Department of Mechanical and Aerospace Engineering

Modelling and Simulation of a Photovoltaic System for Increasing the Comfort Levels in a Primary School in Dhanaura, India

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Signed: Akhil James Date: 31st August, 2016

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Abstract

Access to basic electricity has become a luxury in developing countries with tropical hot climate. This is more prominent in rural regions where basic comfort like cooling is not met due to insufficient power supply. This thesis proposes to setup a photovoltaic system in a primary school in Dhanaura, a small town in the Northern belt of India. Also, to meet the cooling demands, it proposes to setup solar powered air conditioner and compare different scenarios to make the system feasible. Auxiliary power and storage is not considered in any one of the scenarios, so as to check the feasibility of the photovoltaic system without battery, as the PV system is considered to be grid connected. The purpose behind the off-grid photovoltaic system is to reduce the strain from the already congested grid and to balance the cost required to provide adequate cooling.

Modelling and simulation is carried out on ESP-r for specific types of classrooms and comfort levels is determined. The solar data of the school is determined by PVGIS and analysis of different scenarios were done in Excel spreadsheet.

1. INTRODUCTION and LITERATURE

1.1. Demographics

India is a mega-diverse nation in South Asia, which is the seventh largest in the world by area (3,287,590 km^2), second most populous in the world (1,293,057,000) with a population density of 388.7/km^2. It has a hot tropical climate on an average, but geographically the climate varies from being extremely sunny, rainy, windy or snowy. There four seasons on an average (winter, summer, monsoon and post-monsoon). It has more than 300 sunny days a year and equal number of windy days in the majority of the area. The population can be dense depending on their socio-economic conditions and are high in rural (more than 70%) than urban (nearly 30%). The rural population mainly belongs to the primary and secondary sector while the urban population belongs to secondary and tertiary sectors. Also, 22% of the population is below poverty line.

1.2. Energy Crisis

As of June 2016, India has an installed capacity of 304 GW (Anon, 2016), of which 61% of the power plants are run from coal and this number is rising by the year. Coal being a finite resource, is a non-renewable form of energy and with India's growing population, this means it will dwindle a lot earlier than predicted. Also, nearly 90% of the total primary energy consumption comes from fossil fuels and nearly 45% of these fossil fuels are imported yearly. So statistically, this gives rise to the question of sustainability. Currently, more than 23% of the population, which is nearly 300 million people does not have access to electricity (Martin, 2016). This percentage is likely to grow if the energy policy remains the same. Being a developing country, it is highly expensive to expand the grid to rural areas, and the limiting electricity generation will not cope up with the extra load. Also a large section of rural population is not connected with efficient modern cooking fuel sources. The per capita energy consumption is 440 kg of oil equivalent, which is a lot less than the world average of 1688 kg. Moreover, India is one of the top 5 countries in terms greenhouse gas emission as there is a release of 2,341,000 kiloton of carbon emissions every year, which is 1.8 ton per capita.

1.3. Solar Potential

India has very high renewable energy capacity and it is the first country in the world to setup a ministry for non-conventional energy resources. There are massive plans and policies towards renewables like solar, wind, hydro and biofuel. Moreover, India has one of the biggest solar energy potential in the world (5000 trillion kWh) and this is exponentially more than all the fossil fuel energy reserves it has (Mnre.gov.in, 2016). There is nearly 8062 MW of installed solar power capacity (Anon, 2016) which makes it rank one in terms of energy generated per watt installed. Other than electrification, these solar panels have applications in solar water heaters, agriculture support, street lamps and power grid stabilization. Being the most potential source of renewable energy, the government has shaped many policies for the growth of solar energy in India, like accelerated depreciation where small businesses are given tax benefits for installing solar panels. Subsidies and Renewable Energy Certificates are also provided by the government. Moreover, subsidies up to 40% are provided by the government for installing solar panels, and more benefits are given to educational institutions, hospitals, etc. There is also schemes like Assured Power Purchase Agreement where the state and central government guarantee the purchase of energy produced from solar panels. Recently, India also unveiled the Global Solar Alliance with 120 countries (Neslen, 2015).

2. PROJECT OBJECTIVES

This project aims to model and carry out simulations for solar photovoltaic system to meet the electrical demands of the school. Also, it focuses on reducing the overall strain in the already over congested grid and waiver the cost of electrifying the entire school. And finally, it focuses on feasibility of incorporating air-conditioner in the school to increase the comfort of the occupants.

The main component in the system is a solar photovoltaic system. The secondary components are the air- conditioners based on different cooling loads, battery Storage and insulation materials in different scenarios.

The following are step by step details about the project methodology:

1. Building a current model of two classrooms, adjacent to each other one above the other in two zones, having a specific climate date, construction materials, dimensional parameters, optical properties and orientation.

2. Building a set of models similar to the above model with similar climate data, dimensions and orientation, but differs in control system, materials properties and operation details. These are the different scenarios based on factors like comfort, financial and energy savings.

3. To obtain the estimated data for the solar energy received in the current site and investigate the solar photovoltaic system that will produce the required power to meet the current electrical demands of the school.

4. Investigate and model different scenarios, each of whom which would increase the comfort levels of the original model by providing cooling. Yet these scenarios will be motivated by either financial savings or energy savings or both by applying insulation or simply by changing the operation hours.

5. Based on different cooling scenarios, photovoltaic system of higher capacity is investigated to accommodate the cooling loads of different air-conditioners.

Figure 1: Building of the school to model and simulate the PV system

3. MODELLING and SIMULATION

3.1. Building a current model

The project focuses on a school named Shanti Devi Memorial Public School, in a town named Dhanaura in Uttar Pradesh, India with coordinates 28.9546° N and 78.2647° E. It is a two floored building with 26 rooms in total with an approximate building area of 1850 m^2. They have 7 kW connection to the grid, but majority of the power comes from the diesel generator, as there are severe power cuts in the region during school hours. A base case model based on the current parameters of the school was made to obtain the electrical demand profile. The model consisted of two adjoining zones, each representing a classroom, one on the ground floor and the other on the first floor. To create a demand profile, ESP-r was chosen as a modelling tool over others because it was a versatile and user-friendly tool that would provide accurate simulation and modelling results. Also, there are two types of models, ones which have three face (external wall) facing the external environment, which are located in the two ends of the building and the other with two face facing the external environment, which are located between the end classrooms and makes up majority of the models.

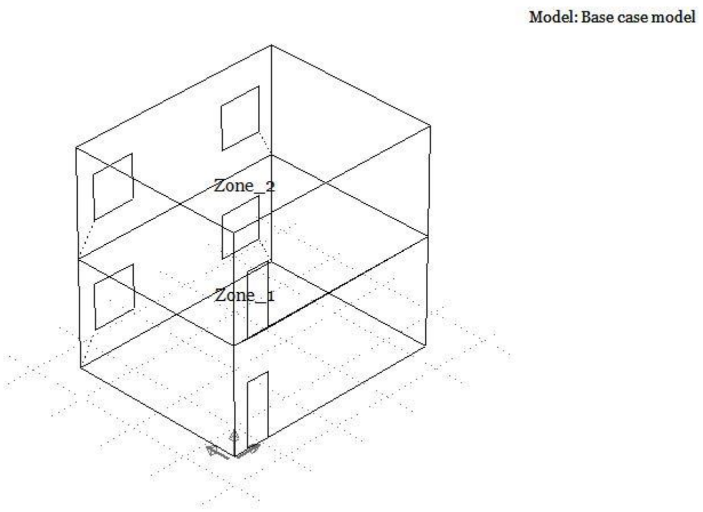

Figure 2: Base Case Model with two zones

3.1.1. Model Geometry, Construction and Attribution

In Figure (2), the illustrated model represents two identical classrooms in two zones. Zone 1 represents the ground floor classroom and zone 2 represents the classroom in the first floor. A single classroom has a length of 7.6 meter (25 feet), breadth of 6.1 meter (20 feet) and height of 3.7 meter (12 feet). The base floor area in both the zones are 46.5 m^2 and the volume in both the zones are 170 m^3. In both the zones 'Wall 1' faces the west, where a door of height 2.2 meter and width of 0.8 meter is located and 'Wall 3' faces the east, where two single glazing windows of height and width of 1 meter are located. 'Wall 1' and 'Wall 3' are the only walls facing the external environment. The walls facing other classrooms in both the zones are 'Wall 2' which faces the south and 'Wall 4' which faces the north. The floor in zone 1 represents the ground and the ceiling in zone 2 represents the roof of the entire building respectively. On the other hand, the ceiling in zone 1 is the same symmetrical but reverse surface of the floor in zone 2.

The following table shows the construction materials used in the base case model and their thermos-physical properties:

Surface	Surface Layer	Material	Thickness (mm)	Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)	Emissivity	Absorptivity
External wall (West & East)	1	Dense Plaster	12	0.50	1300	1000	0.91	0.50
	2	Light Brown Brick	215	0.96	2000	650	0.90	0.70
	3	Light Plaster	15	0.16	600	1000	0.91	0.50
Internal Wall (North & South)	1	Dense Plaster	12	0.50	1300	1000	0.91	0.50
	2	Light Brown Brick	215	0.96	2000	650	0.90	0.70
	3	Dense Plaster	12	0.50	1300	1000	0.91	0.50
Ceiling (zone 1 – ceiling & zone 2 –	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Light Mix Concrete	250	0.38	1200	653	0.90	0.65

floor)	3	Dry Rendering	10	1.13	1431	1000	0.91	0.50
Ground (zone 1 – floor)	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Light Mix Concrete	200	0.38	1200	653	0.90	0.65
	3	Limestone	200	1.50	2180	720	0.90	0.60
	4	Gravel Based	200	0.52	2050	184	0.90	0.85
Roof (zone 2 – ceiling)	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Light Mix Concrete	200	0.38	1200	653	0.90	0.65
Window (single glazing)	1	Glass Plate	6	1.50	2500	750	0.83	0.05
Door	1	Oak Wood	25	0.19	700	2390	0.90	0.65

Table 1: Base Case Model Construction materials and Properties

3.1.2. Model Operation Details

Casual Gains

The operational details for both the zones are defined for weekdays, holidays, Saturdays and Sundays with the corresponding casual gains for the occupants, the lighting and the equipment which in this case are the ceiling fans. Based on the seasonal school timings, there is a separate casual gains data during the summer timings (March-October) and winter timings (November-February). Also, as shown in figures (3) and (4), the casual gains are identical in both the zones due to identical operational details.

The school is only functional on the weekdays, so as a result there is significant reading of casual gains in the figures. Due to the fact that on Saturday, Sunday and holidays the school is remained closed, no activities in the casual gains can be seen.

The peak sensible gain of an occupant is 75W for a child and 100W for an adult (Anon, 2016), whereas peak latent gain is 37.5 W for a child and 50 W for an adult, which is exactly half of the value of peak sensible gain. For lighting, the classrooms are fitted with fluorescent tubes, which has a peak sensible gain of 40W and for equipment, the ceiling fans are fitted in the classrooms, which has a peak sensible gain of 60W. Both of these have zero latent gains.

For Summer (March-October):

For the summer period, the school opens at 7:00 am and closes at 2:00 pm and the class timings are between 8:00 am and 1:00 pm. There is a summer break from 14th May to 10th July, so the school will be closed during these days.

- **7:00 am - 8:00 am**

  During this period the sensible and latent gains for the occupants are 400W and 200W and the sensible gains for lighting and equipment (ceiling fans) are 40W and 60W respectively. This is because during this period it is assumed that there won't be more than 4 pupils (300W) and 1 adult teacher (100W) in the classroom which would be 400W in total, so as a result only 1 lighting (40W) and ceiling fan (60W) was switched on.

- **8:00 am - 1:00 pm**

  During this period, which is the class hours, the sensible and latent gains for the occupants are 3100W and 1550W and the sensible gains for lighting and equipment are 80W and 240W. This is because during this period it is assumed that the class is filled with 40 pupils (3000W) and 1 adult (100W) in the classroom which would be 3100W in total. Here, it is assumed that 2 lights (80W) and all 4 fans (240W) would be switched on.

- **1:00 pm - 2:00 pm**

  This is the after class period, where the sensible and latent gains for the occupants will be again reduced to 400W and 200W and the sensible gains for lighting and equipment will be reduced to 40W and 60W respectively. This is because during this period it is assumed that other just than 4 pupils (300W) and 1 adult (100W), the rest of the students the school premises, which would be 400W in total. Due to this even the activity of lightings and ceiling fans would be reduced to 1 light (40W) and 1 fan (60W).

The casual gains remain zero during the off-hours, that is from 2:00 pm to 7:00 am in the next working day.

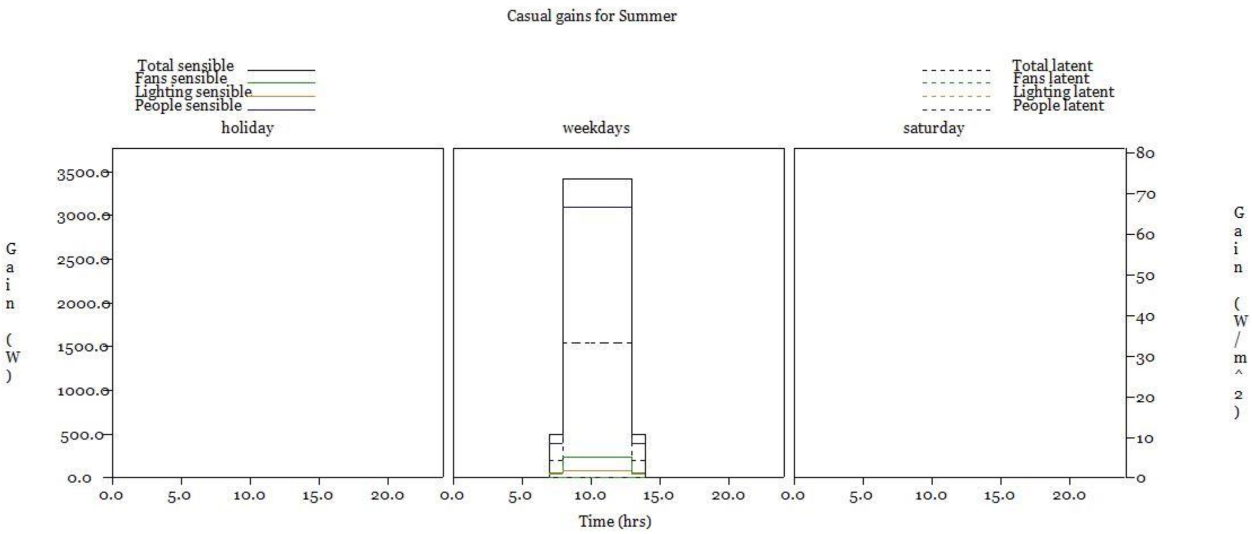

Figure 3: Casual Gains of the Model for Summer

For Winter (November-February):

Now during the winter period, the school opens from 8:00 am to 3:00 pm and the class timings are between 9:00 am and 2:00 pm. There is a winter break from the last week of December till 10th of January of the current year, and from 23rd of December till the first week of January, so the school will be closed during these days.

