Application of Building Integrated Photovoltaic:

Design Strategies for Optimization of Renewable Energy Through Envelope and Daylight Harvesting

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Abstract

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Chairs of the Supervisory Committee:
Associate Professor Dean R. Heerwagen
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Architecture

Buildings account for roughly 39% of the atmospheric carbon dioxide produced in the United States. To mitigate the impact of our buildings on the environment, our buildings need to take advantage of the abundance of sunlight that falls on them. Despite recent advances in photovoltaic technology, building integration of photovoltaic falls short of its potential. This thesis proposes design strategies for optimization of renewable energy from sunlight through building integrated photovoltaic, and incorporating daylight harvesting as an additional means to decrease buildings' energy use.

I would like to say thank you to my family for their support and my thesis committee for their valuable contributions and help during entire thesis process.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM OVERVIEW

Our buildings energy need has gone up significantly and it continues to rise with increase in population and urbanization. Buildings are responsible for at least 40% of total energy use in most countries.[1] To meet their energy needs most buildings rely on external sources. This thesis suggests that it does not have to be this way. The three main sources of Electricity according to Electricity Information Administration, U.S. Department of Energy are, natural gas 33.8%, coal 30.4% and nuclear, 19.7%.[2] Others sources including hydro-electric accounts for less than 10% from any one single source. Natural gas is generally believed to be cleaner in comparison to coal but still adds carbon to the environment and we are well aware of issues surrounding the nuclear power plants. All three major electricity sources have environmental and health impact. This thesis proposes that buildings can produce sufficient renewable energy on site from solar energy, and does not need to rely solely on energy from external sources, and thus can decrease its' impact on our health and environment.

Cities like Seattle with its growth provides a unique opportunity to design new-buildings to be energy efficient. The effect of carbon on our environment is becoming more apparent in the form of extreme weather events that we are seeing increasingly now. Additionally, detrimental effects of carbon on human health and its' cost in the form of direct care and lost productivity effects both individuals and businesses.[3] In case of Nuclear plant disaster, the impact on environment as well as human health and wellbeing could be wide spread and long lasting. It does not make much sense to build more power plants, that run on fossil fuels or nuclear power to meet increasing energy

1 Energy Efficient in Buildings. Business realities and opportunities summary report. World Business Council for Sustainable Development

2 US Energy Information Administration. Retrieved from (https://www.eia.gov/tools/faqs/faq.php?id=427&t=3)

3 Annual Review of Energy and environment. Health and productivity gains from better indoor environment and their relationship with

demands. This thesis proposes that buildings need to operate on energy that lands on it and decrease its' reliance on off-site energy production. Using the design approach elaborated here in this thesis, building envelope will effectively be used for renewable energy as well as daylight harvesting.

1.2 PROJECT RATIONALE

With the realization of how energy utilization impacts our health and enviro-ment, comes the question how to decrease our buildings' reliance on energy sources that impacts these variables negatively. The logical answer is to utilize renewable re-soures available to us like sunlight. In urban landscape the challenge is lack of space to put photovoltaic panels for energy production. Mid and high-rise buildings can provide space for this purpose.

Seattle with its' high concentration of young adults (age 25 to 34) and education level, has high level of awareness about the environment and sustainability.[4] Environ-mentally friendly building would have greater appeal for these young educated individ-uals and they would prefer to work and live in such buildings. Additionally, businesses housed in such buildings can improve their image and relationship with the community. Hence, by incorporating building integrated photovoltaics in design of multistory mid to large office building can influence how future buildings would be designed to optimized renewable energy production on site and decrease its reliance on grid.

1.3 OVERVIEW OF THESIS

Sun has been source of natural light and energy for mankind from the beginning. The solar energy received by the earth is 10,000 times larger than human needs but most buildings fail to make use of abundance of solar energy landing on their surfaces. Building integrated photovoltaic can serve as envelope, as well as source of renewable energy. In spite of advances in photovoltaic technology and falling cost, building

4 Source: https://www.seattle.gov/opcd/population-and-demographics/decennial-census#2010

integration of photovoltaics fall short of its' potential. This thesis will elaborate on the application of building integrated photovoltaic through design strategies for optimization of renewable energy through building envelope and maximize daylight harvesting.

CHAPTER 2

LITERATURE REVIEW

2.1 RENEWABLE ENERGY

According to Architecture 2030 “how we plan and design the built environment from here out will determine whether climate change is manageable or catastrophic”. The American Institute of Architects and 2030 challenge has set incremental target as a way for buildings to meet performance standards including its energy source as way to address climate change.[5] On site energy production from renewable sources is one of the key components of this. The architects are faced with the challenge of incorporating renewable energy generation in their building designs. The solution could be on site energy generation from solar energy.

Challenges of integrating photovoltaic in urban setting include scarcity of space to put solar array, site location and configuration, issue of shadow from existing structures and aesthetic concerns. First and foremost, the challenge is the availability of space for mounting photovoltaic arrays in an urban setting. Roof and envelope of medium to large size buildings could be ideal for this. One of the main attractions of building integrated photovoltaic (BIPV) and the reason for their acceptance is that building envelopes are used to mount photovoltaic panels and there is no need for additional land (Scognamiglio & Garde, 2016).

Using simulation programs like Grasshopper, Diva and radiance for sun path and annual daylight, the designer can truly assess the limitations of their site, in terms of energy and daylight harvesting potential. First these iterations show well ahead in the design process the impact of annual shadow on the site and how much daylight interior space can gain. Secondly, they provide a true picture of how much solar radiation each side of the facade is encountered with and how much energy BIPV could generate.

5 How we plan and design the built environment from here on out will determine whether climate change is manageable or catastrophic. Source: (http://architecture2030.org/buildings_problem_why/the-solution/)

Thus, utilizing these parametric tools architects could modify orientation or configure their design for maximum optimization. Additionally, aesthetic aspect could be improved by using customized products that besides integrating could improve the look of the building. Photovoltaic applied in a well thought way can contribute to greater acceptance of photovoltaic technology, add value to the project and make the design architecturally pleasing (Kaan & Reijenga, 2004).

2.2 DAYLIGHT HARVESTING

The energy saving from daylight harvesting has been studied by many and several of these studies concluded that substantial energy reduction could be achieved. A recent assessment of energy saving potential in office buildings, from Greece, estimates that lighting energy consumption can be reduced up to 60%. Indeed, many factors including space and occupant's behavior affects this potential. The investigators calculated that even with reduction up to 40% the primary energy consumption could go down by 17%.[6] This provides an opportunity to reduce energy consumption of the building that could be substantial. Thus, daylight harvesting with its potential needs to be integrated and maximized with BIPV.

Daylight benefits on health and wellbeing of building occupants have been subjects of numerous studies. Although the researchers could not quantify the benefits on health and productivity, most studies concluded that daylight does improve worker's satisfaction, mood, and productivity. Similar studies found beneficial effects of daylight in other settings like school, healthcare and even retail. "According to a survey by Environmental Protection Agency, humans in modern cities spend 90% time indoors".[7] To summarize the cited studies, the use of daylighting in buildings not only reduce utility costs, but will also improve the health and wellbeing of building occupants. The computational lighting design tools provides in depth knowledge of interior space and help optimize and maintain upper and lower light thresholds.

6 Source: https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

7 Source: (https://cfpub.epa.gov/roe/chapter/air/indoorair.

2.3 PRECEDENTS

The precedents in the following pages show Building Integrated Photovoltaic on building envelope and roof surface.

BULLITT CENTER, SEATTLE

Number of Floors: Six

Total Floor Area: 52,000 sq.ft

Total number of BIPV on the roof: 575

Total Energy Production Capacity: 244,375 kWh/year

Predicted EUI: 16 kBTU/sq.ft

Fig.1. Bullitt Center with extended roof line with BIPV

The Bullitt Center is in Seattle, located in Capitol Hill. The building is six stories high with total floor area of 52,000sq.ft. The building envelope has triple glazing. The window panel is automated for air flushing and natural ventilation. The outer envelope is a source of daylight harvesting equipped with automated exterior louvered blind to prevent glare and over lit situation. The roof extends about 35% beyond the floor plate

Fig.2: Bullitt Center staircase

Fig.3. Bullitt Center Roof with 575 BIPV

providing extra space for BIPV. The total surface area of roof is 13,500sq.ft. 74% of the roof surface is covered with 575 Building Integrated Photovoltaic panels, each with 435 Watt energy production capacity, they have produced 230,000 kWh/year of renewable energy.

The EDGE, AMSTERDAM

Number of floors: 15

Total Floor Area: 430,000 sq.ft

Total number of BIPV: 65,000 sq.ft of PV array on roof top

South Wall: 40 BIPV

EUI : - 0.3 kBTU/sq.ft

Fig.4. The Edge, Amsterdam

The Edge building is located in Amsterdam. The total covered area of the building is 430,000sq.ft. The Edge has photovoltaic arrays over a roof top surface area of 65,000 sq.ft. Additionally, there are 40 BIPV on the south elevation of the building. It also uses neighboring building to mount PV for renewable energy production. The east side of the building has 45% glass windows for daylight harvesting. In addition, its 15 story high atrium is a big source of daylight harvesting for the interior spaces.

