error of 5.9%. Consequently, the simulated results matched the measured data more closely, reflecting the reliability of IES-VE in presenting the energy consumption of the space under study. A similar approach of tuning was followed by Daaboul et al. [6] and Annan et al. [2] in their studies to obtain the calibrated input value and get their results closer to the measured data.

C. Results and Discussion

In the following section, the simulation results are presented, explaining the effect of applying the suggested cooling control strategy on the internal space conditions. The total number of hours of each cooling mode operation corresponding to each month are listed as well, which consequently leads to the total energy consumption of the suggested system and the savings compared to a base case utilizing the conventional mechanical AC system.

Figure 4 to 8 show the hourly variations of the indoor air temperature (T_{space}), the outdoor air temperature (T_{out}), the thermal comfort of occupants, as well as the operation profiles of the different cooling modes during the occupied hours (8:00 till 18:00) of representative days of each summer months of May through September. The simulations refer to the case where the suggested cooling system is applied and the representative days involved are the 15th of each month [4].

For the month of May, and as shown in Figure 4, the windows were closed and PV units delivered moderated fresh air during the morning working hours (8:00-12:00). The windows were opened when the outdoor air temperature (T_{out}) exceeded the indoor air temperature (T_{space}), and PV units were thus turned off since T_{space} is less than T_{min} of 23 ^{o}C. The occupants were comfortable throughout all the working hours of the day, with a PMV scale ranging between -0.3 and 0.2. During June, the average indoor air temperature increased compared to that of May. Figure 5 shows that natural ventilation was sufficient only during the early working hours (8:00 till 11:00) since the outdoor air was cooler than the indoor air. PV units were operated when window opening was not sufficient anymore for occupants' thermal comfort. Windows were closed and PV units were turned on when T_{out} exceeds T_{space} during the afternoon. Thermal comfort of occupants was attained throughout the whole day with a PMV scale of (0.2-0.5) when PV units are turned off and Zhang et al. scale of (1.6-1.7) when PV units are operated.

As for the months of July, August and September (Figure 6-8), similar cooling mode operation occurred as that of June, but with different time slots during the working day. However, July and August, which represented the peak of the cooling season, involved mechanical AC operation in addition to PV operation when T_{space} exceeds T_{max} of 29 ºC, while windows were kept closed. Figure 7 shows that August involves the highest number of operating hours of the mechanical AC among all the other months of the cooling season. During these three months, the occupants were comfortable throughout the whole day, with a thermal comfort scale of Zhang et al. ranging between 1.5 and 1.7.

Following the working hours, natural ventilation was employed to avoid heat build-up within the space. It implies that the indoor and outdoor air temperatures during this period would have a similar behavior [34]. This explains the difference which may show up in T_{space} values for the beginning of two consecutive days, as shown in Figure (4-8).

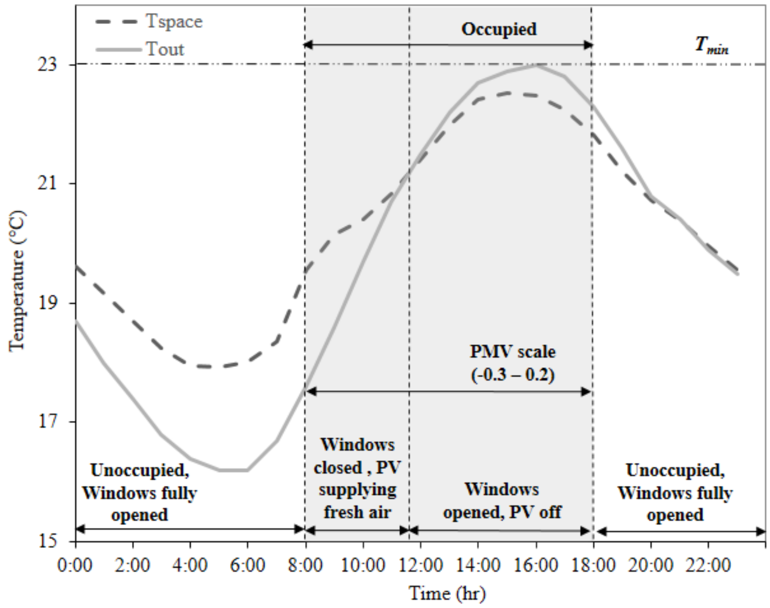

Figure 4. T_{space}, T_{out}, the modes of cooling system operation, and thermal comfort hourly variations for the 15th of May