- **8:00 am - 9:00 am**

  Just like summer, it is assumed that during this period the sensible and latent gains for the occupants are 400W and 200W and the sensible gains for lighting and equipment (ceiling fans) are 40W and 60W respectively, as it's assumed that there won't be more than 4 pupils (300W) and 1 adult teacher (100W) in the classroom which would be 400W in total. As a result, only 1 lighting (40W) and 1 ceiling fan (60W) would be switched on.

- **9:00 am - 2:00 pm**

  During this period, which is the class hours, the sensible and latent gains for the occupants are 3100W and 1550W and the sensible gains for lighting and equipment are 80W and 240W. This is because during this period it is assumed that the class is filled with 40 pupils (3000W) and 1 adult (100W) in the classroom which would be 3100W in total. Here, it is assumed that 2 lights (80W) and all 4 fans (240W) would be switched on.

- **2.00 pm - 3:00 pm**

  This is the after class period, where the sensible and latent gains for the occupants will be again reduced to 400W and 200W and the sensible gains for lighting and equipment will be reduced to 40W and 60W respectively. This is because during this period it is assumed that other just than 4 pupils (300W) and 1 adult (100W), the rest of the students the school premises, which would be 400W in total. Due to this even the activity of lightings and ceiling fans would be reduced to 1 light (40W) and 1 fans (60W).

Again, as mentioned in the summer data, the casual gains will remain zero during the off-hours, that is from 3:00 pm to 8:00 am in the next working day.

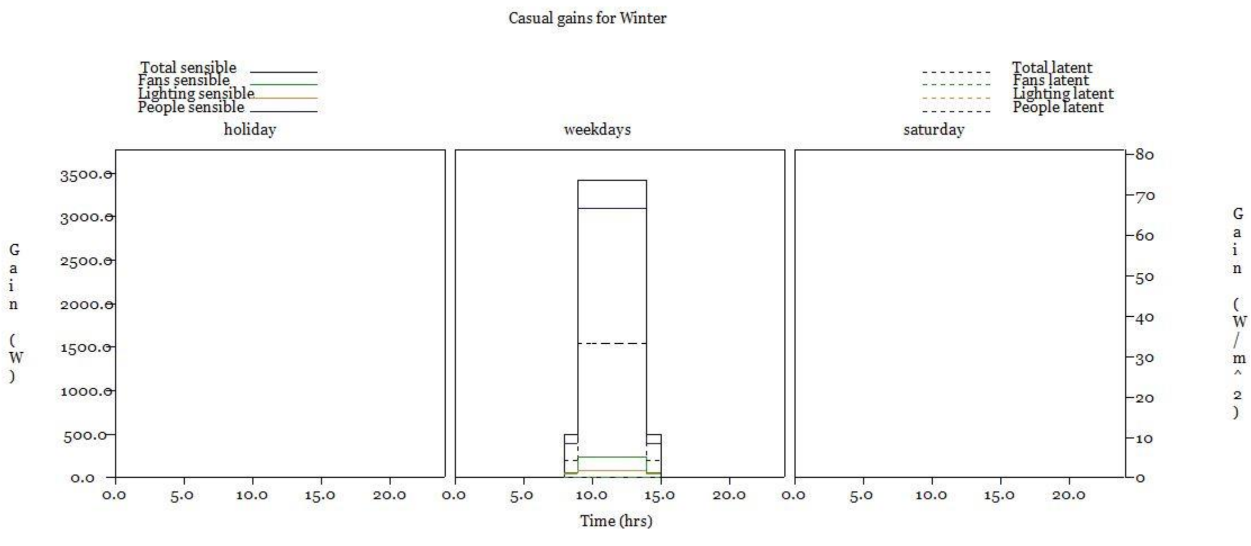

Figure 4: Casual Gains of the Model for Winter

Air Schedules

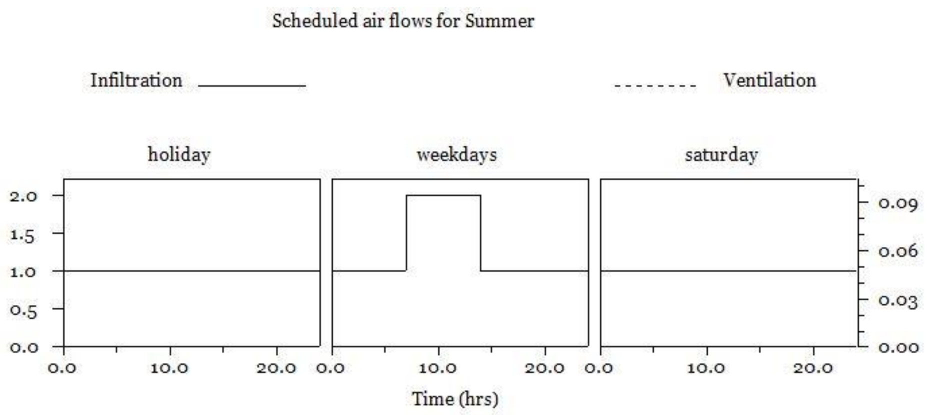

Figure 5: Schedule Air Flows of the Model for Summer

From figure (5), we can see that the scheduled air flow period during summer. The infiltration rate is maximum at 2 ac/hr which is during school hours and minimum at 1 ac/hr which during off hours. The air flow schedule is similar for winter with same infiltration data, but differs in timing, based on the winter school timings.

Climate File

The base case model is set to be located at latitude 28.97^{o}N and a longitudinal difference of -4.33^{o}. Also, the weather file of New Delhi, India was obtained from the EnergyPlus website and exported to ESP-r, as the weather file of Dhanaura, India was neither available in ESP-r nor EnergyPlus website. This is due to the extreme similarities in weather the conditions between these two regions with the same humid sub-tropical climate.

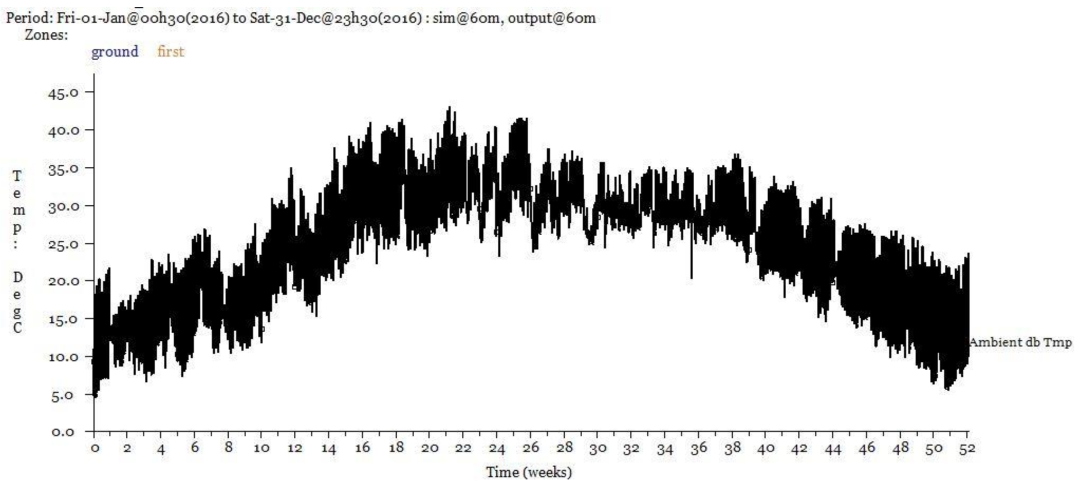

Figure 6: Temperature Profile of Dhanaura over the year

In figure (6), it can be seen that the temperature graph is increasing steadily from winter to summer and decreasing gradually from summer to winter. The average peak ambient temperature from January to March is about 20^{o}C and the lowest average during this period is around 10^{o}C. The trend increases drastically at April from 25^{o}C to 30^{o}C and increases even more from May to June from 30^{o}C to 40^{o}C. The average peak from May to June is around 40^{o}C yet the lowest set of ambient temperature is around 27. The average peak ambient temperature starts decreasing in July from 40^{o}C to 35^{o}C and remains at 35^{o}C till October. From October, the peak average starts decreasing to around 20^{o}C and lowest ambient temperature average returns to 10^{o}C, thereby returning to the same set of temperatures as occurred in the first 3 months.

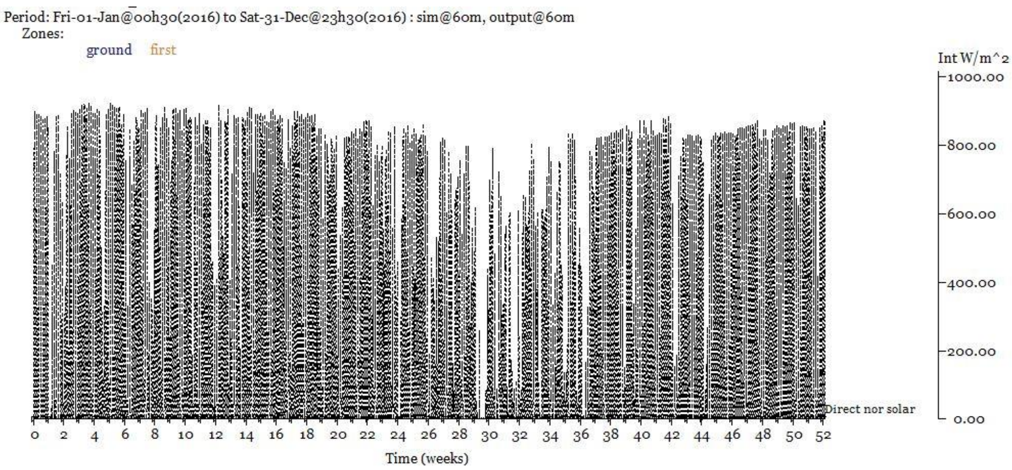

Figure 7: Direct Solar Radiation over the year

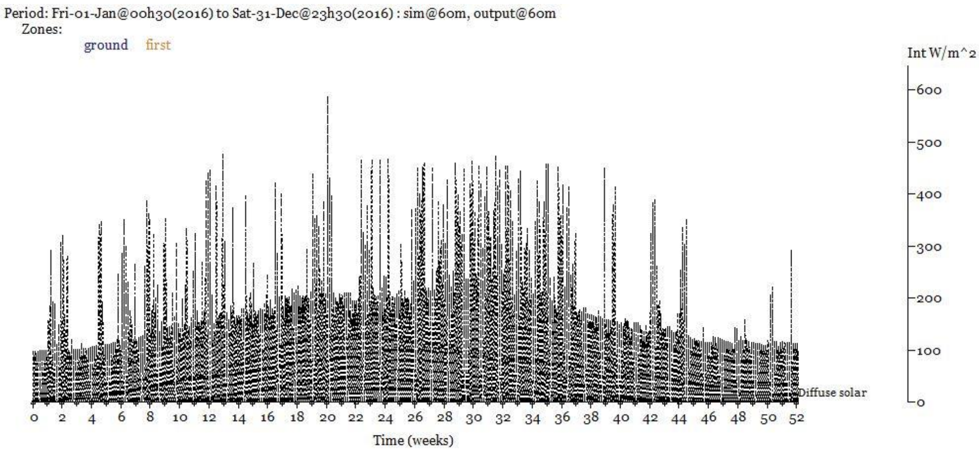

Figure 7: Diffused Solar Radiation over the year

In figures (7) and (8), the solar data of the region is seen. It can be noted that the Direct Insolation of the region is steady throughout the year between 800 W/m^2 and 1000 W/m^2. Exceptions being at around July and August, where the Direct Insolation reduces. Also, it is observed that the Diffused Radiation increases steadily from 100 W/m^2 in the winter to 200 W/m^2 in the summer and back to 100 W/m^2 in the winters. The anomaly being in July and August, where the peaks of Diffused Radiation reaches up to 400 W/m^2 frequently. The reason for these anomalies during these two months for both Direct and Diffused solar data is because of the cloudy season that takes in these months.

A comparison of the solar data for a typical winter week and summer week is given in figure (9) and (10).