Fig.5. BIPV cladded with concrete on 40% of south facade

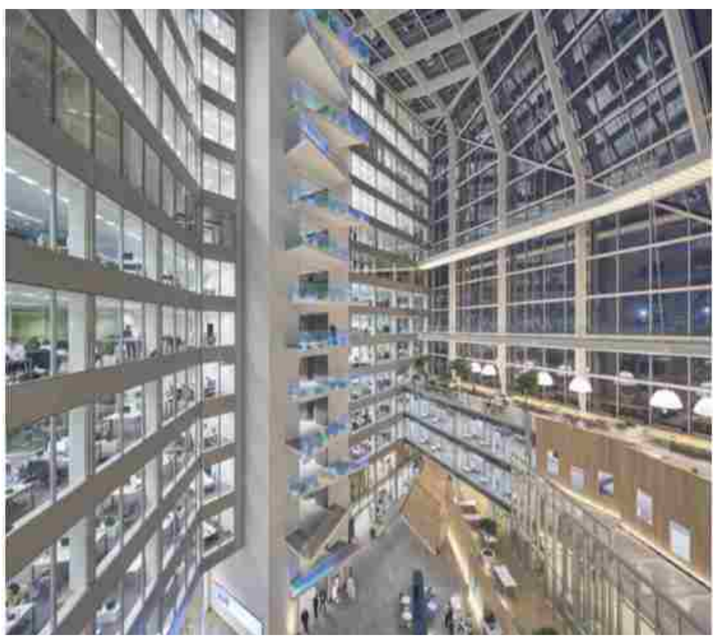


Fig.6: Atrium 15 story is big source of Daylight harvesting

In Edge building BIPV is used on south elevation and roof. The extra energy demand is fulfilled by using neighboring building for renewable energy production without compromising the aesthetic elements of facade. For daylight harvesting envelope and atrium are used to maximize daylight harvesting.

2.4 CONCLUSION

The two precedents and the literature review suggest different ways to integrate building photovoltaic panels on the surface area of the envelope and strategies to optimize both renewable energy and daylight harvesting. In the case of Bullitt Center, walls are not utilized for photovoltaic, however, the roof surface area within the parameters of the building walls is insufficient. The roof is extended by almost 35% from the floor plate, increasing total available surface for building integrated photovoltaic. This approach to increase the surface area for BIPV definitely helped, enabling the Bullitt Center to achieve net zero, apart from other contributing factors. Secondly, for daylight harvesting, all the windows are within 30 feet of task area. The height of the window is another factor in maximizing daylight harvesting. The case study of Bullitt Center suggested that the manipulation of the envelope surface area can optimize both renewable energy as well as daylight harvesting. In the second precedent, the Edge building we see a different approach. To compensate for insufficient area available for BIPV the roof of neighboring building is used. For optimization of daylight harvesting, 15 floor high atrium is incorporated in the design. The main intent of these precedents and literature review is to understand how renewable energy production and daylight harvesting could be maximized. Although, the approach is somewhat different, both buildings goal is to maximize on or near site renewable energy production while optimize daylight harvesting potential.

CHAPTER 3

METHODOLOGY

The thesis objective is to find different design strategies for application of BIPV and how to optimize envelope for renewable energy and daylight harvesting. At first, analysis of all the theoretical framework of the project is conducted. In the second part is the analysis of both base case and design case.

3.1 EFFECT OF TILT ANGLE ON RENEWABLE ENERGY YIELD

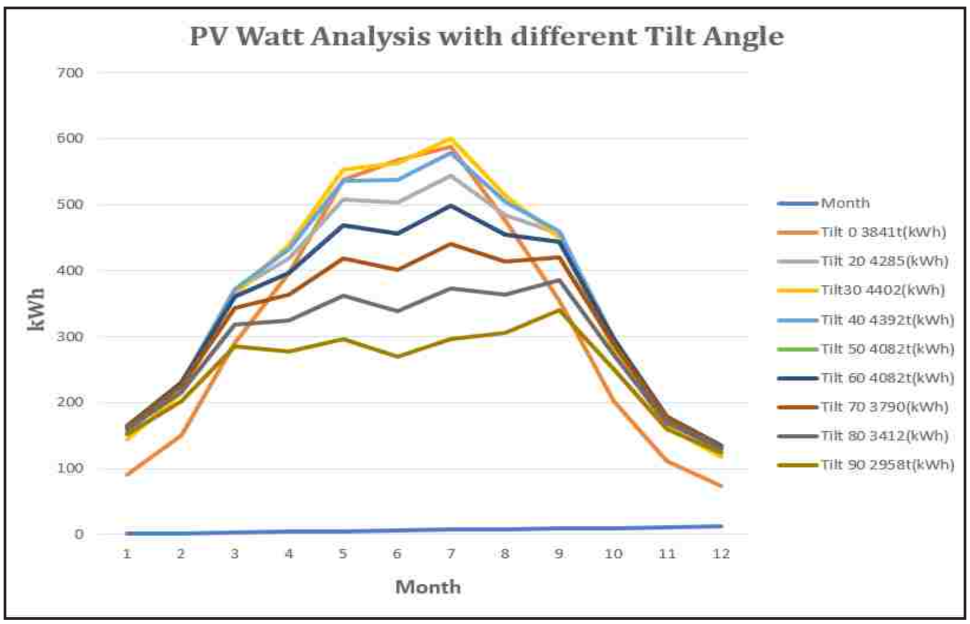


Fig.7: PV Watt study with different Tilt angle

The theoretical framework analysis starts with study of effect of different tilt angles using PV watt.[8] PV watt is a tool from NREL (National Renewable Energy Laboratory) that estimates performance of photovoltaic system accurately. This analysis gives energy production potential of photovoltaic at different tilt for specific month of the year.

8 Source:http://pvwatts.nrel.gov/pvwatts.

Month	Tilt 0	Tilt 20	Tilt30	Tilt 40	Tilt 50	Tilt 60	Tilt 70	Tilt 80	Tilt 90
1	90	162	144	155	164	164	164	159	151
2	150	230	214	225	230	230	226	216	201
3	290	370	363	370	360	360	343	318	285
4	397	419	438	433	395	395	364	324	277
5	538	507	554	536	468	468	419	361	296
6	567	502	562	538	456	456	401	338	269
7	588	544	600	579	498	498	440	372	296
8	475	484	514	504	453	453	413	363	305
9	353	456	449	458	443	443	419	385	339
10	202	297	280	292	296	296	287	272	251
11	111	177	162	172	178	178	176	169	159
12	74	131	117	126	134	134	133	129	123
Total	**3841**	**4285**	**4402**	**4392**	**4082**	**4082**	**3790**	**3412**	**2958**
	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr	kWh/yr

Fig.8: Different tilt. study with PV Watt

A 4 kW system with rated output of 335 Watt for 12 photovoltaic panels was used in this analysis. Each panel size is 17.5 sq.ft. Tilt is the angle of photovoltaic array from horizontal surface. Sun's path and altitude varies from winter to summer and so does the ideal tilt angle. Azimuth is horizontal angle generally measured clockwise from north, means angle of array oriented south is 180 degrees. If the azimuth angle is fixed at 180 degrees which is ideal for Seattle area and tilt is changed from 0, 20, 30, 40, 50, 60, 70, 80 and 90 degrees, the amount of kilo-watt-hour of renewable energy production varies. Every tilt has different impact on renewable energy production kilo-watt-hour/year. In the Seattle area, maximum yield of renewable energy is achieved between 30 and 40-degree tilt. The tilt angle of photovoltaic panel is one of the key factors for optimization of renewable energy yield from solar source. The intent of this analysis is to choose the best suitable tilt of the photovoltaic arrays for the project and modify the design for optimization.

3.2 BIPV PERCENTAGE AREA ANALYSIS ON FACADE AND ROOF

The BIPV percentage analysis is conducted to calculate available surface area on facade and roof for BIPV. The width of the site is 180 feet facing east and west, whereas it is 108 feet facing south and north. The calculation is done with assumption that building covers the entire 180 feet by 108 feet and has floor to wall height of 12 feet.