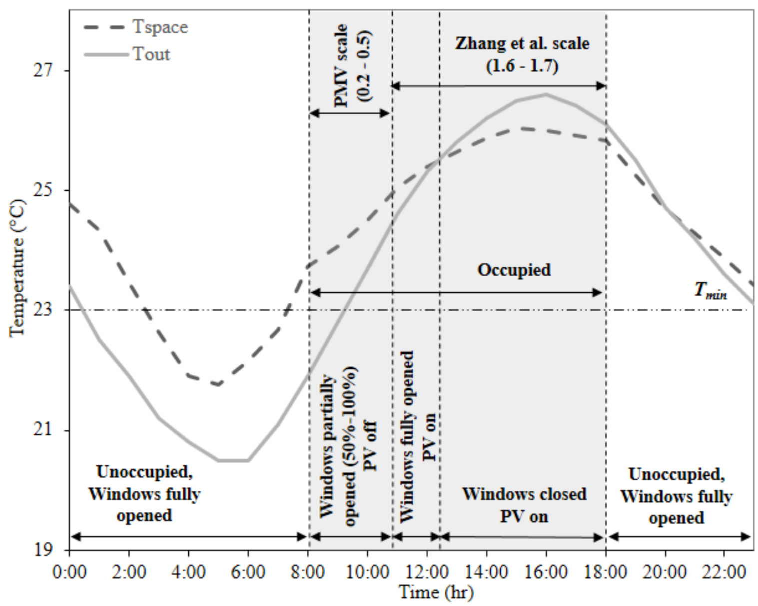

Figure 5. T_{space}, T_{out}, the modes of cooling system operation, and thermal comfort hourly variations for the 15th of June

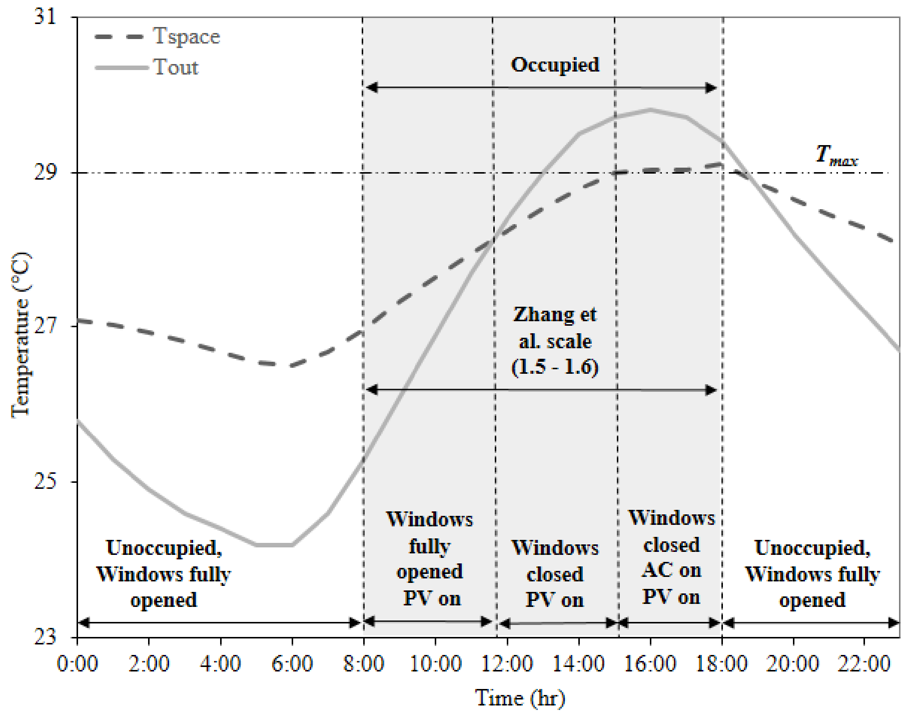

Figure 6. T_{space}, T_{out}, the modes of cooling system operation, and thermal comfort hourly variations for the 15th of July