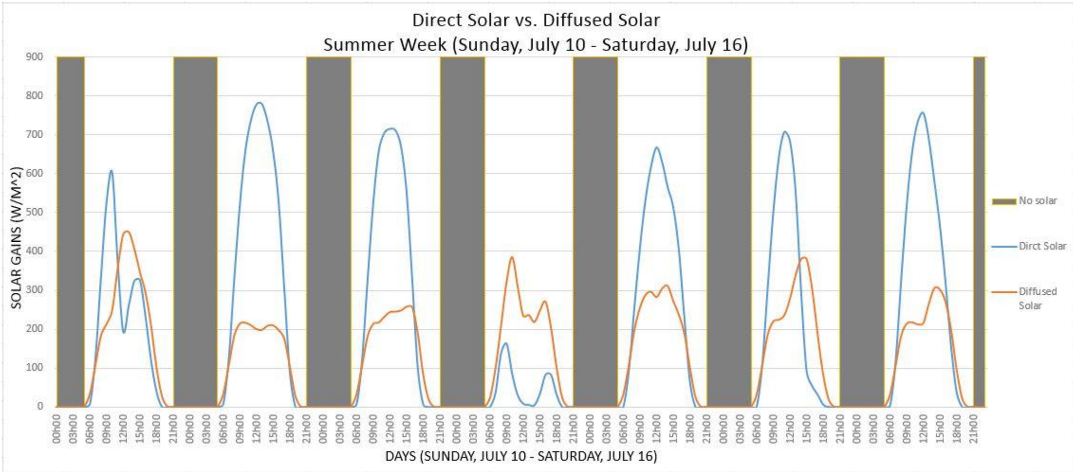

Figure 9: Direct Solar vs. Diffused Solar during a typical summer week

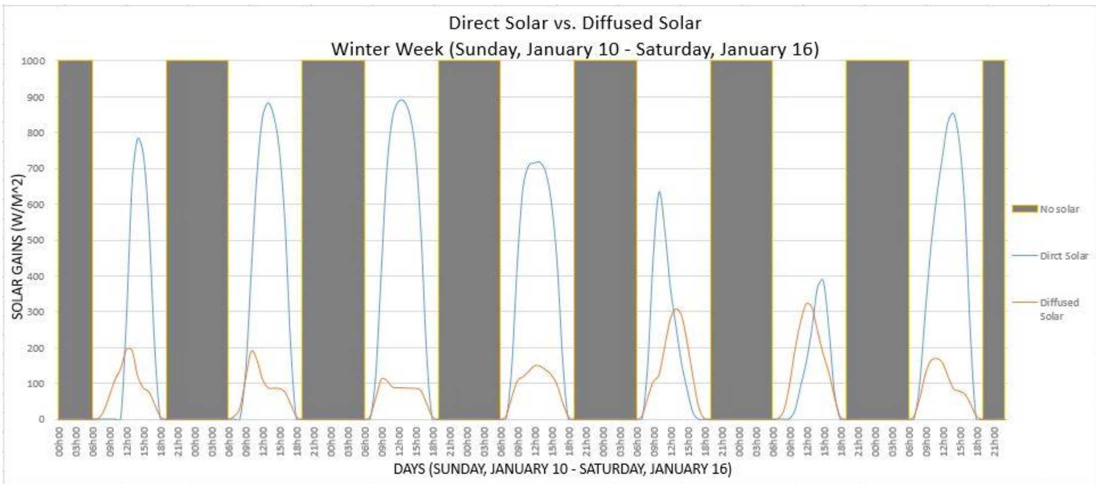

Figure 10: Direct Solar vs. Diffused Solar during a typical winter week

3.2. Simulations

After the completion of the base case model, simulations are run for the current scenario (Scenario 0) to analyse the comfort levels. Simulations are also run for different scenarios, by manipulating the Control data, operation details and construction details.

3.2.1. Scenario 0 – Current Scenario

This is the current scenario of the school, based on the base case model, where there is neither any insulation on the walls nor air-conditioning system. Energy is taken from the grid and the backup generators, as a result the energy and cost savings are considered over the comfort of the occupants.

Scenario 0 - Model with two exterior faces (Summer)

Following are the simulation graphs for model with two exterior face for a typical summer week.

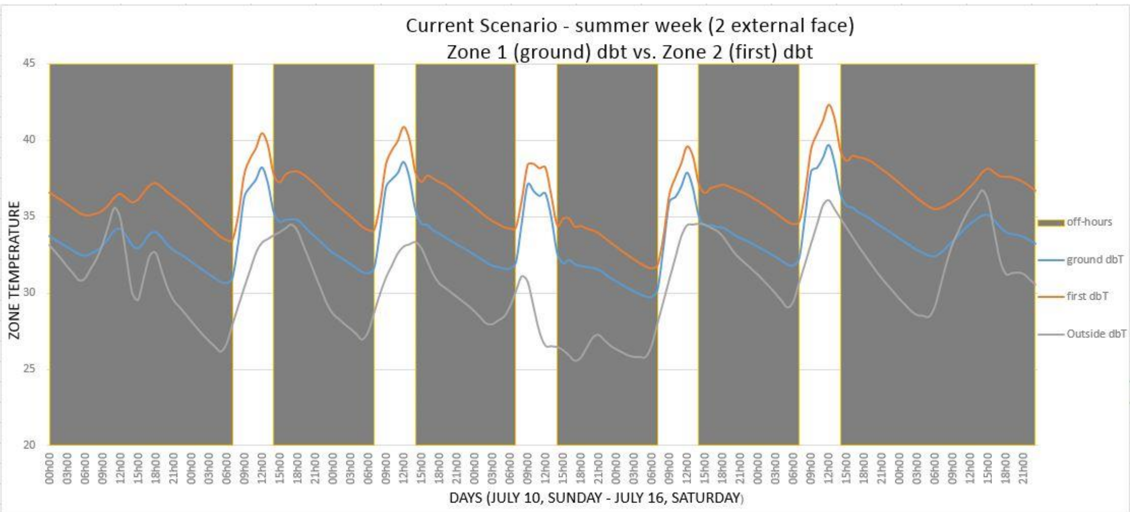

Figure 11: Scenario 0 – Zone temperature comparison during summer

In figure (11) is a comparison of zone temperature in the zone 1 (ground floor) and zone 2 (first floor) with the ambient temperature. It can be seen that for five days (Monday to Friday), the zone temperature goes up to 43^{o}C during school hours for zone 2 and 40^{o}C for zone 1. Also, it can be observed that during the entire week the temperature of zone 2 is higher than zone 1 and that the ambient temperature is less that zone temperatures throughout the trend.

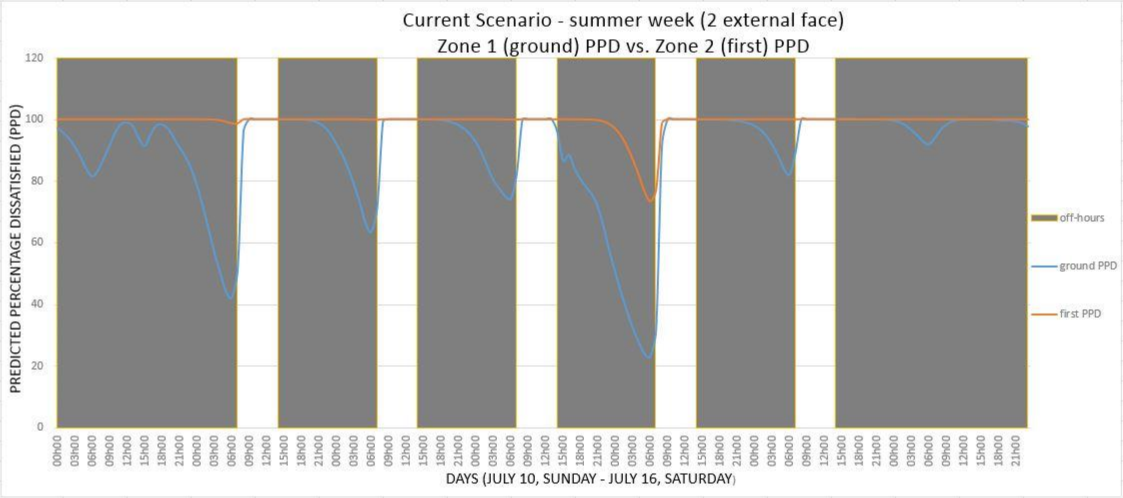

Figure 12: Scenario 0 – PPD comparison between zones during summer

In figure (12), the Predicted Percentage Dissatisfied (PPD) of zone 1 and zone 2 is provided. The comfort metrics in ESP-r was set accordingly based on the seasons. For the summer, the clothing level was set at 0.5 due to minimal clothing like shirt, shorts, socks and shoes. The activity level was set at 1.0 MET level, due to the fact that the occupants were seated. Also, the air velocity was set at 1.7 m/s, due to the running of ceiling fans (Chiang, 2016). During school hours the PMV of zone 2 is higher than zone 1. Also, except for one instance, the PPD of zone two is almost 100 throughout, unlike zone 1 where PPD is considerably lower during night. In both the graphs it can be seen that due to the absence of cooling the comfort conditions is unbearable during school hours, especially for zone 2. The reason for the huge difference in the comfort metrics of zone 1 and zone 2 is due to poor building construction materials, poor insulation and the heat trapped, also because zone 2 gets more sunlight directly due to its facing towards the roof.

In figure (13) is a graph between two base case model over a period of 24 hours on a summer day. One of them has two exterior faces and the other one has three exterior faces. The temperature of both these zones are compared and there is a difference of less than 1°C, such that the zone with three exterior face is hotter.

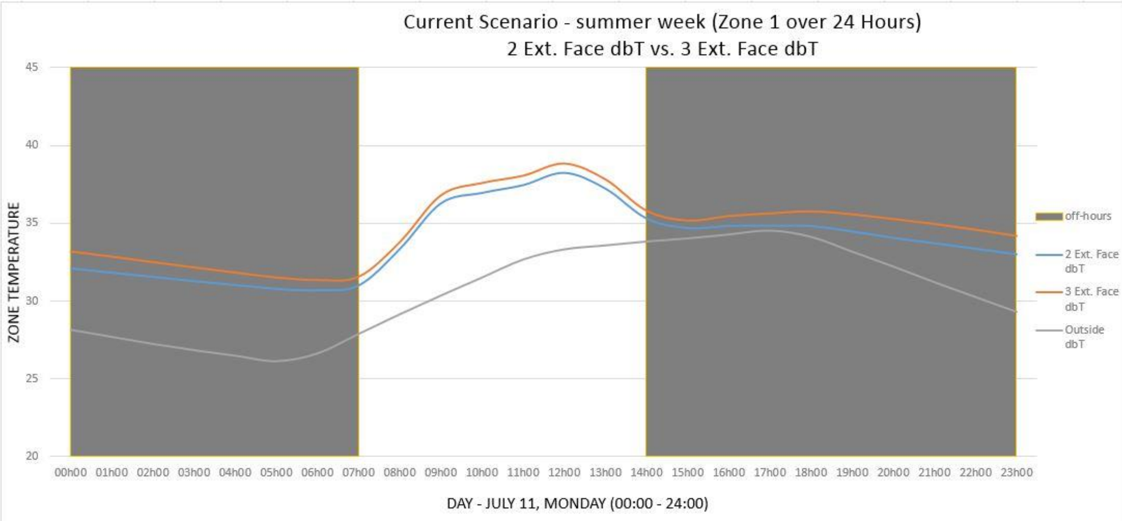

Figure 13: Scenario 0 – Zone temperature comparison of 3 Ext. Face vs 2 Ext. Face during summer

Scenario 0 - Model with two exterior faces (Winter)

Following are the simulation graphs for model with two exterior face for a typical winter week.

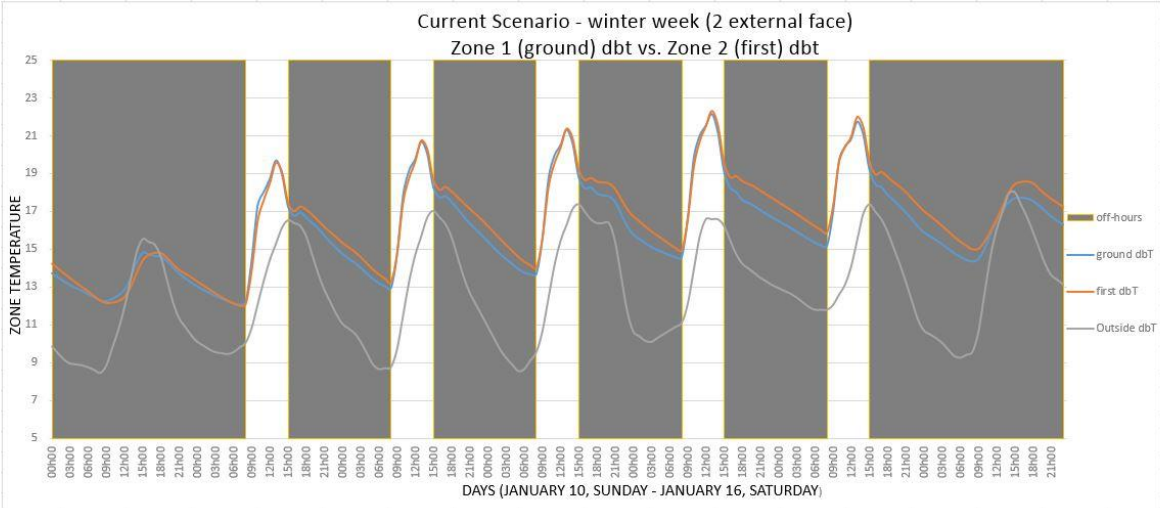

Figure 14: Scenario 0 – Zone temperature comparison during winter

In figure (14) is a comparison of zone temperature in the zone 1 (ground floor) and zone 2 (first floor) with the ambient temperature. It can be seen that for five days (Monday to Friday), the zone temperature goes up to 23^{o}C during school hours for both the zones and also the temperature for zone 1 and are same throughout according to the trend. Although, it can be observed that during the working days the ambient temperature is less that zone temperatures throughout the trend.