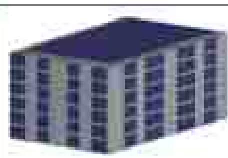
Number of Floors	Area sq. ft.	Wall Surface sq. ft.		Roof Surface sq. ft.		Total BIPV sq. ft
		TOTAL WALL	WALL 60% BIPV	TOTAL ROOF	ROOF 80% BIPV	60%WAL+80%ROOF
 One Floor	19,440	5,616	3,370	19,440	15,552	18,921
 Two Floors	38,880	11,232	6,740	19,440	15,552	22,290
 Three Floors	58,320	16,848	10,109	19,440	15,552	25,659
 Four Floors	77,760	27,600	11,040	19,440	15,552	29,030
 Five Floors	97,200	28,080	16,848	19,440	15,552	32,400
 Six Floors	116,640	33,696	20,217	19,440	15,552	35,769

Table 1

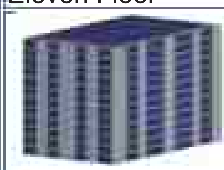
Number of Floors	Area sq. ft.	Wall Surface sq. ft.		Roof Surface sq.ft.		Total BIPV sq. ft.
		TOTAL WALL	WALL 60% BIPV	TOTAL ROOF	ROOF 80% BIPV	60%WALL+80% ROOF
 Seven Floor	138,080	39,312	23,587	19,440	15,552	39,139
 Eight Floor	155,520	44,928	26,956	19,440	15,552	42,508
 Nine Floor	174,960	50,544	30,326	19,440	15,552	45,878
 Ten Floor	194,400	56,160	33,696	19,440	15,552	49,248
 Eleven Floor	213,840	61,776	37,065	19,440	15,552	52,617
 Twelve Floors	233,280	67,392	40,435	19,440	15,552	55,987

Table 2

The site is located in the South lake Union, Seattle. The first analysis only calculate the effect of building scale on energy production, without taking into account the impact of shades from the surrounding buildings. The east and west side has more surface area available for BIPV. The building integrated photovoltaic is applied on 60% of south, east and west walls and the remaining 40% is left for glazing. On the roof, 80% is covered with BIPV for renewable energy production. The results are recorded floor by floor.

3.3 RELATIONSHIP BETWEEN BUILDING VOLUME AND ENVELOPE SURFACE AREA

Volume of a building is directly proportional to the surface area of it's envelope. The common reason for higher building volume to envelope ratio is wider floor plate and in general narrower the floor plate, lower will be this ratio. Thus this ratio can be manipulated by decreasing the floor plate depth and changing configuration of the building.

Although, energy production is directly proportional to surface area available for BIPV, the relationship becomes complex when energy need and daylight harvesting potential is incorporated into it. Optimization of renewable energy production and daylight harvesting is effected by floor plate depth and envelope surface area. For optimization, what would be needed is to make floor plates narrower but increase envelope surface area while keeping volume of building same or lower. Decreasing the ratio between building volume and envelope size could be challenging.

3.4 BUILDING GEOMETRY AND ITS RELATIONSHIP WITH VOLUME

To achieve the design objective of making the floor plates narrow and increase envelope area, different shape and configuration were considered. The design case was felt to fit in this criterion the most. Additionally, it increased the south and north wall size to increase energy and daylight harvesting potential.

3.5 CONCLUSION | BALANCING COMPETING GOALS

The goal of the project is to decrease reliance for energy on external source through decreasing energy need by daylight harvesting and for rest of energy needs produce it on site using solar energy landing on it’s surface. It could be quite a challenge to optimize the envelope for both daylight harvesting and renewable energy production. Theoretically, these are two competing goals, as higher envelope surface available for BIPV could translate into less glazing. Additionally, narrow floor plate improves daylight harvesting potential, however, this in general will lead to less surface available for BIPV. This delicate goal of finding a right balance is reached by running simulations for daylight and solar analysis, then utilizing the data in the design process.

In order to achieve the design objective of making the floor plates narrow and increase envelope area, different shape and configuration were considered. The design case was felt to fit in these criteria the most without loosing much building volume. Additionally, it increased the south and north wall size to increase energy and daylight harvesting potential.

CHAPTER 4

DESIGN ANALYSIS I

4.1 BASE CASE OVERVIEW

In the base case, all twelve stories of the building cover the entire site area of 180’ x108’. Floor to ceiling height is 12’ and window to wall ratio is 40%. In base case, iteration is run on building mass covering the entire site in South Lake Union neighborhood, measuring 108’ x180’. At first, renewable energy production simulation is run on the entire envelope using Archsim from grasshopper. Daylight harvesting iteration, using Diva is run the next. Then, the data collected from these two simulations for renewable energy and daylight harvesting is analyzed.

In the simulation for renewable energy, after adding the square footage of each floor, the envelope surface area is calculated. Secondly, the role of floor plate and envelope surface area is carefully studied. In the base case the impact and relationship of each floor square footage, surface area, window to wall ratio, floor to ceiling height and energy production intensity provides in depth analysis of the scenario. Each floor’s envelope surface area and energy production intensity is recorded separately. Because the site is rectangular with108’ facing south and north. The larger length of the site 180’ is on the east and west side. Thus the surface area of the east and west side of the envelope is also greater than the south side. On eighty percent of the roof and sixty percent of the wall surface on three sides BIPV is applied and used for energy production.

4.2 PRELIMINARY ANALYSIS | BIPV

The intent of this section is to analyze on site energy production potential of the envelope. Total number of BIPV on roof, east, west and south wall’s and their energy production in kWh is calculated individually. Of the three walls the most energy production potential is by east and west walls given their larger surface area.

ROOF

Floor Plate Area of Roof 108' x 180' = 19,440 sq.ft

80% of Roof = 15,552 sq.ft

Total number of BIPV 19 Panel x 46 Panel = 874

Total Energy Production = 284,050 kWh/yr

Efficiency 22%

Kilowatt-hour Multiplied by 3.41 to obtain kBTU =

968,610 kBTU

WEST WALL

Total Wall Surface Area 25,920 sq.ft

Window to Wall Ratio 40% 10,368 sq.ft

Each Floor has 60 BIPV panels on wall

Total number of BIPV module on West Wall 720

Total Energy Production on West Wall181,617 kWh=

619,313 kBTU

EAST WALL

Total Surface Area 25,920 sq.ft

Window to Wall Ratio 40% 10,368 sq.ft.