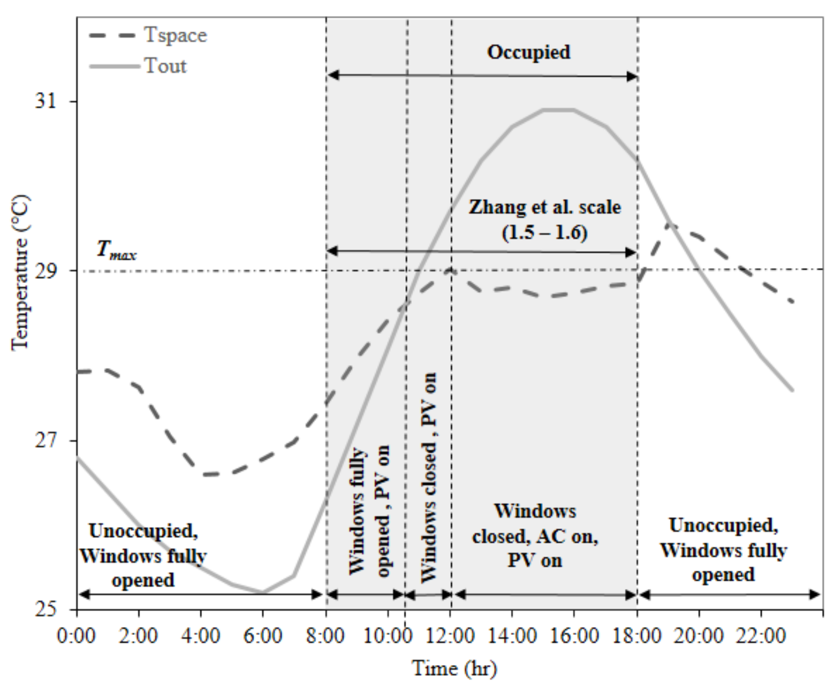

Figure 7. T_{space}, T_{out}, the modes of cooling system operation, and thermal comfort hourly variations for the 15th of August

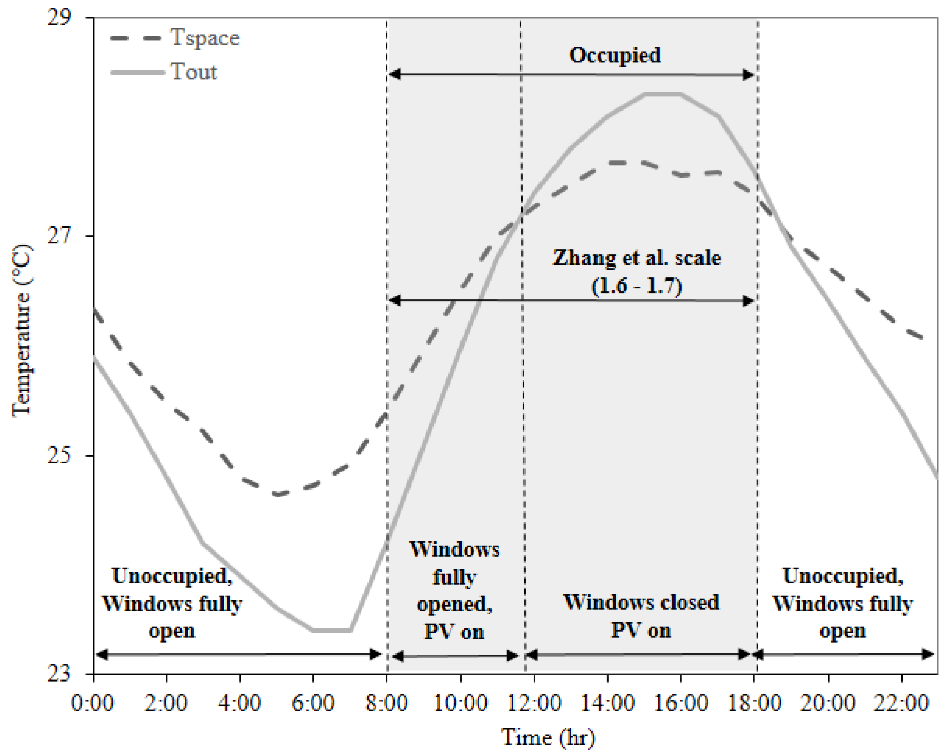

Figure 8. T_{space}, T_{out}, the modes of cooling system operation, and thermal comfort hourly variations for the 15th of September