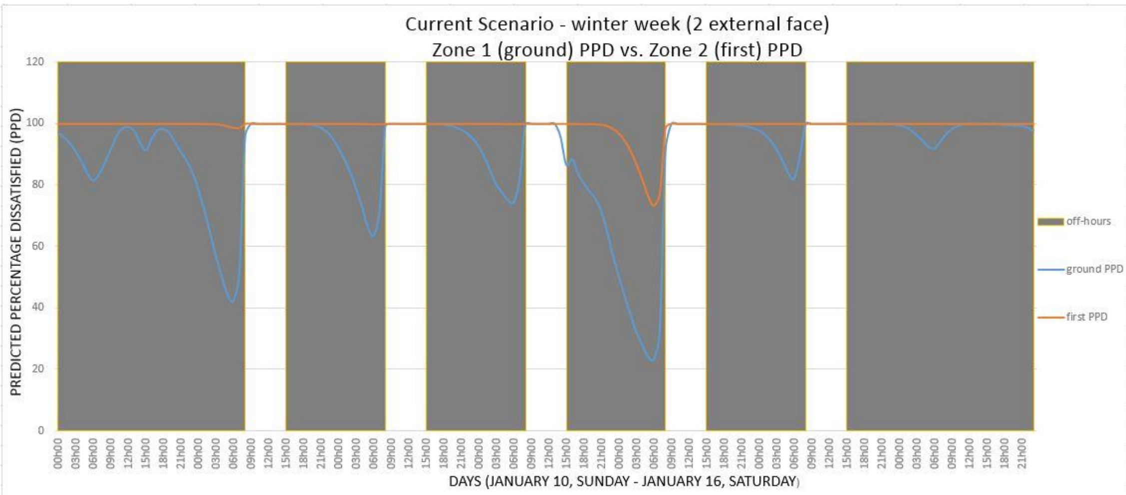

Figure 15: Scenario 0 – PPD comparison between zones during winter

In figures (15), the PPD of zone 1 and zone 2 for winter is provided. For the winter, the clothing level was set at 0.7 due to winter wear like sweaters and woollen pants.

The activity level was set at 1.0 MET level, due to the fact that the occupants were seated. Also, the air velocity was set at 0.1 m/s, as ceiling fans are not operated during winters. Unlike summer, the PMV and PPD of zone 1 and zone 2 is equal during school hours. Also, it can be observed that unlike summer, the comfort conditions is considerably good and its better in zone 2 that zone 1. This shows that heating is not necessarily required for this model during the winters.

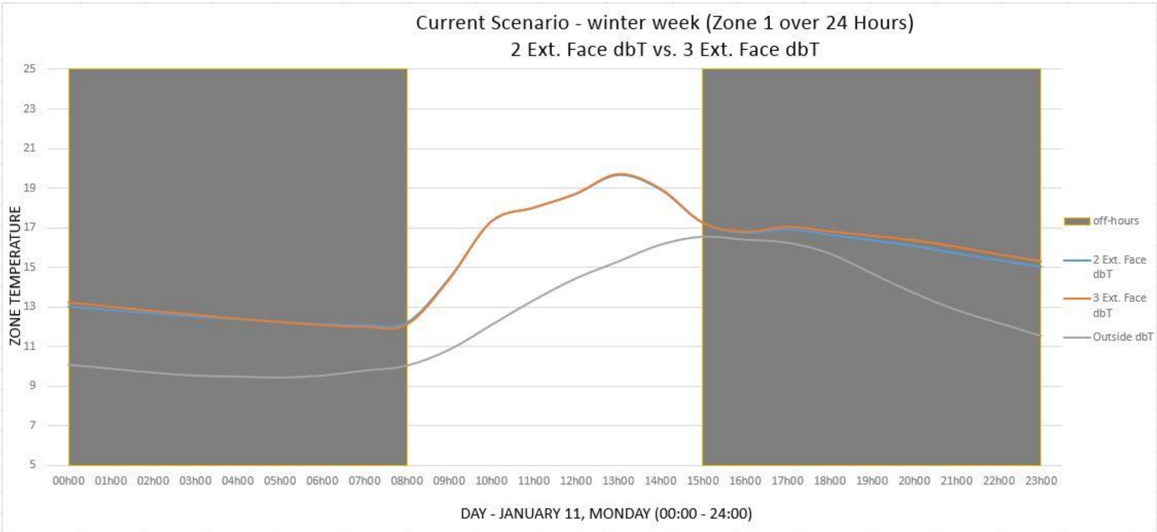

Figure 16: Scenario 0 – Zone temperature comparison of 3 Ext. Face vs 2 Ext. Face during winter

In figure (16) is a graph between two base case model over a period of 24 hours on a winter day. One of them has two exterior faces and the other one has three exterior faces. Both the models have almost the same zone temperature throughout, and the same comfort levels. Although there is a little temperature difference at night, but it can be ignored as it is off-hours.

3.2.2. Scenario 1 – Perfect Scenario

This scenario can be termed as the perfect scenario, due to the fact that this is the only scenario, where heating is involved. In this scenario there is no financial restraints and the comfort of the occupants are considered over energy savings.

In this scenario, separate zone controls are setup for summer and winter based on the seasonal school timings. Details about the zone controls and the air conditioner is given below.

Air-conditioner Brand/Model	LG A18RL
Rated Cooling Capacity	5.2 kW
Cooling Power Input	**1.50 kW**
EER	**3.47**
Rated Heating Capacity	6.3 kW
Heating Power Input	**1.65 kW**
COP	**3.81**

Table 2: Scenario 1 - Air-conditioner details

Cooling Set Point	**24°C**
Cooling Load	**5.2 kW**
Cooling Hours	**6 Hours** **(7:00 am – 1:00 pm)**
Heating Set Point	**20°C**
Heating Load	**6.3 kW**
Heating Hours	**5 Hours** **(9:00 am – 2:00 pm)**

Table 3: Scenario 1 - Control details

Scenario 1 - Model with two exterior faces (Summer)

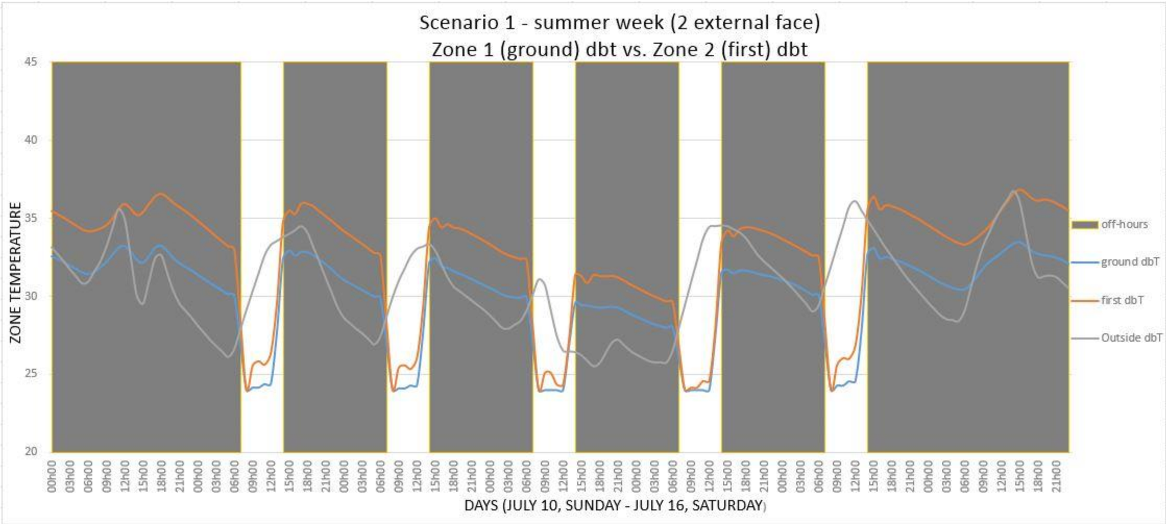

Figure 17: Scenario 1 – Zone temperature comparison during summer

The summer model for the perfect scenario is given in figure (17). Here the temperature of the two zones is compared with the outside temperature. It can be seen that during school hours the temperature comes down drastically to up to 24°C for both the zones. Also it can be seen that the set point temperature of zone 2 is maintained for lesser time as compared to zone 1.

A comparison between the zone temperatures of zone 1 in the current scenario and scenario 1 is given in figure (18). It can be seen there is a huge difference, as the zone temperature is maintained up to 24°C in Scenario 1 but it is going up to 40°C in current scenario, and there is a difference of 12°C to 15°C every day.

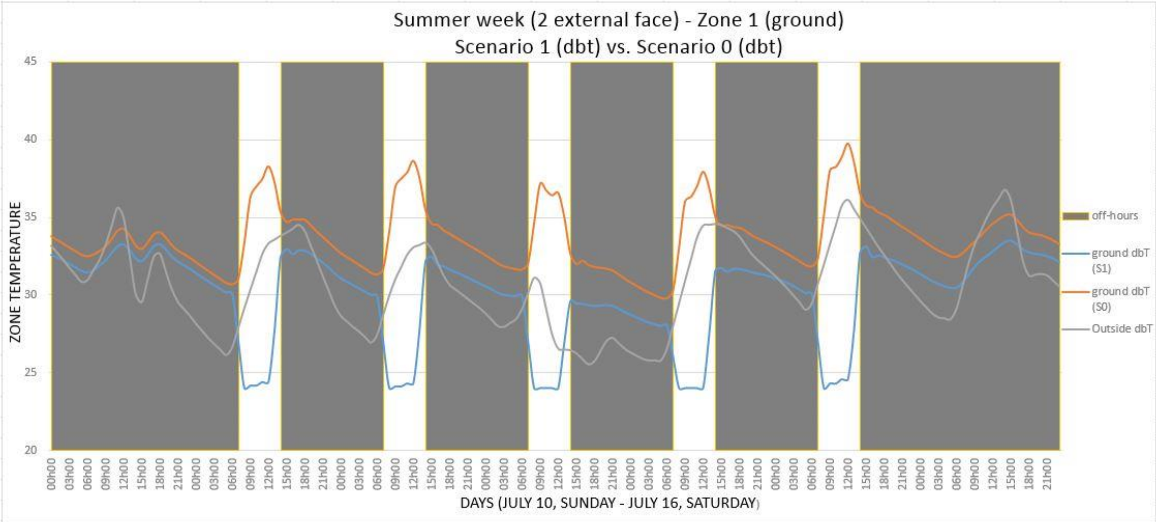

Figure 18: Scenario 1 – Zone 1 Temperature comparison of Scenario 0 vs. Scenario 1

When compared the cooling loads of zone 1 and zone 2, it can be seen that the cooling load touches the 5.2 kW limit for zone 2, because of which the cooling set point was not maintained in zone 2. But the cooling load was adequate in zone 1, as it didn't cross 5 kW.

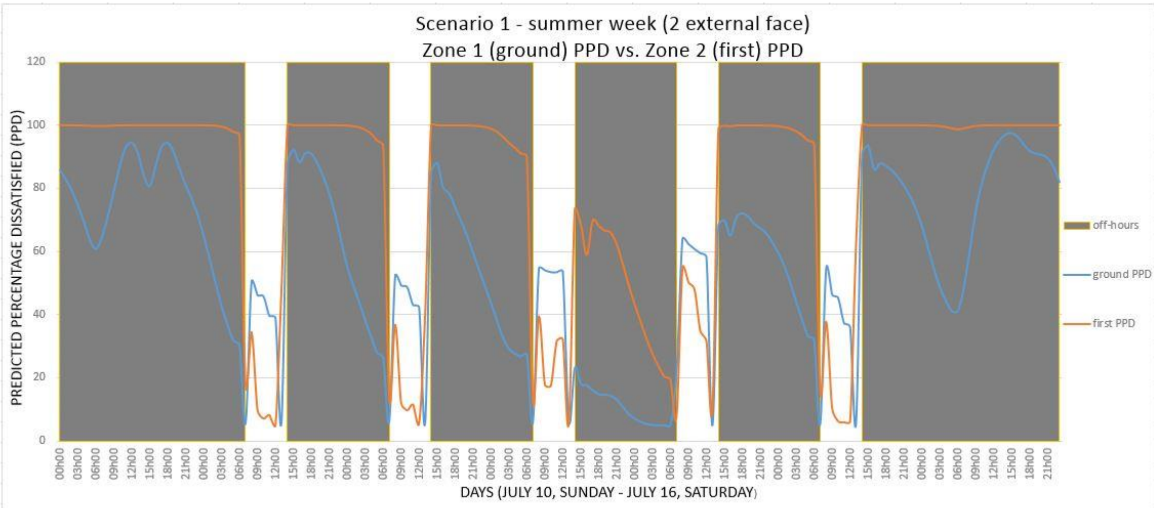

Figure 19: Scenario 1 – PPD comparison between zones during summer

The PPD of both the zones are seen in figure (19). The PPD is extremely less compared to other scenarios for both the zones. It can be seen that during school hours the PPD of zone 2 is less than zone 1, which shows that the cooling is very high for some occupants. The PMV of zone 1 is lower than zone 2.

A comparison between the PPD of zone 1 in the Scenario 0 (current) and scenario 1 is given in figure (20). It is observed that there is a difference of at least 40%, as the PPD in Scenario 0 is at 100% throughout the school hours.