Each Floor has 60 BIPV panels on wall

Total number of BIPV on East Wall 720

Total Energy Production on East Wall183,363kWh =

625,267 kBTU

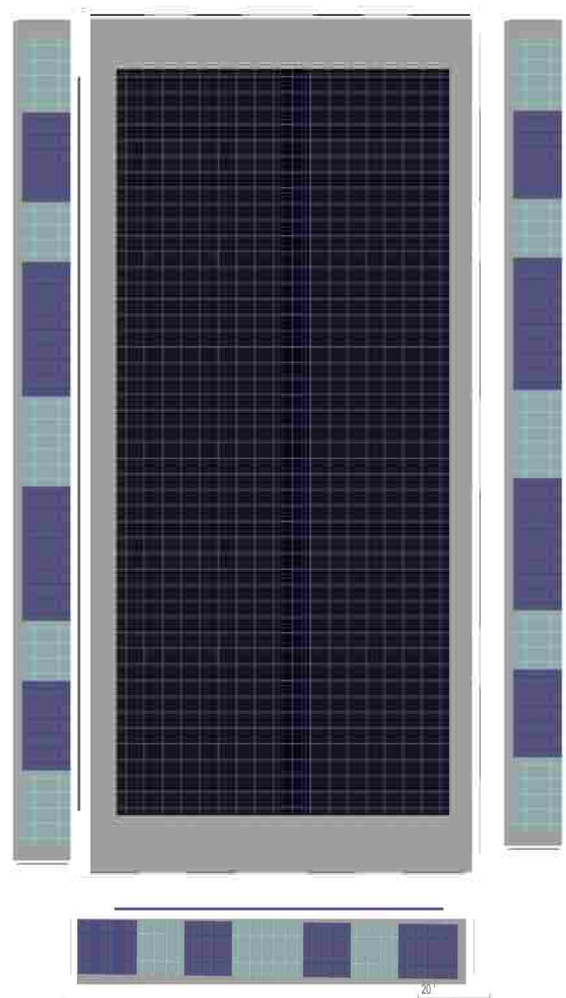


Fig.9: Plan of Base Case and 3-BIPV Elevations

SOUTH WALL

Total Surface Area 15,552 sq.ft

Window to Wall Ratio 40% 6,220.8sq.ft

Each Floor has 36 BIPV

Total number of BIPV on South Wall 432

Total Energy Production on South Wall 143,939 kWh/yr =

490,832 kBTU

4.3 ENERGY PRODUCTION INTENSITY

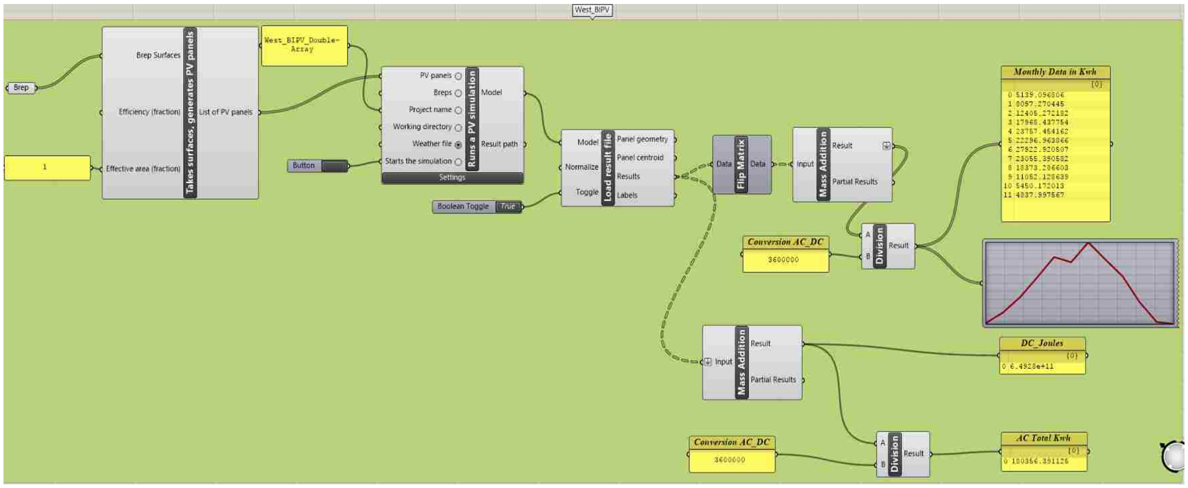


Fig. 10: Grasshopper Simulation output using Archsim

The purpose of base case analysis is to find ways to optimize renewable energy production of the envelope. Archsim grasshopper simulation is used for this analysis. Sun power photovoltaic panel of 325 watts with efficiency of 22% is used in this analysis. In this section, how the addition of floors increases the amount of energy production is studied too. As expected first floor produced most energy because of roof surface area after which energy production proportionally increases with additional floor. Energy production is directly proportioned to surface area. As opposed to total energy production, energy production intensity is variable and decreases with the addition of floors.

ENERGY PRODUCTION INTENSITY = TOTAL ENERGY PRODUCED kWh / FLOOR AREA sq.ft

Energy production intensity of first floor is 56 and the intensity decreased to 11 for 12th floor. Energy Production Intensity is inversely proportion to floor area in square feet. The energy production intensity is total energy production divided by total floor area.

ENERGY PRODUCTION INTENSITY OF FLOOR

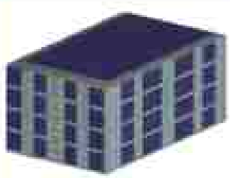
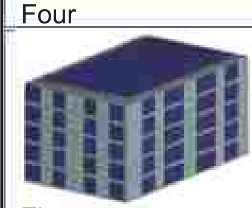
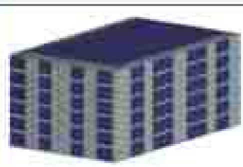
FLOORS	AREA sq. ft.	BIPV AREA sq. ft.		ENERGY PRODUCTION kWh			EPI kBTU/sq. ft.
		WALL60%	ROOF60%	WALL	ROOF	TOTAL	
 One	19,440	3,370	15,552	41,495	284,050	325,545 kWh OR Multiply 3.41 to kBTU= 1,110,108kBTU	1,110,108 19,440 = **56**
 Two	38,880	6,740	15,552	82,990	284,050	367,040 kWh OR 1,251,606 kBTU	1,251,606 38,880 = **32**
 Three	58,320	10,109	15,552	124,485	284,050	408,535 kWh OR 1,393,104 kBTU	1,393,104 58,320 = **23**
 Four	77,760	11,040	15,552	165,980	284,050	450,030 kWh OR 1,534,602 kBTU	1,534,602 77,760 = **19**
 Five	97,200	16,848	15,552	207,475	284,050	491,525 kWh OR 1,087,701 kBTU	1,087,701 97,200 = **17**
 Six	116,640	20,217	15,552	248,970	284,050	533,020 kWh OR 1,817,598 kBTU	1,817,598 116,640 = **15.5**

Table 3: Base Case | Energy Production Intensity of floors

ENERGY PRODUCTION INTENSITY OF FLOOR

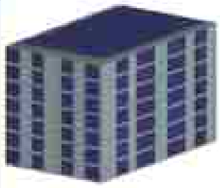
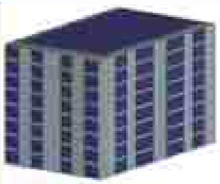
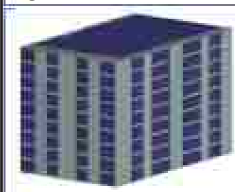
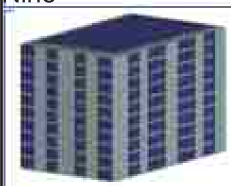
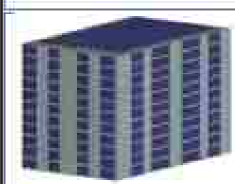
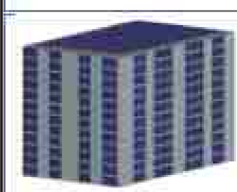
FLOORS	AREA sq. ft.	BIPV AREA sq. ft.		ENERGY PRODUCTION kWh			EPI kBTU/sq. ft.
		WALL60%	ROOF80%	WALL	ROOF	TOTAL	
 Seven	136,080	23,587	15,552	290,465	284,050	574,515 kWh OR Multiply 3.41 to kBTU= 1,959,096 kBTU	1,959,096 136,080 = **14.39**
 Eight	155,520	26,956	15,552	331,960	284,050	616,010 OR Multiply 3.41 to kBTU= 2,100,594	2100594 155,520 = **13.5**
 Nine	174,960	30,326	15,552	373,455	284,050	657,505 kWh OR Multiply 3.41 to kBTU= 2,242,092	2242092 174,960 = **12.8**
 Ten	194,400	33,696	15,552	414,950	284,050	699,000 kWh OR Multiply 3.41 to kBTU= 2,383,590	2,383,590 194,400 = **12.2**
 Eleven	213,840	37,065	15,552	456,445	284,050	740,495 kWh OR Multiply 3.41 to kBTU= 2,525,087	2,525,087 213,840 = **11.8**
 Twelve	233,280	40,435	15,552	497,940	284,050	781,990 kWh OR Multiply 3.41 to kBTU= 2,666,585	2,666,585 233,280 = **11.4**