Table 2 summarizes the hours of operation of each cooling mode for each month of the cooling season. For the months of the cooling season, starting from May till September, the dominant mode of cooling was for windows being closed while the PV units were operating to supply cool air. Since the average outside air temperature for May was considered the lowest during the whole cooling season, natural ventilation corresponds to the highest number of hours of operation among all the other months, attaining thermal comfort for a total of 56 hours. Windows were closed as well for a total of 35 hours, while PV units were operating to supply moderated fresh air for occupants. The rest of the cooling modes were considered minor during this month. As for June, natural ventilation is sufficient for a total of 20 hours, compared to 14 hours where windows were opened but still PV units were needed to supply cool air to maintain local thermal comfort for occupants.

Since indoor air temperatures reached their peak during July, August, and September, the mechanical AC was operated for 53, 75, and 28 total hours respectively during these months, to moderate the macroclimate temperature, aided with the operation of PV units. During this period windows were rarely opened, since outdoor air temperature was less likely to be cooler than the indoor air. However, September exhibited the highest number of hours of window opening among the peak months (41 hours), aided with the operation of PV units to supply cool air. Natural ventilation was almost absent during these three months of the cooling season.

Table 2. Number of operation hours for each mode of the cooling system

	Number of operation hours per month for each mode of the cooling system				
Month	Window closed / PV supplying fresh air (hrs)	Window Closed / PV on (cooling mode) (hrs)	Window Opened / PV on (cooling mode) (hrs)	Windows Opened / PV off (hrs)	AC on / PV on (cooling mode) (hrs)
May	35.0	118.0	1.0	56.0	0.0
June	0.0	176.0	14.0	20.0	0.0
July	0.0	144.0	23.0	0.0	53.0
August	0.0	118.0	27.0	0.0	75.0
September	0.0	149.0	41.0	2.0	28.0

Following the schedule of operation of the different cooling modes, the suggested system energy consumption were estimated for the whole cooling season and were compared to that of a base case utilizing the conventional mechanical AC. The energy consumptions of the two cooling systems for the five months of the cooling season are plotted in Figure 9. The base case energy consumption indicated higher values than those of the study case, which utilized the suggested control strategy of the hybrid cooling system of mixed ventilation with PV. The highest energy consumption for both cases were associated with the months of July, August, and September at 0.56 MWh, 0.77 MWh, and 0.32 MWh respectively, compared to 1.58 MWh, 1.82 MWh, and 1.0 MWh for the conventional AC system. Hence, the proposed hybrid cooling system resulted in lower energy consumption than the base case with the conventional AC system. The least energy saving was attained during the month of June, with 48.5%, compared to 67.5% maximum energy saving attained during September.

Upon summing up the total energy consumption for each system over the whole cooling season, the suggested cooling system case resulted in a total of 1.93 MWh consumption, which is significantly lower than that of the conventional AC system with a value of 5.01 MWh. Consequently, applying the suggested cooling system of special mixed ventilation with PV units resulted in 61% reduction in energy consumption for cooling compared to using the conventional mechanical AC.

According to Daaboul et al [6], their study examined applying mixed mode ventilation to an office in a building in Beirut, while evaluating thermal comfort using ASHRAE 55 adaptive comfort model. This mixed mode ventilation system was reported to achieve 24.5% energy saving for the months of July, August and September, which was less than the saving attained with the current control strategy of this study (62% for the same months) [6]. This was due to the extended hours of AC operation in the study of Daaboul et al., where it operated during weekends and outside the working hours whenever the indoor air temperature dropped below 26 ºC. Pesic et al [27] performed a study about the potential of natural ventilation in attaining energy saving in an office located in the Mediterranean coast of Catalonia [27]. The mixed mode ventilation system was comprised of natural ventilation and mechanical AC operating at different times depending on the indoor air temperature, while night time natural ventilation is employed as well. This system achieved an energy saving up to 32.9% for the whole cooling season, compared to the full time AC operation case. The hybrid system proposed in our study resulted in more energy savings than the reported mixed ventilation system of Pesic et al. [27]. This is due to two reasons: i) their AC system was allowed to operate for a longer span of the working day (6:00 till 18:00 hr) compared to our system (8:00 till 18:00 hr); and ii) their AC system was turned on at lower set point indoor air temperature of 23 °C compared to our proposed mixed ventilation system with PV where AC is turned on at 29 °C.