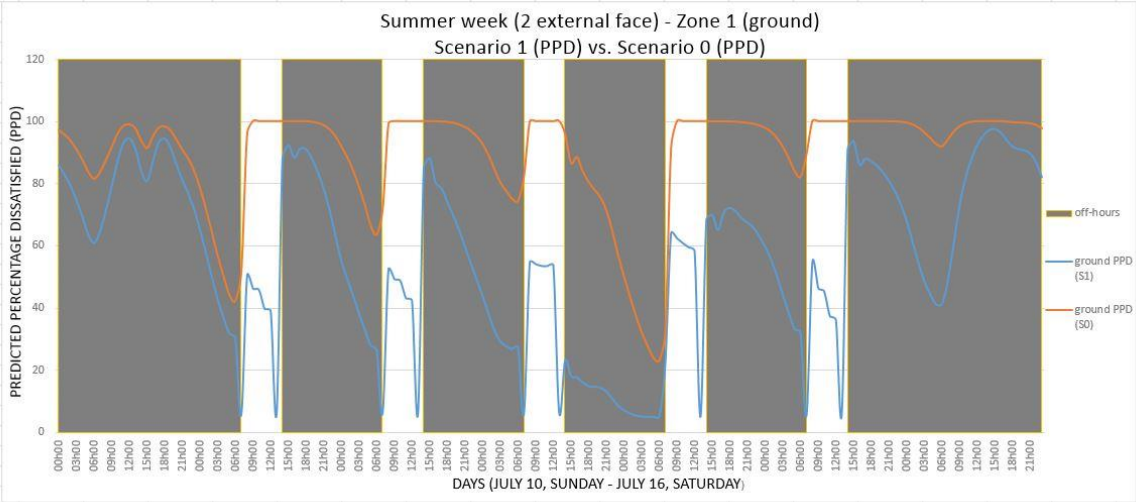

Figure 20: Scenario 1 – Zone 1 PPD comparison of Scenario 0 vs. Scenario 1

Scenario 1 - Model with two exterior faces (Winter)

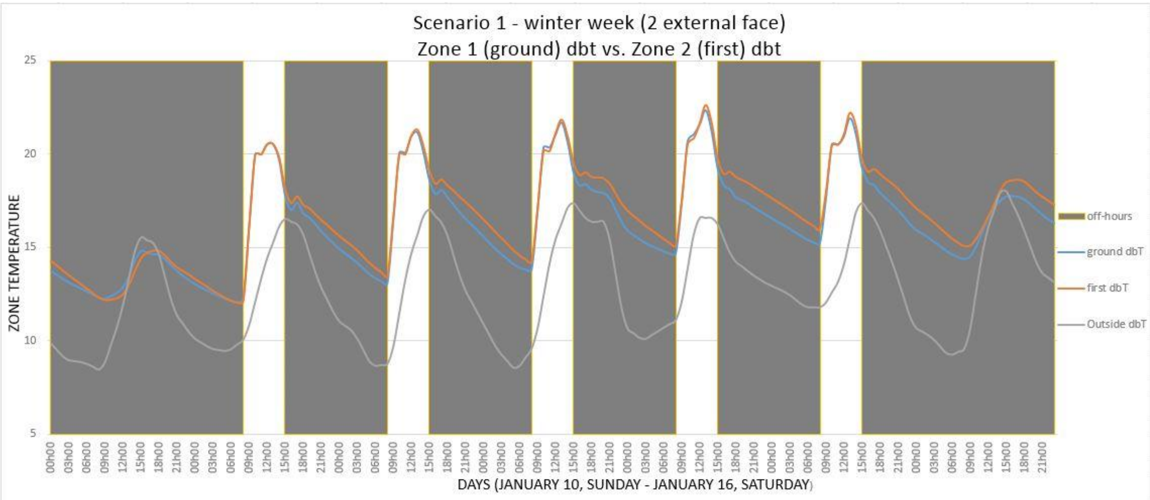

Figure 21: Scenario 1 – Zone temperature comparison during winter

The winter model for the perfect scenario is given in figure (21). Here, heating was involved and the temperature of the two zones is compared with the outside temperature. It can be seen that during school hours the temperature goes up to 23^{o}C for both the zones even though the set point for heating was 20°C. This must be due to the casual gains of the occupants. Also it can be seen that unlike other models, her the trend for zone 1 and zone 2 is equally corresponding with each other.

The heating loads of the zone 1 and zone 2 are compared, where it is seen that the trend is reducing steadily from 1.4 kW is zone 2 and 1 kW in zone 1 to 0.3 kW in both the zones. By this trend it can be assumed that heating won't be required after a few days, as the ambient temperature will reach the set point temperature. Also it is observed that the heating load of 6.3 kW is unnecessary, as that figure won't be reached.

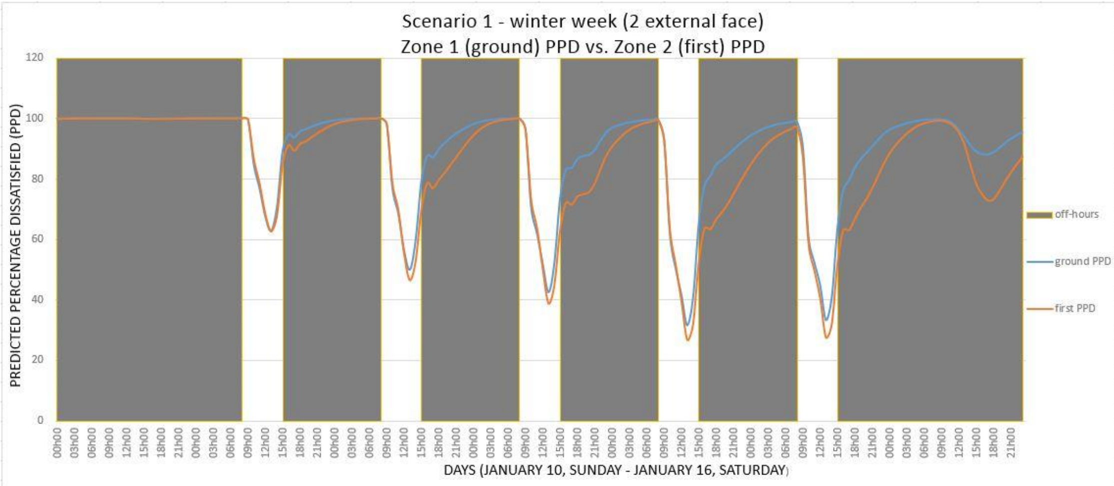

Figure 22: Scenario 1 – PPD comparison between zones during winter

The PMV and PPD trends of the zones in winter for scenario 1 is very similar to the trends of current scenario. During school hours the PMV and PPD trend is almost equal for both the zones. Here we can conclude that heating was unnecessary during the winters as it doesn't improve the PPD in a significant scale when compared to the current scenario.

3.2.3. Scenario 2 – Decreasing Comfort

As the name suggests, the second scenario primarily deals with reducing comfort levels by reducing the cooling loads and increasing the temperature set point, keeping in mind both the energy and cost savings. Just like the current scenario, heating is not involved in this scenario during winters. The details of the zone controls and the air conditioner is given below.

Air-conditioner Brand/Model	LG BSA12PMZD
Rated Cooling Capacity	3.576 kW
Cooling Power Input	**1.01 kW**
EER	**3.54**

Table 4: Scenario 2 - Air-conditioner details

Cooling Set Point	**26^{o}C**
Cooling Load	**3.576 kW**
Cooling Hours	**6 Hours** **(7:00 am – 1:00 pm)**

Table 5: Scenario 2 - Control details

Scenario 2 - Model with two exterior faces (Summer)

The temperature of the two zones is compared with the outside temperature for Scenario 2. It can be seen that during school hours the temperature comes down 26^{o}C for both the zones. Both the zones have difficulty in maintaining the set point cooling temperature, because of insufficient cooling load. Also it can be seen that the set point temperature of zone 2 is maintained for lesser time as compared to zone 1.

A comparison between the zone temperatures of zone 1 in the Scenario 0 (current) and Scenario 2 is given in figure (23). It can be seen there is a high difference, but less compared to the gap between Scenario 0 and Scenario 2 as the zone temperature is maintained at just 26^{o}C in Scenario 2. It can be seen that there is a difference of 8^{o}C to 12^{o}C every day.

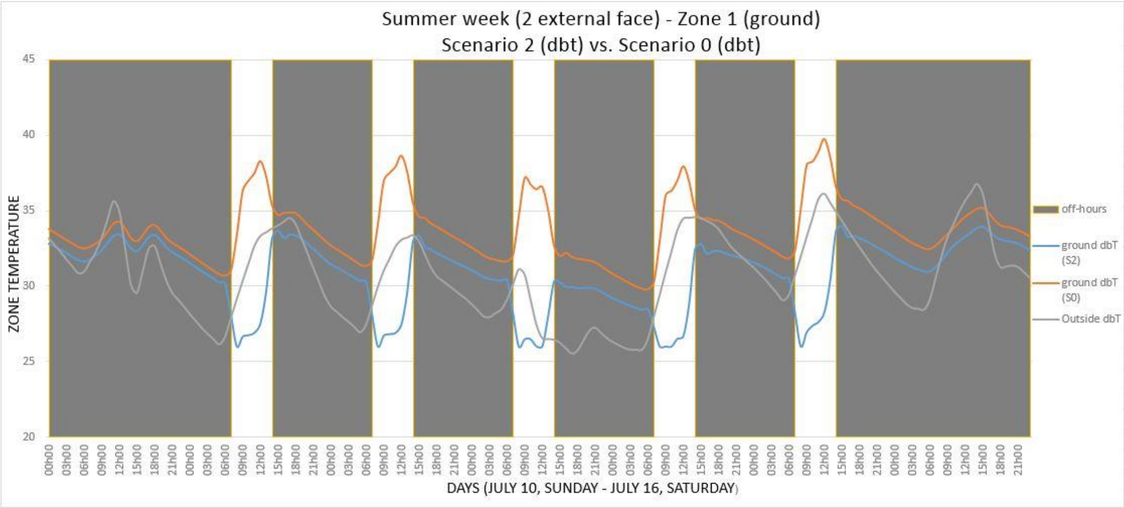

Figure 23: Scenario 2 – Zone 1 Temperature comparison of Scenario 0 vs. Scenario 2

When compared the cooling loads of zone 1 and zone 2, it can be seen that the cooling load touches the 3.576 kW limit for both zone 1 and zone 2, because of which the cooling set point was not maintained in both the zones.

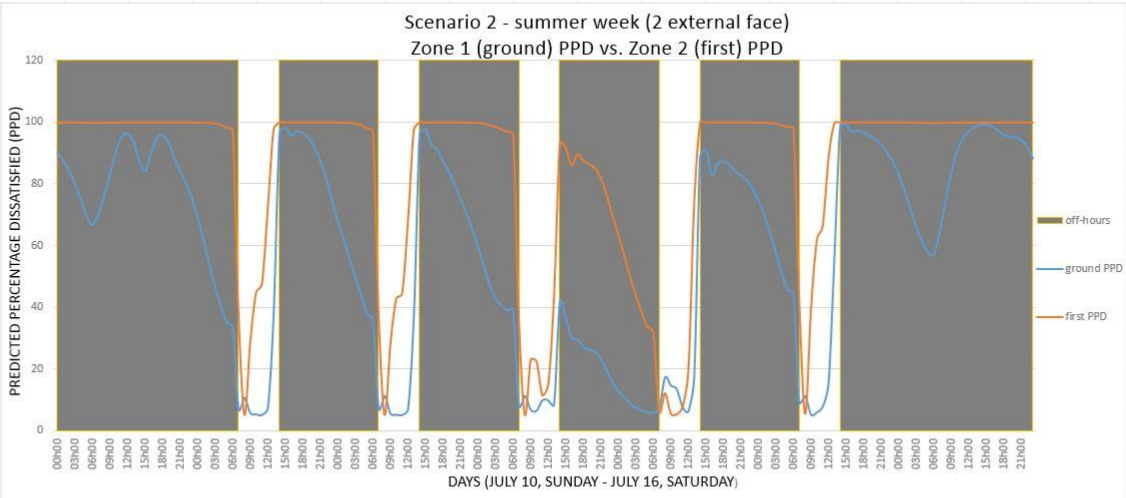

Figure 24: Scenario 2 – PPD comparison between zones during summer

The PPD of both the zones are seen in figure (24). The PPD is unexpectedly less compared to Scenario 1 for both the zones, which had higher cooling load and lower cooling set point. It can be seen that during school hours the PPD of zone 1 is stable, yet for it is not maintained for zone 2, which shows the cooling was not sufficient for zone 2 towards the end of the day.

A comparison between the PPD of zone 1 in the Scenario 0 (current) and scenario 2 is given in figure (25). It is observed that there is a difference of at least 80%, which double the difference when compared between Scenario 1 and Scenario 0.

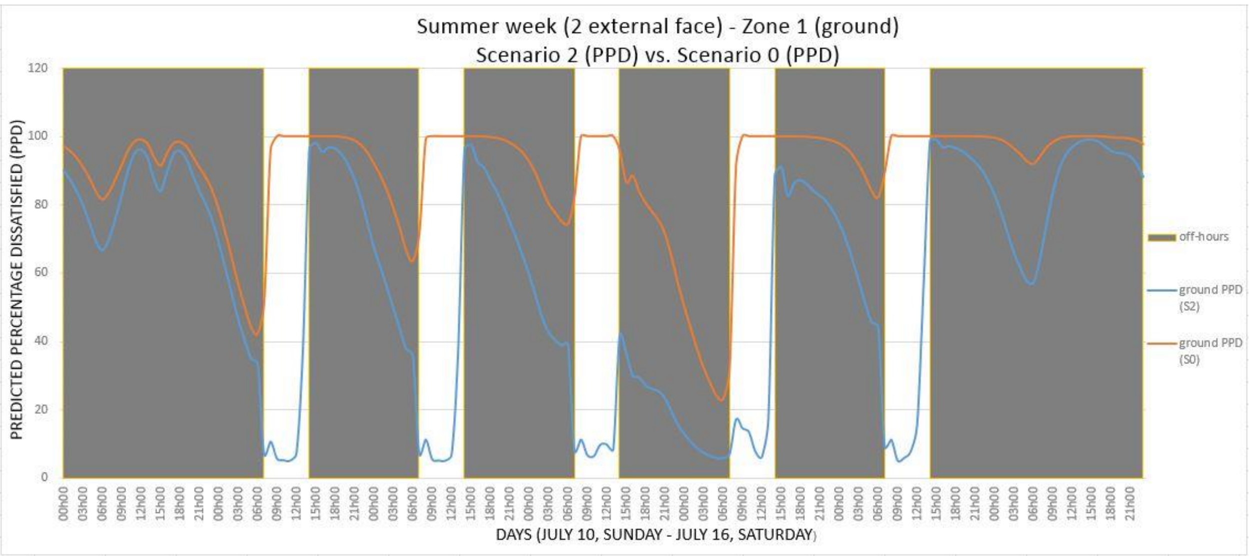

Figure 25: Scenario 2 – Zone 1 PPD comparison of Scenario 0 vs. Scenario 2

Scenario 2 - Model with two exterior faces (Winter)

The winter model of Scenario 2 is identical to that of scenario 0. Due to the absence of the effort to increase comfort levels, the PPD in both the models are identical.