Table 4: Base Case | Energy Production Intensity of floors

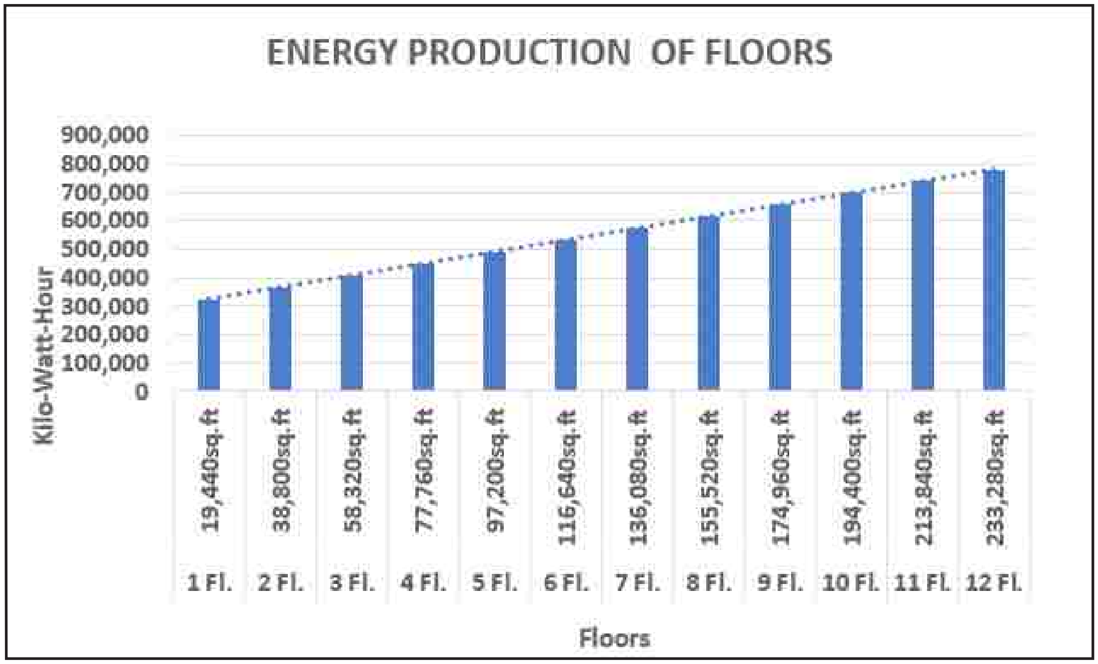


Fig.11: Energy Production of floors

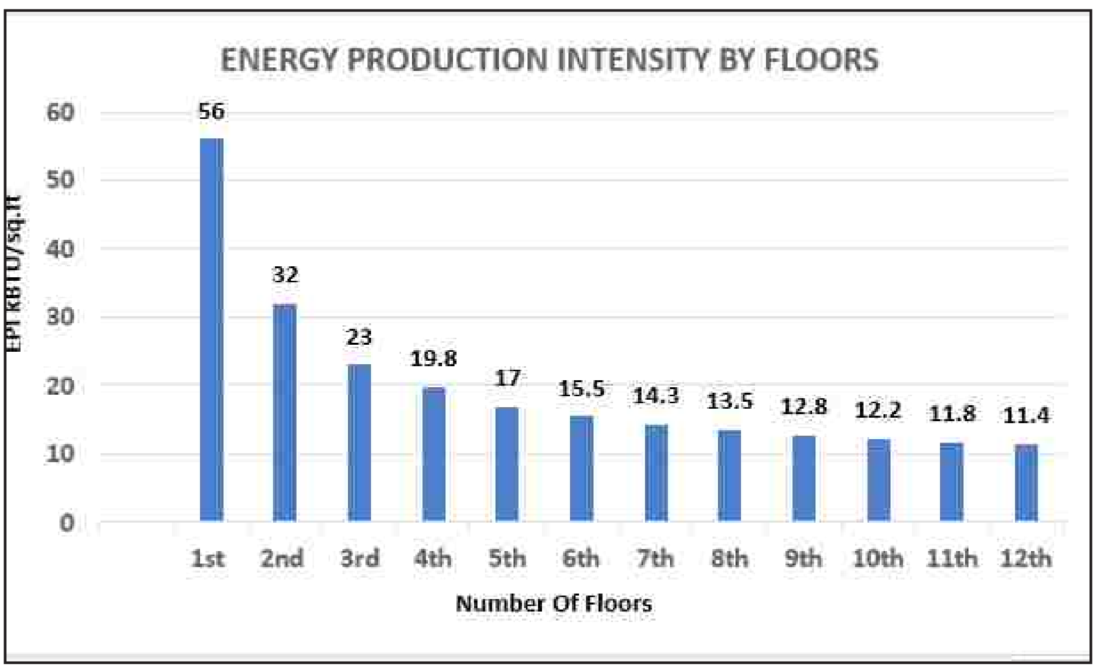


Fig.12: Energy Production Intensity by floors

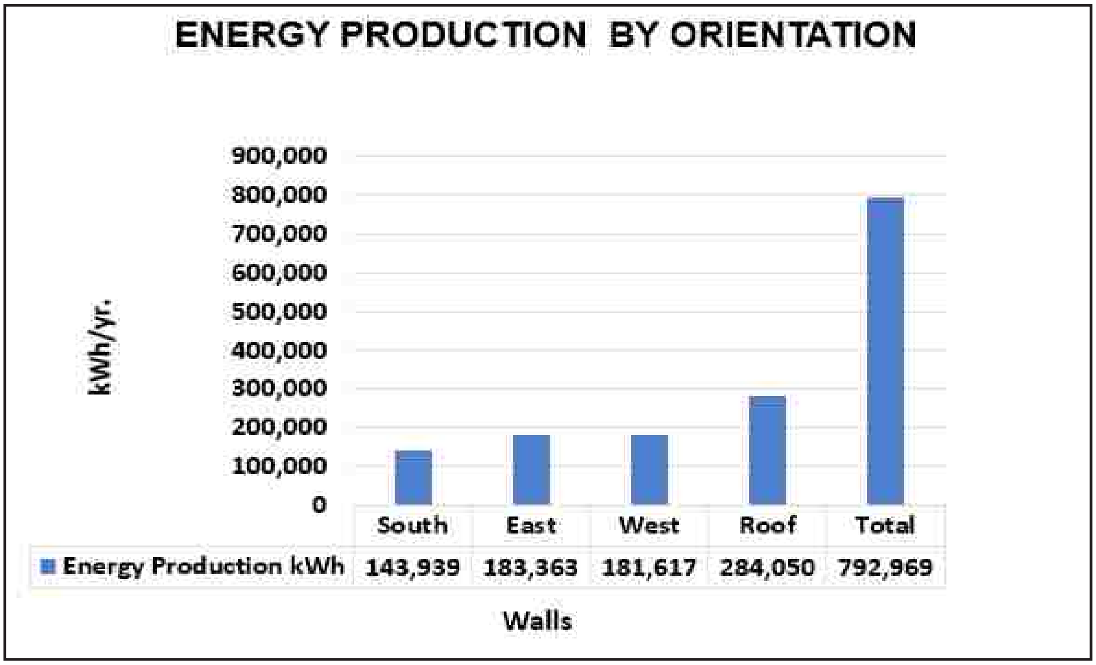


Fig.13: Energy Production of BIPV

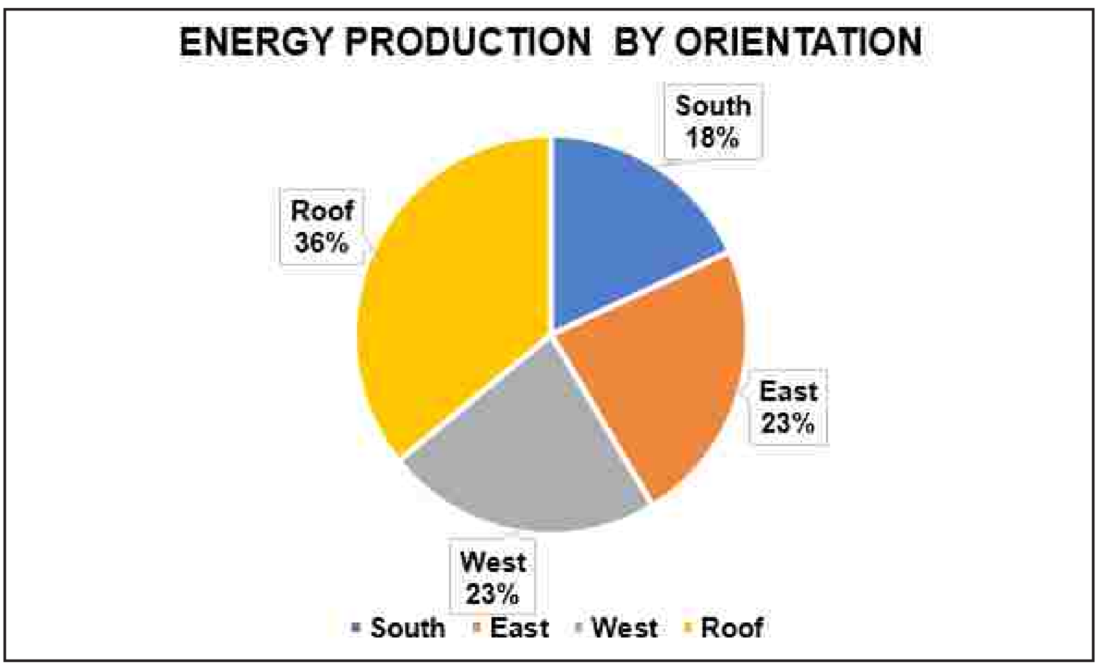


Fig.14: Percentage of Energy Production by Orientation

4.4 BASE CASE ANALYSIS | DAYLIGHT HARVESTING

Useful daylight illuminace is annual daylight illuminance simulation utilizing energy + Weather data for the entire year evaluates daylight level inside the interior space. Lighting level between 300- 3000 lux is considered appropriate for the interior space. UDI analysis identifies four indoor daylight scenarios as listed.

1- < 100 lux: Percentage of the year the light level is less than 100 lux, it means that space is insufficiently lit for work and would need additional lighting source.

2- 100- 300 lux: Percentage of the year the light level is between 100 - 300 lux, the space is under lit and would benefit from more windows or electrical lighting.

3- 300- 3000 lux: Percentage of the year the light level between 300-3000 lux, it means the space is desirable and appropriate for work.

4- > 3000 lux: Percentage of the year the light level is greater than 3000 lux, it means the space needs interior or exterior shading device.