Ezzeldin et al. [10] performed a study about employing mixed mode ventilation and other low energy cooling systems on office buildings in arid climate regions [10]. The mixed mode system ensured thermal comfort of occupants, based on 80% acceptability of ASHRAE 55 adaptive comfort model, and maintaining PMV index between -0.85 and 0.85 upon activating the mechanical AC system. The system saved up to 63% HVAC energy compared to the conventional active cooling system application. This saving is close to the one attained with the current hybrid suggested system in this study while 20% discomfort is accepted for Ezzeldine et al. work, compared to 100% acceptable comfort levels for the current proposed hybrid system.

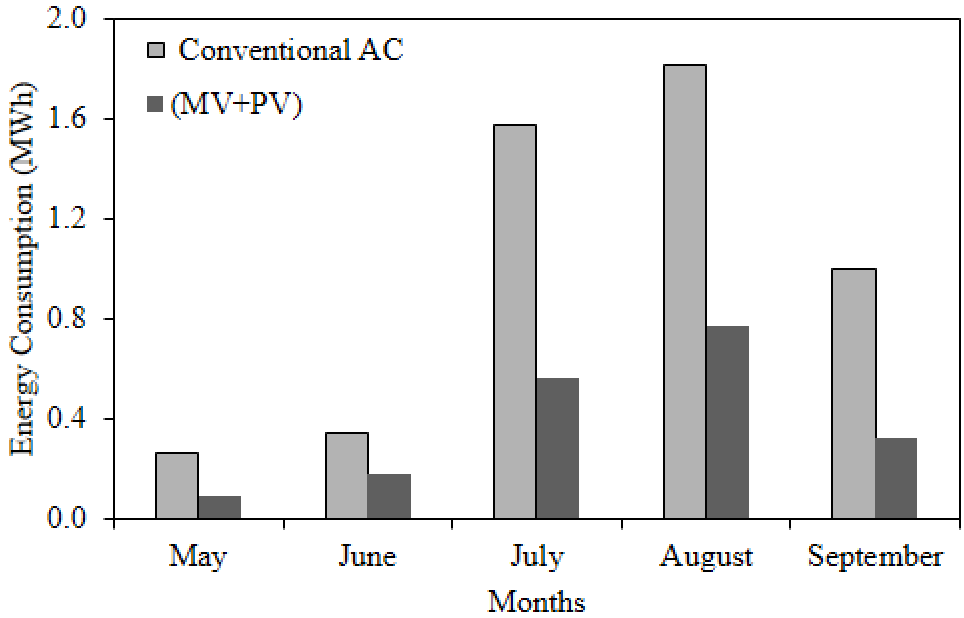

Figure 9: Energy consumption of the proposed cooling system and that of a base case using the conventional AC

D. Conclusion

This paper studies the effect of employing a hybrid mixed ventilation system aided with personalized ventilation units on energy consumption saving while maintaining thermal comfort and good air quality. The hybrid ventilation system utilizes natural ventilation, when outdoor conditions are suitable, through window opening. Otherwise, and when natural ventilation is not sufficient, it stabilizes the indoor space temperature at a relatively high set-point using the mechanical AC system. PV units are operated, with fixed supply air temperature and flow, to restore thermal comfort for occupants and supply them with fresh air.

The suggested cooling system was applied for an office space area, in a building in Beirut, which exhibit the typical building features in Lebanon. The simulations were done based on TMY weather data, to estimate the indoor air temperature variations for the whole cooling season. The latter was compared to the outdoor air temperature, and the resultant cooling modes of operation for the whole cooling period are defined, along with the corresponding thermal comfort status of occupants. The use of PV units and natural ventilation significantly reduced the hours of operation of the mechanical AC, while achieving thermal comfort through all the time during the cooling season. The simulations, as well, estimated the resultant energy consumption of the suggested cooling system, which reveals 61% energy saving compared to that of a base case that utilized the mechanical AC system as the only means of cooling.

In conclusion, the PV units should be properly considered in future office space design, along with controlled window opening to drop the amount of the HVAC consumed energy. Further studies about customizing the PV air flow and temperature according to the needs of each occupant may be beneficial to harness higher levels of energy saving.

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