3.2.4. Scenario 3 – Changing School Time

The forth scenario is an experimental one, again keeping in mind the energy savings and the reduced costs. Here the school timing is moved forward by 2 hours in the summer and 1 hour in the winter for maximum solar gains. The zone control are as follows.

Air-conditioner Brand/Model	LG LSA5SP5D
Rated Cooling Capacity	5.275 kW
Cooling Power Input	**1.465 kW**
EER	**3.60**

Table 6: Scenario 3 - Air-conditioner details

Cooling Set Point	**24°C**
Cooling Load	**5.275 kW**
Cooling Hours	**6 Hours** **(9:00 am – 3:00 pm)**

Table 7: Scenario 3 - Control details

In this scenario the operation details like casual gains and air schedules for summer and winter is same throughout the year.

Time Period	Number of Occupants	Occupant Sensible Gains (W)	Occupant Latent Gains (W)	Lighting Sensible Gains (W)	Equipment Sensible Gains (W)
0:00 – 9:00	0	0	0	0	0
9:00 – 10:00	4 pupils 1 adult	400 W	200 W	40 W	60 W
10:00 – 15:00	40 pupils 1 adult	3100 W	1550 W	80 W	240 W
15:00 – 16:00	4 pupils 1 adult	400 W	200 W	40 W	60 W

16:00 – 0:00	0	0	0	0	0

Table 8: Scenario 3 – Operation details

Scenario 3 - Model with two exterior faces (Summer)

The temperature of the two zones is compared for Scenario 3. It can be seen that during school hours the temperature comes down and maintains at 24°C for zone 1 but it doesn't maintain for zone 2, due to high solar gains at this period.

A comparison between the zone temperatures of zone 1 in the Scenario 0 (current) and Scenario 3 gives the same result as its comparison with Scenario 1. It can be seen there is a high difference of 12°C to 15°C, just like to the gap between Scenario 0 and Scenario 1 as the zone temperature is maintained at 24°C.

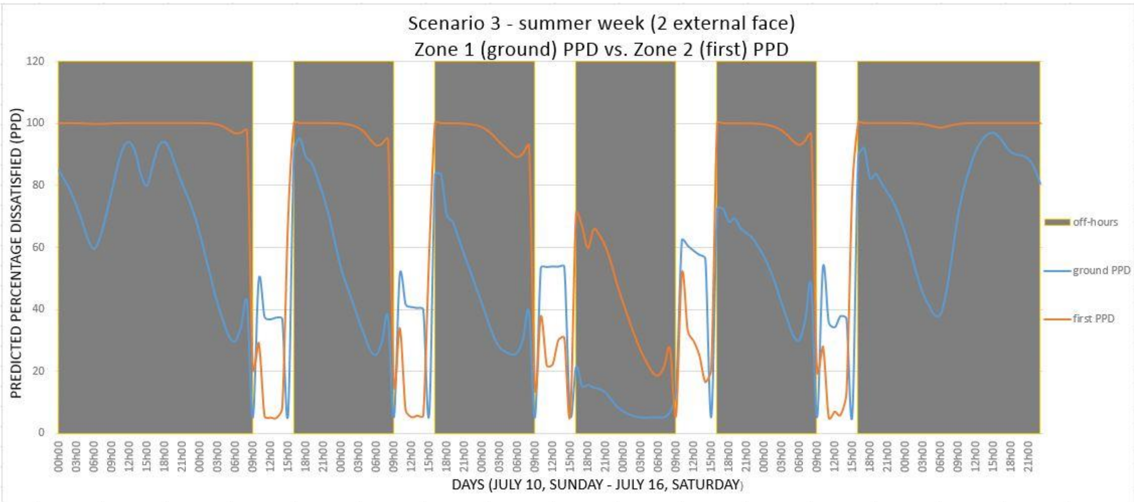

Figure 26: Scenario 3 – PPD comparison between zones during summer

The PPD of both the zones are seen in figure (26). The PPD of Zone 1 is unexpectedly higher than compared to Zone 2, which shows that cooling is higher than expected, making occupants of zone 1 dissatisfied. It can be seen that during school hours the PPD of zone 2 is more stable than zone 1.

A comparison between the PPD of zone 1 in the Scenario 0 (current) and Scenario 3 is given in figure (27). It is observed that there is a difference has reduced to 40-50%, which make the scenario unfavourable during summer.

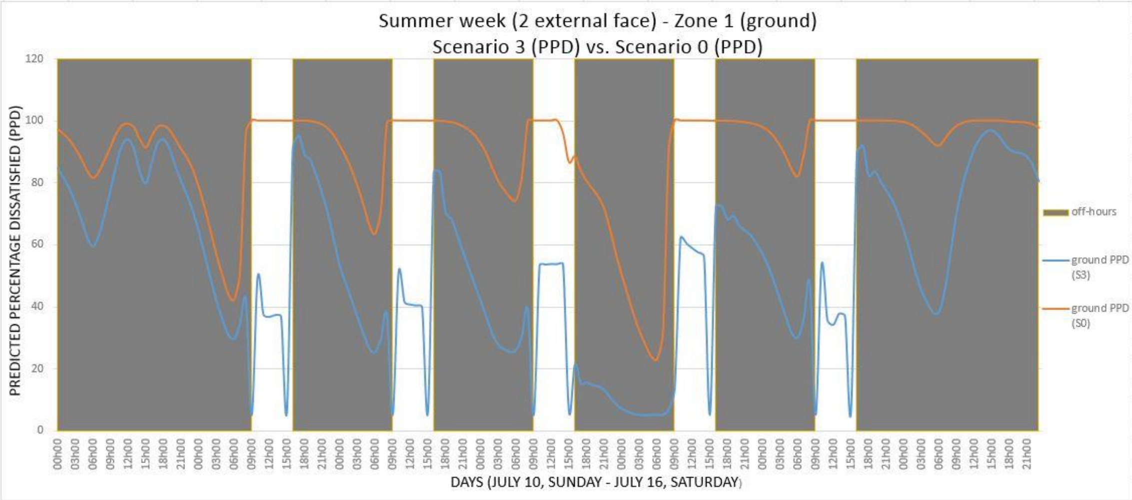

Figure 27: Scenario 3 – Zone 1 PPD comparison of Scenario 0 vs. Scenario 3

Scenario 3 - Model with two exterior faces (Winter)

The PPD is more favourable in the winter, where due to the change in school hours, more solar gains and heat in available. The PPD are lower than compared to summer for this scenario.

Figure (28), shows the available solar gains during the school hours corresponding to Scenario 3, from 9:00 – 16:00 during weekdays in winter. It can be seen that high amount of direct radiation is available for some day, leading to the higher PPD among occupants.

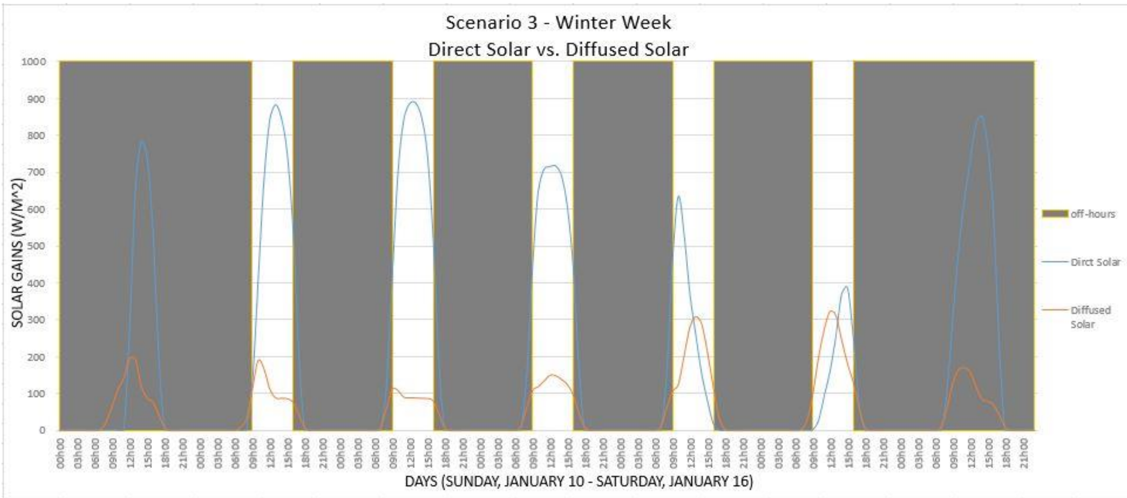

Figure 28: Scenario 3 – Solar gains available during school hours

3.2.5. Scenario 4 – Insulating the Walls

In this scenario the school walls and windows are properly insulated, which thereby could change the comfort levels in the classroom drastically. The zone controls are as follows.

Air-conditioner Brand/Model	LG LSA5SP5D
Rated Cooling Capacity	5.275 kW
Cooling Power Input	**1.465 kW**
EER	**3.60**

Table 9: Scenario 4 - Air-conditioner details

Cooling Set Point	**24°C**
Cooling Load	**5.275 kW**
Cooling Hours	**5 Hours** **(8:00 am – 1:00 pm)**

Table 10: Scenario 4 - Control details

The following table shows the construction materials with insulation, used in the Scenario 5 model and their thermos-physical properties:

Surface	Surface Layer	Material	Thickness (mm)	Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)	Emissivity	Absorptivity
External wall (West & East)	1	Dense Plaster	12	0.50	1300	1000	0.91	0.50
	2	Air Gap	30	0	0	0	0	0
	3	Glasswool	20	0.04	250	840	0.90	0.30
	4	Light Brown Brick	215	0.96	2000	650	0.90	0.70
	5	Light Plaster	15	0.16	600	1000	0.91	0.50
Internal Wall (North & South)	1	Dense Plaster	12	0.50	1300	1000	0.91	0.50
	2	Air Gap	20	0	0	0	0	0
	3	Light Brown Brick	215	0.96	2000	650	0.90	0.70
	4	Air Gap	20	0	0	0	0	0
	5	Dense Plaster	12	0.50	1300	1000	0.91	0.50

Ceiling (zone 1 – ceiling & zone 2 – floor)	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Glasswool	10	0.04	250	840	0.90	0.30
	3	Light Mix Concrete	250	0.38	1200	653	0.90	0.65
	4	Glasswool	10	0.04	250	840	0.90	0.30
	5	Dry Rendering	10	1.13	1431	1000	0.91	0.50
Ground (zone 1 – floor)	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Glasswool	15	0.04	250	840	0.90	0.30
	3	Air Gap	5	0	0	0	0	0
	4	Light Mix Concrete	200	0.38	1200	653	0.90	0.65
	5	Limestone	200	1.50	2180	720	0.90	0.60
	4	Gravel Based	200	0.52	2050	184	0.90	0.85

Roof (zone 2 – ceiling)	1	Dry Rendering	10	1.13	1431	1000	0.91	0.50
	2	Glasswool	30	0.04	250	840	0.90	0.30
	3	Air Gap	10	0	0	0	0	0
	4	Light Mix Concrete	200	0.38	1200	653	0.90	0.65
Window (double glazing)	1	Glass Plate	6	0.760	2710	837	0.83	0.05
	2	Air Gap	12	0	0	0	0	0
	3	Glass Plate	6	0.760	2710	837	0.83	0.05
Door	1	Oak Wood	25	0.19	700	2390	0.90	0.65

Table 11: Scenario 4 – Insulation details

Scenario 4 - Model with two exterior faces (Summer)

A comparison between the PPD of zone 1 and zone 2 is given in the figure (29). It can be seen there the PPD is maintained less than 15% in zone 2, but it has increased and has settled at 55-60% for zone 1. Although cooling was sufficient, this can be due to high cooling in zone 1, leading to dissatisfaction of occupants.

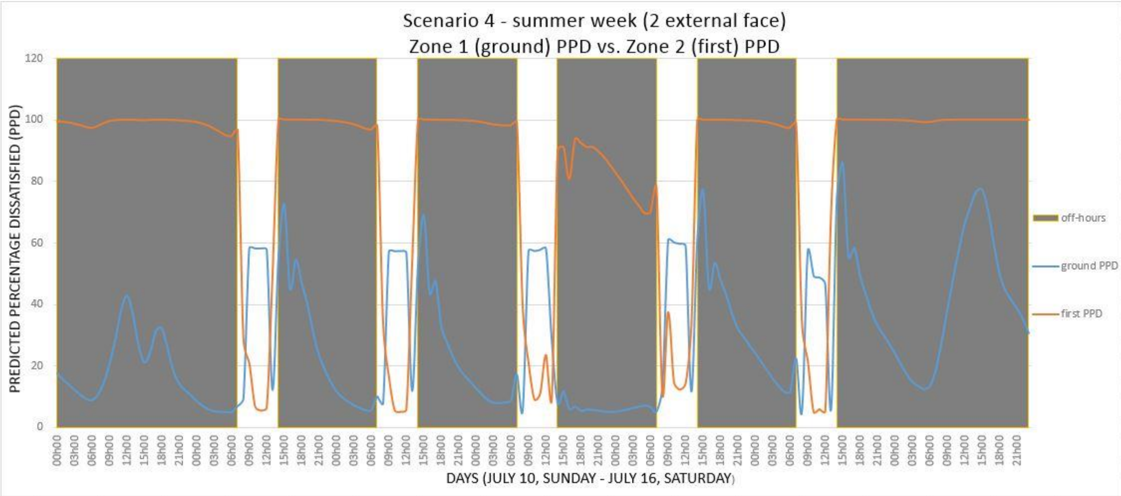

Figure 29: Scenario 4 – PPD comparison between zones during summer

In the figure (30) below, we can see the comparision of zone 1 in the Scenario 0 (current scenario), and zone 1 in Scenario 4, where insulation is done. It can be seen that, the occupants in Scenario 4 are not satisfied with the cooling, which was high in presence of insulation. The differnce in PPD is around 40%, which is very less when compared with other scenarios.