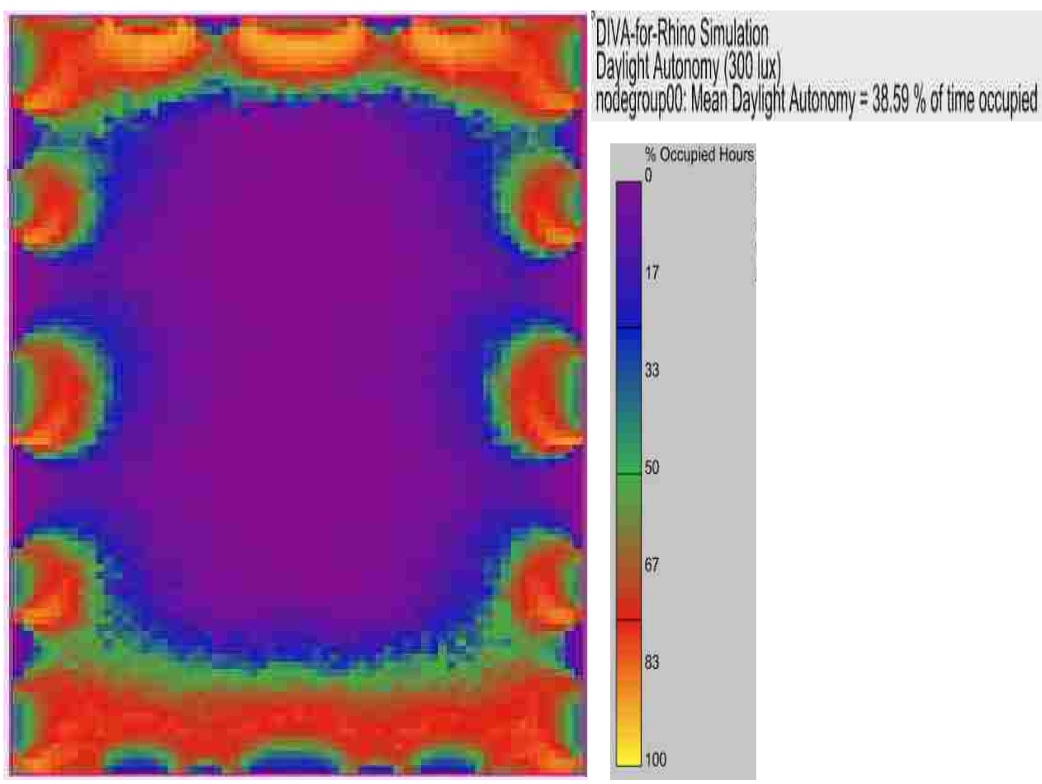


Fig.15:Base Case Floor Plan

Figure.15 shows that 38.59% of the occupied time, useful daylight illuminance is between 300-3000 lux. This is not sufficient, as ideally UDI should be in desirable range at least 75% of the occupied time. The middle of the floor is under lit because the floor plate is 108' wide and daylight could not reach the middle area. In order to optimize daylight harvesting, window to floor ratio of 1:2 is required. In the base case window height is 9 feet on both east and west side of the wall, it can only harvest 18' depth of floor area from both side. Thus, light cannot reach the middle portion of the floor. The Diva simulation shows island of dark spaces in the middle of the floor. plate.

The main goal of daylight harvesting is to have useful daylight without glare across the space, most of the year. The iteration is run on base case, data is collected to identify all the problematic areas. Those issues are then addressed in the design case.

4.5 CONCLUSION

In conclusion, for building to take full advantage of sun light that lands on it, one has to manipulate design, floor plate as well windows to wall ratio. The results of base case simulation provided understanding of the solar potential of the site and the factors that could maximize.

The understanding of the impact of envelope surface area on energy production as well as on daylight harvesting is critical for designing any high-performance building. Additionally, small floor plate depth is one of the key factors for optimization of daylight harvesting. Useful daylight illuminance simulation for annual daylight identified problematic areas in the interior spaces.

CHAPTER 5

DESIGN ANALYSIS II

5.1 DESIGN CASE OVERVIEW

The main intent of design case is to increase overall renewable energy yield and daylight harvesting from base case. Although base case analysis identified several challenges, in terms of renewable energy production, base case is performed fairly well but in terms of daylight harvesting its performance is on lower threshold.

First challenge in design case is how to increase envelope surface area from base case to optimize energy and daylight harvesting. After running couple of iteration in Archsim Grasshopper for energy production and diva radiance for daylight harvesting, several types of massing options were executed in rhino model . The biggest challenge was how to achieve UDI in the range of 300 -3000 lux in most of the interior space for more than 75% of the occupied time and keep under lit and over lit spaces in the lower threshold. In terms of renewable energy, the emphasis is on increase in roof and south wall surface area. In terms of daylight harvesting the main idea is on reduction in floor plate depth and increase surface areas for windows. However, increasing the surface area for window will reduce the surface available for renewable energy production. Maintaining balance between these two elements looks very challenging and the outcome is unpredictable.

Finally, the goal is set for design case to increase renewable energy yield and target Useful Day Illuminance, of 300 - 3000 lux for more than 75% of the occupied time.

For initial site analysis sun-path single shadow diagram and Useful daylight Illuminate iteration are recorded and studied. Comparative analysis between surface area, energy production, energy production intensity, floor plate and useful daylight illuminace were recorded and analyzed in organized way.

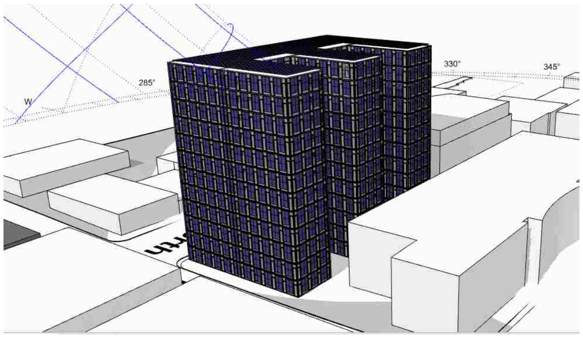


Fig.16:Shadow diagram of March 21st at Noon

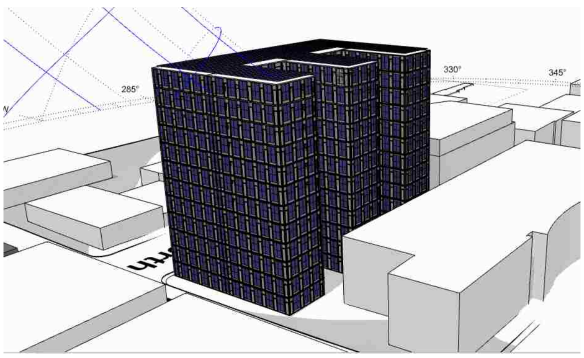


Fig.17: Shadow diagram of June 21st at Noon

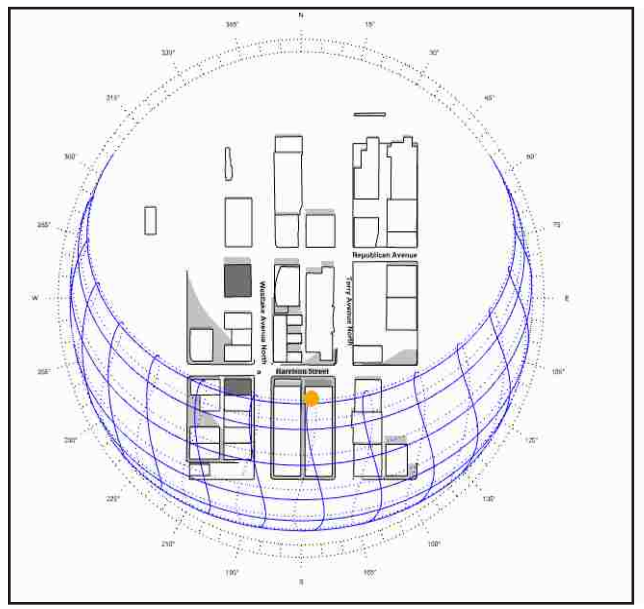


Fig.19: Plan of shadow diagram of June 21st at Noon

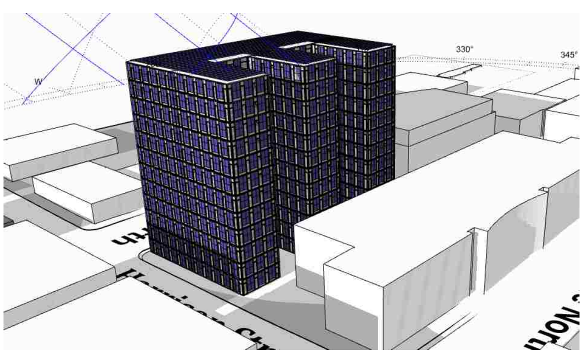


Fig.18: Shadow diagram of Dec. 21st at Noon

Single shadow diagram gives exact location of shadow on the site. It helps to maximize daylight and solar harvesting by proper placement of the windows and orientation of the building mass.

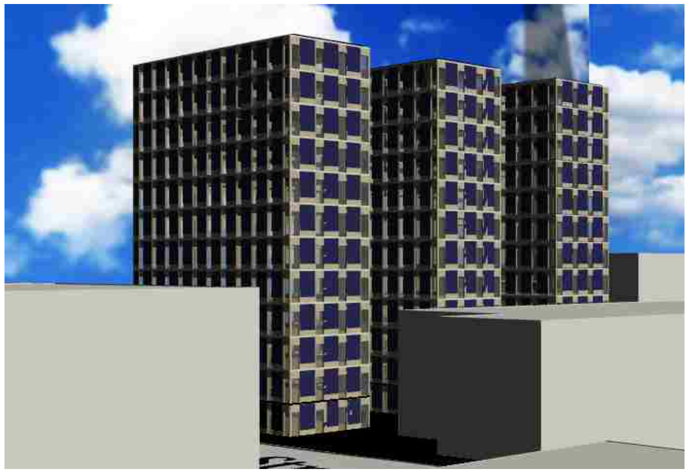


Fig.20: Perspective from east side

Fig..21: Perspective from southwest

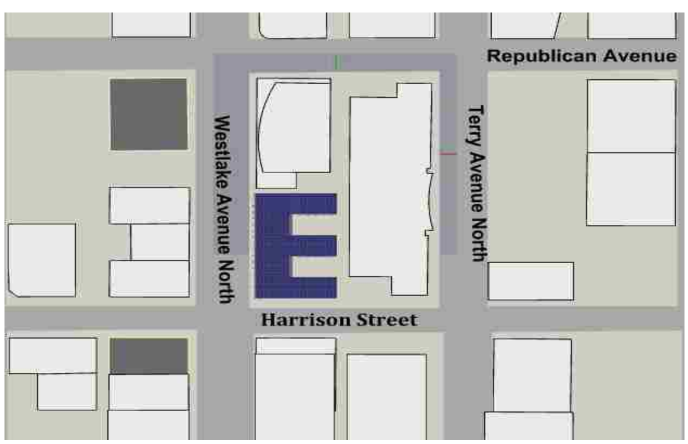


Fig.22: Site Plan

Fig.23: East Elevation with BIPV

Fig.24: West Elevation with BIPV

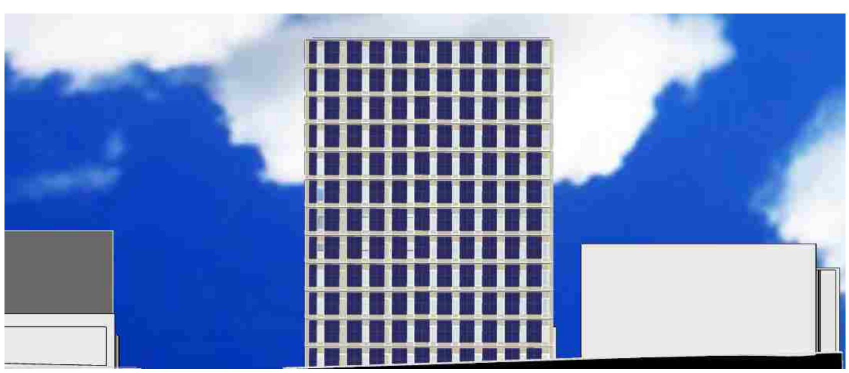


Fig.25: South Elevation with BIPV

5.2 DESIGN CASE | BIPV SURFACE AREA

ROOF Floor Area of Roof 15,030 sq.ft

97% of Roof = 14,586 sq.ft

Total number of BIPV 858

Total Energy Production = 278,850 kWh

Efficiency 22%

Kilowatt Hour Multiplied by 3.41 to obtain kBTU =

950,878 kBTU

WEST WALL

Total Wall Surface Area 25,920 sq.

Window to Wall Ratio 42% 10,800 sq.ft

Each Floor has 38 BIPV panels on wall

Total number of BIPV module 456

Total Energy Production 116,892 kWh =

398,601 kBTU

EAST WALL

Total Surface Area 25,920 sq.ft

Window to Wall Ratio 34% 8748 sq.ft.

Each Floor has 52 BIPV panels on wall

Total number of BIPV on East Wall 624

Total Energy Production 159,516 kWh=

543,949 kBTU

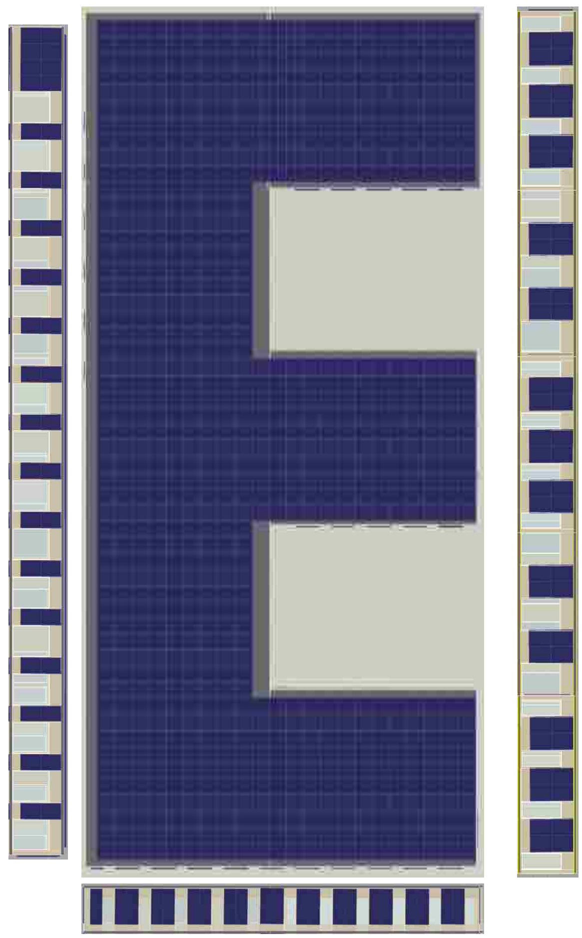


Fig.26: Design Case Plan and Elevations

SOUTH WALL

Total Surface Area 32,832 sq.ft

Window to Wall Ratio 25% 8064 sq.ft

Each Floor has 82 BIPV

Total number of BIPV on South Wall 984

Total Energy Production on South Wall 324,444 kWh

1,106,354 kBTU

5.3 ENERGY PRODUCTION

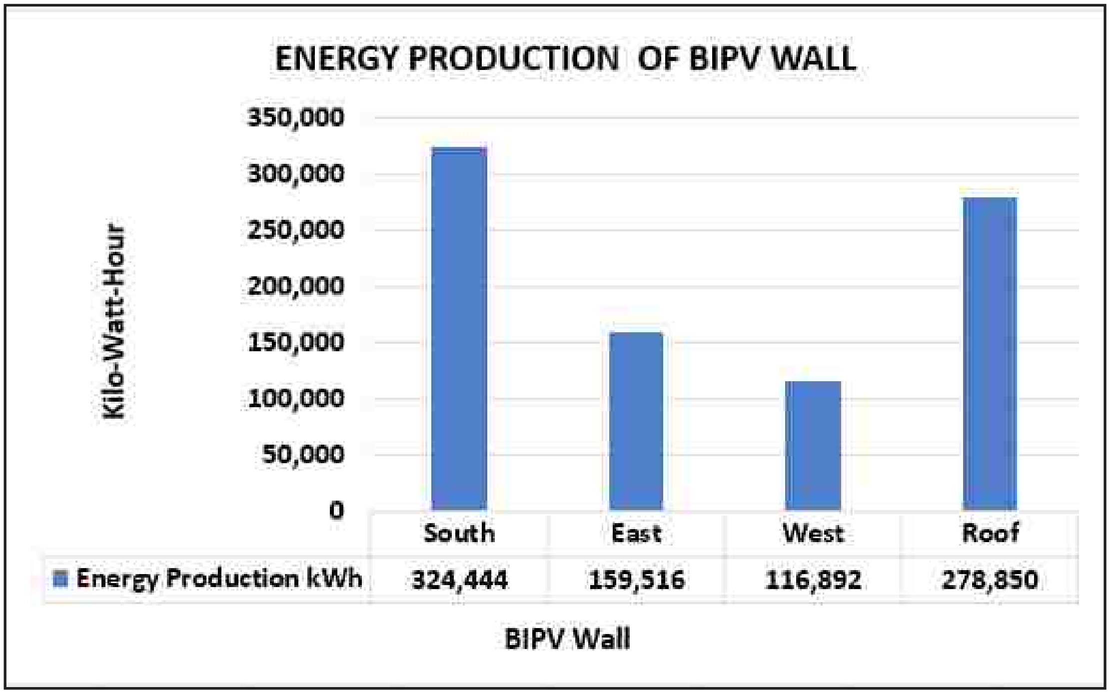


Fig.27: Energy Production of BIPV by Orientation

In design case, energy production gain comes from south wall and roof while there are some loss of energy production from east and west walls. The energy yield from south wall increased tremendously in the design case. The main factor for this gain is increase in surface area of south wall from the base case. Gain in south wall surface for BIPV comes from two factors, configuration of the building as well reduced window size. Decrease in window surface area means increased area for renewable energy production. The ratio of window to wall is reduced to 25% on south wall, 34% on east and 42% on west wall from 40% all around in base case. Additional benefit of keeping the windows on the south side small is decrease in glare and over lit areas in the interior space.