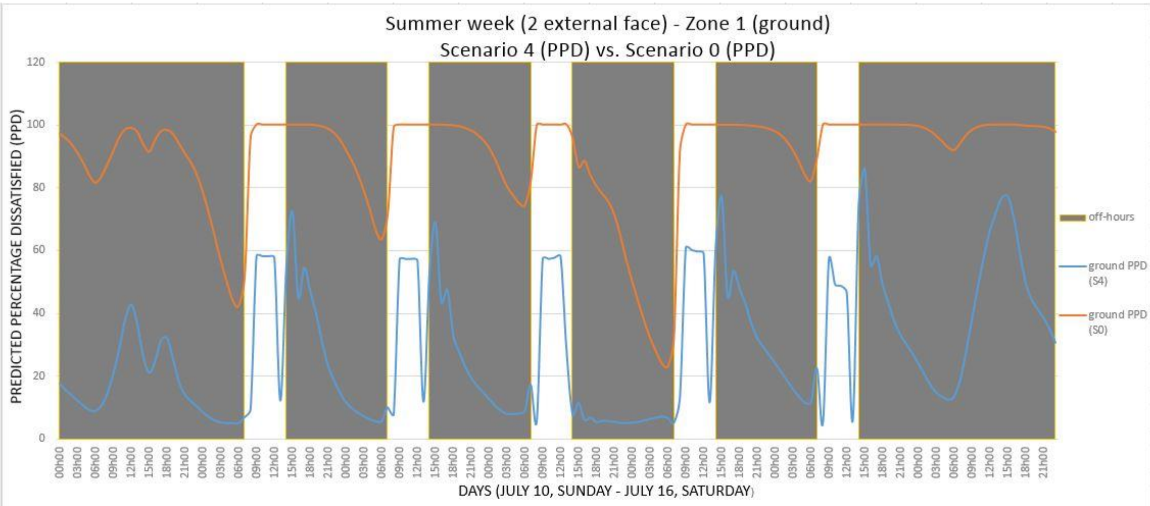

Figure 30: Scenario 4 – Zone 1 PPD comparison of Scenario 0 vs. Scenario 4

3.2.6. Comfort Results in different Scenarios

A detailed report about the PPD in all the different scenarios are given below. This table only consists the PPD results of Summer for the model with two external face.

Predicted Percentage Dissatisfied – 2 Ext. Face (During School Hours) **Summer week (Monday, 11th July – Friday, 15th July)**										
Scenario Number	**Days**	**PPD (minimum) (%)**				**PPD (average) (%)**				
		Zone 1	**Zone (min)**	**Zone 2**	**Zone (min)**	**Zone 1**	**Zone 1 (av.)**	**Zone 2**	**Zone 2 (av.)**	**Model Average**
0	Mon	51.17		98.68		92.44		99.81		
	Tue	71.23		99.82		95.77		99.97		
	Wed	82.01	31.75	99.92	76.96	97.41	**94.62 %**	99.99	**99.26 %**	**96.94 %**
	Thu	31.75		76.96		89.00		96.51		
	Fri	89.32		99.99		98.47		100.00		
1	Mon	5.61		5.00		33.26		18.62		
	Tue	5.86		5.67		35.41		18.55		
	Wed	5.93	5.00	5.62	5.00	40.25	**37.86 %**	22.40	**22.83 %**	**30.35 %**
	Thu	5.00		7.76		47.35		33.89		
	Fri	5.42		6.15		33.04		20.68		
2	Mon	5.00		5.01		11.14		47.68		
	Tue	5.00		5.00		11.03		46.03		
	Wed	6.35	5.00	5.00	5.00	8.54	**11.65 %**	22.20	**38.39 %**	**25.02 %**
	Thu	6.15		5.20		11.84		18.54		
	Fri	5.06		5.28		15.68		57.51		
3	Mon	5.00		5.00		29.88		20.43		

	Tue	5.12		5.24		32.11		18.87		
	Wed	5.03	5.00	5.84	5.00	39.91	**35.32 %**	23.41	**22.26 %**	**28.79 %**
	Thu	5.17		5.82		44.86		26.07		
	Fri	5.07		5.00		29.83		22.51		
4	Mon	6.92		5.48		37.22		30.65		
	Tue	7.78		5.07		36.85		31.22		
	Wed	5.71	5.10	9.12	5.02	40.19	**37.65 %**	30.32	**31.03 %**	**34.34 %**
	Thu	5.10		10.82		38.43		28.70		
	Fri	5.21		5.02		33.56		34.28		

Table 12: PPD details for 2 Ext. face models during summer week

Below are the summer and winter PPD details for the models with 2 external faces and 3 external faces. Two types of average are given, the scenario average and adjusted scenario average. Adjusted scenario average is more accurate for the result analysis, as it considers the ratio of the seasonal PPD average.

Scenario Number	**PPD Summer Average (%)**		**Summer Total (%)**	**PPD Winter Average (%)**		**Winter Total (%)**	**Scenario Average (%)**	**Adjusted Scenario Average (%)** (Summer Average x 8/12 + Winter Average x 4/12)
	2 Ext. Face	**3 Ext. Face**		**2 Ext. Face**	**3 Ext. Face**			
0	96.94	97.52	**97.23 %**	73.32	74.63	**73.96 %**	**85.60 %**	**89.47 %**
1	30.35	27.57	**28.96 %**	67.36	68.64	**68.00 %**	**48.48 %**	**41.97 %**
2	25.02	29.88	**27.45 %**	73.32	74.63	**73.96 %**	**50.71 %**	**42.95 %**
3	28.79	26.98	**27.89 %**	68.76	69.89	**69.33 %**	**48.61 %**	**41.70 %**
4	34.34	33.41	**33.86 %**	61.85	64.98	**63.42 %**	**48.64 %**	**43.71 %**

Table 13: Adjusted PPD average for the all scenarios

3.3. Photovoltaic System

PVGIS was used as modelling tool to calculate the average daily and monthly values of electricity production and irradiation for the solar PV array (Photovoltaic-software.com, 2016) in Dhanaura, India. Modelling of PV array is done based on different scenarios. This was done to get a more accurate data about the electricity and PV needed for supporting cooling and heating. A suitable PV module was chosen and following is the manufacturers specifications.

Model Name	**Indosolar** (Anon, 2016)
Model Number	**ISLM-320**
Nominal Maximum Power (STC)	**320W**
Module Efficiency (STC)	**16.71%**
Module Dimension	**1949 x 982.20 x 35mm**

Table 14: Photovoltaic module detail

Scenario 0 – Current scenario

The school has a 7 kW grid connection operating for 7 hours per day. So the daily electricity to be generated must be at least 49 kWh. Following are the PVGIS data with the system losses.

Location Coordinates		**28°57'50" North, 78°15'17" East**
Elevation		219 m (above sea level)
Nominal power of the PV system **(to generate the required electricity)**		**12.0 kW (crystalline silicon)**
	due to temperature and low	14.2%

Losses	irradiance	
	due to angular reflectance effects	2.7%
	Other losses (cables, inverter etc.)	14.0%
	Total (Combined PV system losses)	**28.3%**

Table 15: PVGIS location details

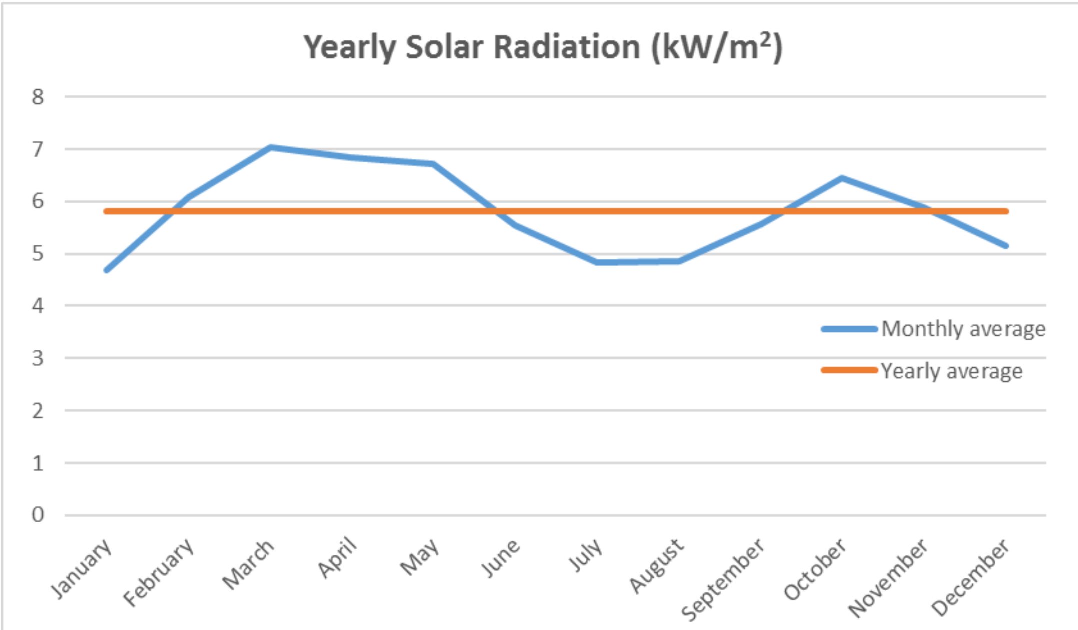

Figure 31: Comparison of monthly and yearly solar radiation average

Energy Required from PV = Energy Demand * Losses

= 49 * 1.283

=62.867 kWh

$$Watt\ Peak\ Rating = \frac{Energy\ Required\ from\ PV}{Panel\ Generation\ Factor}$$

(Leonics.com, 2016)

$$= \frac{62.867}{5.80}$$

$= 10.84\ kW_p$

$$No.\,of\ Modules\ required = \frac{Watt\ Peak\ Rating}{Peak\ Rated\ Output\ Module}$$

$$= \frac{10.84 * 1000}{320}$$

= 34 modules

Area of the total PV array = No. of modules * Area of one module

= 34 * 1.91

$= 64.94\ m^2$

So, it can be concluded that 34 modules are required to generate the electricity that is required to run the current scenario of 7 kW, where the PV array will at least take an area of 64.94 m^2. (Khatri, 2016)

The following are the data for the different scenarios about the required number of modules.

Scenario Description	**Connection for Summer (kW)**		**Electricity Required per day in summer (kWh)**	**Connection for Winter (kW)**		**Electricity Required per day in winter (kWh)**	**Minimum number of Modules required**	**Area (m^2)**
	Cooling Input	Total (CI + 7kW)		Heating Input	Total (HI + 7kW)			
1 – Perfect Scenario: Here there is both	39	46	283	42.9	49.9	263	**196**	374.36

cooling and heating with cooling input of 1.5 kW and set point of 24ºC with a load of 5.2 kW and heating input of 1.65 kW and set point of 20ºC with a load of 6.3 kW.								
2 – Decreasing Cooling Load and Comfort Levels: Cooling load is decreased so the input power of the 3.576 kW air conditioner is 1.01 kW and the set point is increased to 26ºC.	26.26	33.26	206.56	0	7	49	**143**	273.13
3 – Changing School Timing: The school timings are changed from 10:00 am – 3:00 pm with cooling input of 1.465 kW at set point of 24ºC.	38.09	45.09	277.54	0	7	49	**192**	366.72
4 – Insulating the Walls: Here the walls are properly insulated to increase comfort, with a cooling input of 1.465 kW at the set point of 24ºC.	38.09	45.09	239.45	0	7	49	**166**	317.06

Table 16: PV requirement details

4. DISCUSSION

The results for different scenarios was acquired from modelling and simulation analysis. It can be seen that to meet the current electricity demands of the school, at least 34 PV modules of 320W are required with a PV array area of 64.94 m2. This system will have grid connection and a generation factor of 7 kW. When compared with the comfort level in the ESP-r model of the current scenario, the Predicted Percentage Dissatisfied during summer is 97.23% and 73.96% during winters with an adjusted scenario average of 89.47%. This rate is unacceptable for the zones in the school, such that nearly 90% of the occupants are dissatisfied with the comfort levels throughout the year, thereby making their learning process more difficult. To reduce this PPD average extensively, cooling and limited heating is introduced in other scenarios.

- **Scenario 1**

Here, an air conditioning unit having rated cooling capacity of 5.2 kW with an EER of 3.47 and heating capacity of 6.3 kW with a COP of 3.81 is introduced in every classroom. If comfort and the electricity demands of the school is to be met using a photovoltaic system, then at least 196 PV modules are required with a 374.36 m2 PV array to generate 283 kWh of electricity. In this scenario the average PPD has been reduced to 28.96% in the summer and 68% in the winter with an adjusted scenario average of 41.97%. Although this improvement has reduced the PPD drastically, it is a very costly one.

- **Scenario 2**

In this scenario, considering the limited finances an air conditioning unit having rated cooling capacity of 3.576 kW with an EER of 3.54 is introduced in every classroom, with a higher cooling set point. Here, 143 PV modules are required to meet the comfort demands of the school, which has a PV array area of 273.13 m2 to generate up to 206.56 kWh of electricity every day. In this scenario the average summer PPD has been reduced to 27.45% with the exact winter PPD average as it is in the current scenario. The adjusted scenario average is 42.95%, which is a huge improvement in the PPD, as it's a considerably cheaper endeavour when compared to 'Scenario 1'.

- **Scenario 3**

This scenario deals with reducing the current PPD average with a different approach by changing the time of performance. Here, an air conditioning unit having rated cooling capacity of 5.275 kW and an EER of 3.60 is introduced in every classroom. For the feasibility of this scenario, 192 PV modules are required with a PV array of 366.72 m2 to generate the required 277.54 kWh of electricity. Here, the average summer PPD has been reduced to 27.89%, but the winter PPD has been reduced to 69.33% without applying heating. The adjusted scenario average is 41.70%, which is a huge improvement in the PPD, yet it is a more expensive than 'Scenario 2' due to higher cooling load.

- **Scenario 4**

In this scenario, insulation is taken as a primary approach to reduce the PPD. Air conditioner with a cooling capacity of 5.275 kW is introduced in every classroom. Due to the insulation, the cooling hours are limited just 5 hours. It is seen that the PPD has been reduced to 33.86% in the summer and the winter PPD has reduced to 63.42% without heating. The adjusted scenario average is 43.71%, which is an excellent progress when compared to the current scenarios, and also the previous scenarios. It requires only 166 PV modules on a PV array area of 317.06 m2 to generate 239.45 kWh of electricity. Although this endeavour cheap when compared with cost of the PV system and air conditioners in other scenarios, it its extremely expensive when the cost of insulation is added.

The above scenarios could be said to be a concrete solution for the energy problems in the region by having a continuous electricity supply for the building during school hours. Also, storage is an approach to be considered, as there is huge amount of solar energy that's being wasted during the off hours, which is nearly 6 hours on a typical summer day. 'Scenario 3' focuses on manipulating maximum solar energy, by changing time to a period of higher solar gain. Also, the performance of the project depends on the fact that in the future, no further construction of the school building would limit the growth of the PV array area by making part of the region inaccessible, as it can block the solar energy coming directly to the array without any obstacles.

On an economic view, the feasibility depends on financial backing of the government, which provides subsidies up to 30% for the PV system (The Times of India, 2016). So, it is economically possible set up the PV system for the current scenario. But for further agendas, like increasing the comfort levels, it becomes financially difficult, as cooling and heating systems are to be bought. For example, in the 'Scenario 1', it is required to install an air conditioner that provides both heating and cooling. In the simulation analysis we see that heating was not necessarily required here, as it didn't give an impressive reduction in the average winter PPD, just 5.96% less from the current average winter PPD. Also, due to poor insulation of the building, the surface temperature of the building walls remains cooler than the zone temperature and even the ambient temperature. As a result, the warm air in the zone due to heating has less effect in the zone temperature in this scenario. So as a result, it is seen that the average winter PPD of 'Scenario 4' is lesser than that of 'Scenario 1', which tells us heating is not the answer for winter. In 'Scenario 4', the walls are properly insulated, due to which heating system is not required, and less hours of cooling are required than other scenarios. Although the cost of insulating the entire school would be even more expensive than installing air conditioners. In 'Scenario 2', where the cooling load is reduced and cooling set point is increased, we can see that the average summer PPD is better than that of 'Scenario 1', where the cooling set point was lower and cooling load was higher. Although in the winter, the average PPD is equal to current scenario, as there is no effort to increase comfort. Also, one of the most important things to understand is that high PPD in the presence of cooling during summer could be because the zone temperature has reduced drastically, which could be because of less clothing level, or high difference between inside and outside temperature. On the other hand, the same is possible in the case of average winter PPD, where the zone temperature could be higher than usual, leading to the dissatisfaction of the occupants.

After distinguishing between necessity and luxury, and comparing them with limit of capital available, out of the above four scenarios, 'Scenario 2' can be considered as the most appropriate one to economically set up a PV system with air conditioners, and eventually increase the comfort metrics. Yet, a hybrid of 'Scenario 2' and 'Scenario 3' would be more applicable to increase the comfort levels throughout the year. The summer approach in 'Scenario 2' can be taken to reduce the average PPD in summer. For winter, the approach in 'Scenario 3' can be taken that is changing the school timing, could be followed in winter by moving the school hours by 1 hour, thereby taking advantage of the high solar gain and heat available at that period of time and reducing the PPD up to 5%.

Comfort Analysis of the Hybrid solution	
Summer Scenario	**Scenario 2** (introducing cooling with load of 3.5 kW and set point of 26°C)
Summer PPD	**27.45%**
Winter Scenario	**Scenario 3** (changing the winter school by moving it 1 hour forward from 9:00 - 16:00)
Winter PPD	**69.33%**
Adjusted Yearly Average (%)	**41.41%**

Economic Analysis of the Hybrid solution		
PV system	Module name	Indosolar ISLM-320
	Number of panels required	**143**
	Total PV expense (before 30% subsidy)	£25740
	Total PV expense (after 30% subsidy)	**£18018**
Air Conditioner	Model name	LG BSA12PMZD
	Cooling load	3.576 kW
	Number of air-conditioners required	**26**
	Total cooling system expense	**£14773**
Total expense (after subsidy)	**£32,791 (INR 2.9 million)**	

Estimated payback	**11 years**

This research methodology took a less detailed approach in technicalities and depended on manufacturers data of both the air conditioner and the PV modules. Certain Also, pricing of the PV system and air conditioners are flexible due to the conversion rates and the payback period is a simple assumption based on the monthly electricity and diesel generator bills. Certain limitations were observed during the modelling in ESP-r, such as the climate file, which belonged to Delhi and not Dhanaura. Certain operation details were based on assumptions, such as the casual gains occupants before and after school hours and during class hours, which is flexible.

5. CONCLUSIONS

This project attempted to model and simulate a photovoltaic system in a primary school in India, and investigate on how to increase the comfort levels of the occupants. A specific approach was found which was economically feasible, and also provided adequate amount of comforts. Majority of the simulations and modelling were done on ESP-r and Excel, with a few solar simulations from PVGIS. Certain limitations in data availability have led to certain approximations and assumptions. Although the capital is an issue, the government subsidies could reduce the cost effectively. In this case, the payback would start in 11 years, which includes the price of AC and PV system. Although this project doesn't consider the wear and tear of the PV module in this location. PV modules give low performance in hot climates, such as this (Raghavan, 2016). Also regular cleaning is required, as the level of dust in the area are very high. Due to limitations in weather conditions throughout the year, it seems difficult for the PV system to become autonomous. But it is possible with expansion of the PV array and the introduction of storage. One of the main goals behind this project is to check the feasibility of a PV system with the current electric demand, and eventually making the learning process comfortable for the students. This project, if successful, would be a milestone for rural electrification in the region, especially for the public institutions. It might encourage nearby residence or institutions to set up a PV system for their electrical needs, and even can take it off-grid, thereby reducing the strain in the grid and eventually eradicate the energy crisis that haunts the region.

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Appendix

A detailed report about the PPD in all the different scenarios are given below for summer week with three external faxes and winter week for models with two external faces and three external faces.

Predicted Percentage Dissatisfied – 3 Ext. Face (During School Hours) **Summer week (Monday, 11th July – Friday, 15th July)**										
Scenario Number	**Days**	**PPD (minimum)**				**PPD (average) (%)**				
		Zone 1	**Zone (min)**	**Zone 2**	**Zone (min)**	**Zone 1**	**Zone (av.)**	**Zone 2**	**Zone (av.)**	**Model Average**
0	Mon	70.70	30.04	99.38	67.25	95.65	**96.08 %**	99.91	**98.96 %**	**97.52 %**
	Tue	86.35		99.93		98.03		99.99		
	Wed	90.88		99.95		98.69		99.99		
	Thu	30.04		67.25		88.69		94.92		
	Fri	95.47		100.00		99.35		100.00		
1	Mon	5.35	5.08	5.56	5.09	26.33	**31.90 %**	19.77	**23.24 %**	**27.57 %**
	Tue	5.15		5.09		27.50		19.40		
	Wed	5.14		6.21		35.06		20.28		
	Thu	5.25		7.46		45.47		33.37		
	Fri	5.08		5.68		25.14		23.38		
2	Mon	5.18	5.00	5.22	5.15	16.56	**15.74 %**	53.22	**44.02 %**	**29.88 %**
	Tue	5.39		5.23		17.08		53.29		
	Wed	5.00		5.23		8.08		28.55		
	Thu	5.08		5.15		11.80		19.26		
	Fri	6.05		6.29		25.16		65.77		
3	Mon	6.49		5.00		23.64		23.37		

	Tue	5.94		5.09		24.89		21.65		
	Wed	5.03	5.03	6.42	5.00	36.68	**29.77 %**	21.12	**24.19 %**	**26.98 %**
	Thu	6.11		5.68		41.59		25.88		
	Fri	7.70		6.89		22.05		28.91		
4	Mon	5.80		5.00		32.96		32.84		
	Tue	5.23		5.12		32.11		34.28		
	Wed	5.11	5.11	5.75	5.00	39.00	**33.96 %**	30.52	**32.85 %**	**33.41 %**
	Thu	7.19		9.21		35.07		29.45		
	Fri	5.37		6.15		30.67		37.15		

Predicted Percentage Dissatisfied – 2 Ext. Face (During School Hours) **Winter week (Monday, 11th January – Friday, 15th January)**										
Scenario Number	**Days**	**PPD (minimum)**				**PPD (average) (%)**				
		Zone 1	**Zone (min)**	**Zone 2**	**Zone (min)**	**Zone 1**	**Zone (av.)**	**Zone 2**	**Zone (av.)**	**Model Average**
0	Mon	72.80		74.43		88.89		90.09		
	Tue	57.56		55.60		80.08		80.07		
	Wed	48.11	34.55	45.90	30.32	73.33	**73.61 %**	73.52	**73.03 %**	**73.32 %**
	Thu	34.55		30.75		62.80		62.14		
	Fri	35.79		30.32		62.94		59.33		
1	Mon	62.82		62.67		80.25		80.51		
	Tue	49.98		46.56		72.77		71.58		
	Wed	42.50	31.61	38.87	26.88	67.88	**68.15 %**	66.75	**66.56 %**	**67.36 %**
	Thu	31.61		26.88		59.74		57.88		
	Fri	33.31		27.64		60.11		56.09		

2	Mon	72.80		74.43		88.89		90.09		
	Tue	57.56		55.60		80.08		80.07		
	Wed	48.11	34.55	45.90	30.32	73.33	**73.61 %**	73.52	**73.03 %**	**73.32 %**
	Thu	34.55		30.75		62.80		62.14		
	Fri	35.79		30.32		62.94		59.33		
3	Mon	67.40		66.15		85.86		86.02		
	Tue	50.90		45.55		75.85		74.22		
	Wed	42.32	30.15	36.83	23.25	69.01	**69.73 %**	67.51	**67.78 %**	**68.76 %**
	Thu	30.59		24.00		58.61		56.34		
	Fri	30.15		23.25		59.34		54.80		
4	Mon	49.45		46.11		76.47		74.28		
	Tue	40.26		34.43		70.63		66.32		
	Wed	33.68	23.59	26.66	14.02	65.11	**64.97 %**	59.31	**58.73 %**	**61.85 %**
	Thu	23.59		16.44		56.21		48.78		
	Fri	24.08		14.02		56.42		44.98		

Predicted Percentage Dissatisfied – 3 Ext. Face (During School Hours)

Winter week (Monday, 11th January – Friday, 15th January)

Scenario Number	Days	**PPD (minimum)**				**PPD (average) (%)**				
		Zone 1	**Zone (min)**	**Zone 2**	**Zone (min)**	**Zone 1**	**Zone (av.)**	**Zone 2**	**Zone (av.)**	**Model Average**
0	Mon	72.78		74.14		89.00		90.05		
	Tue	58.56		56.82		80.81		80.95		
	Wed	49.32	35.82	47.73	32.64	74.32	**74.71 %**	74.95	**74.55 %**	**74.63 %**
	Thu	35.82		32.64		64.16		64.12		

	Fri	38.23		33.63		65.28		62.68		
1	Mon	62.66		62.32		80.28		80.44		
	Tue	51.20		48.07		73.58		72.51		
	Wed	43.96	33.12	40.88	28.94	68.91	**69.23 %**	68.22	**68.05 %**	**68.64 %**
	Thu	33.12		28.94		61.32		60.09		
	Fri	35.68		30.73		62.10		59.01		
2	Mon	72.78		74.14		89.00		90.05		
	Tue	58.56		56.82		80.81		80.95		
	Wed	49.32	35.82	47.73	32.64	74.32	**74.71 %**	74.95	**74.55 %**	**74.63 %**
	Thu	35.82		32.64		64.16		64.12		
	Fri	38.23		33.63		65.28		62.68		
3	Mon	66.85		65.13		85.77		85.69		
	Tue	51.36		46.06		76.44		74.91		
	Wed	42.99	31.32	37.95	25.16	69.87	**70.69 %**	68.78	**69.08 %**	**69.89 %**
	Thu	31.32		25.16		59.79		58.10		
	Fri	32.04		25.68		61.58		57.90		
4	Mon	53.50		51.38		78.68		77.37		
	Tue	44.71		39.85		73.30		69.92		
	Wed	37.89	27.37	31.61	17.79	67.82	**67.61 %**	63.00	**62.35 %**	**64.98 %**
	Thu	27.37		20.51		59.00		52.50		
	Fri	27.76		17.79		59.25		48.97		

Given below is the PVGIS data of monthly solar irradiation for the given location and the daily electricity produced from the PV system at different months

Fixed system: inclination = 30°, orientation = -1° (optimum)		
Month	**E_d (kWh)**	**H_d (kW/m^2)**
January	42.60	4.69
February	54.00	6.07
March	60.10	7.03
April	56.70	6.85
May	54.80	6.71
June	45.80	5.53
July	40.90	4.83
August	41.20	4.86
September	47.20	5.56
October	55.20	6.46
November	51.20	5.89
December	46.60	5.16
Yearly average	**49.70**	**5.80**

E_d: Average daily electricity production from the given system (kWh)

H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)