5.4 ANNUAL DAYLIGHT |USEFUL DAYLIGHT ILLUMINANCE

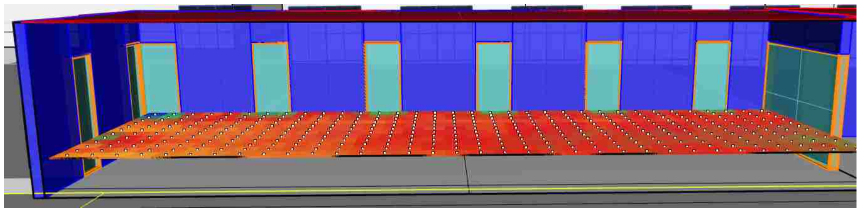


Fig.28: Interior perspective view of east wing

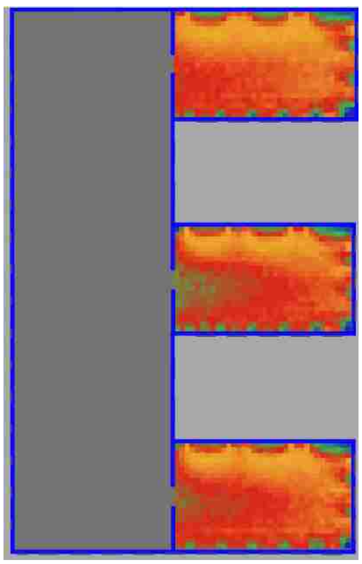


Fig.29: UDI 300 -3000 Lux

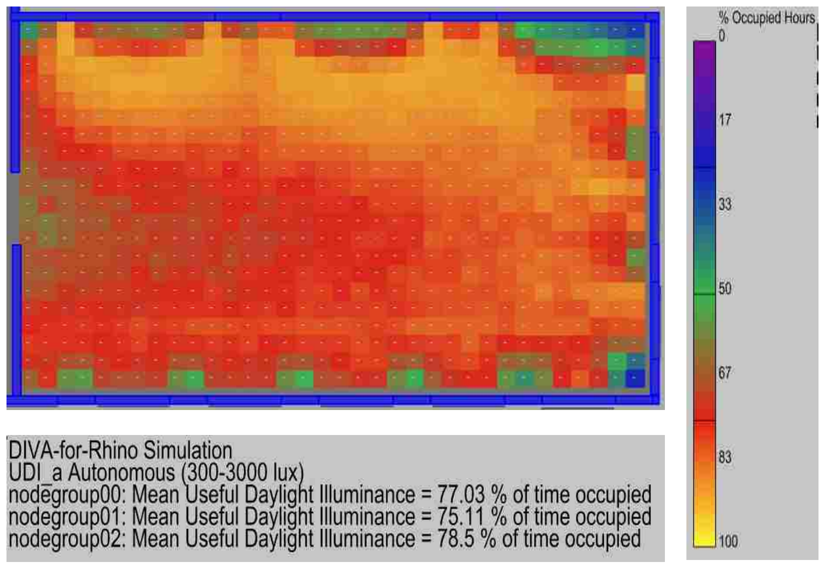


Fig.30: UDI Simulation result:

The intent of this study is to understand the effect of daylighting in the interior spaces by using annual daylight metric, useful daylight illuminance and optimization by using design solution. The impact of daylighting from east, south, and west has different effect on the interior scene. Daylight from east side has low angle and if the envelope is not equipped with the right window louver or screen wall, the interior space might get the challenge of glare in the morning. Useful Daylight Illuminance is annual daylight diva simulation using radiance that identifies over lit and under lit spaces by using weather data for the entire year. It gives flexibility to alter design in order to optimize daylight harvesting and reduce potential glare issues.

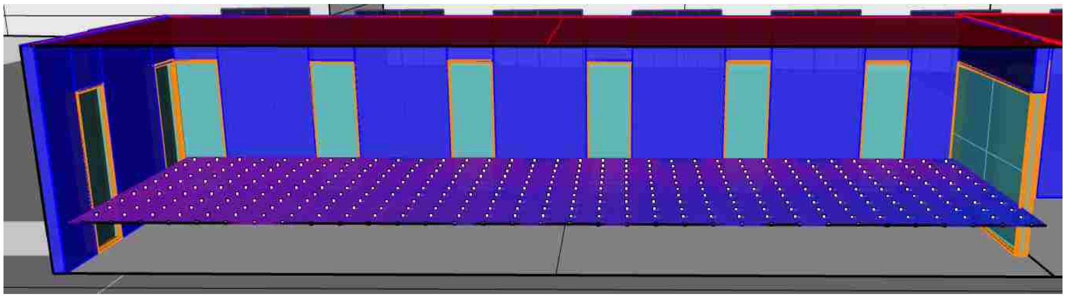


Fig.31: Perspective View of East Window UDI 100-300 Lux

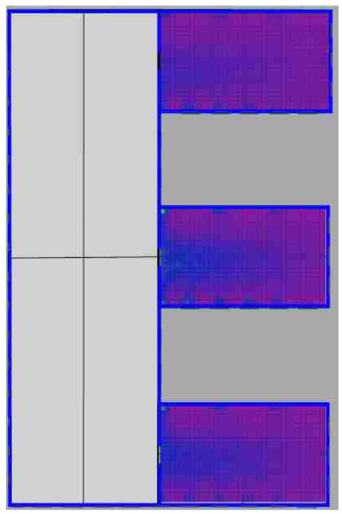


Fig.32: UDI 100-300 Lux

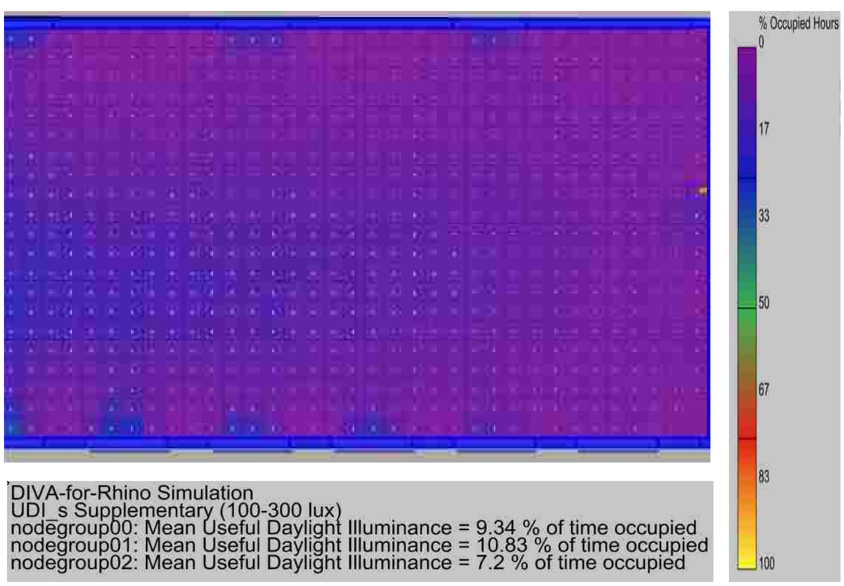


Fig.33: Plan of east wing shows UDI 100-300 Lux

The useful daylight illuminance simulation result in figure 33 shows, average 9% of the occupied time, illuminance is between 100-300 lux in the east wing, which is undesirable for the task. All these spaces need supplemental electric lighting.

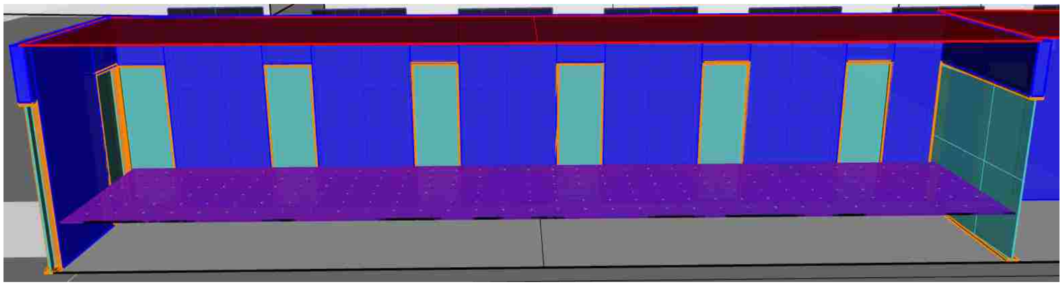


Fig.34: Interior perspective view of east wing facing south

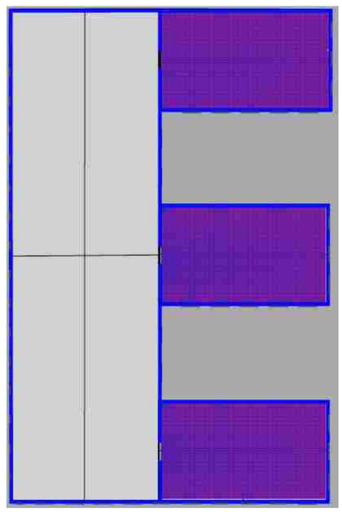


Fig. 35: UDI < 100 Lux

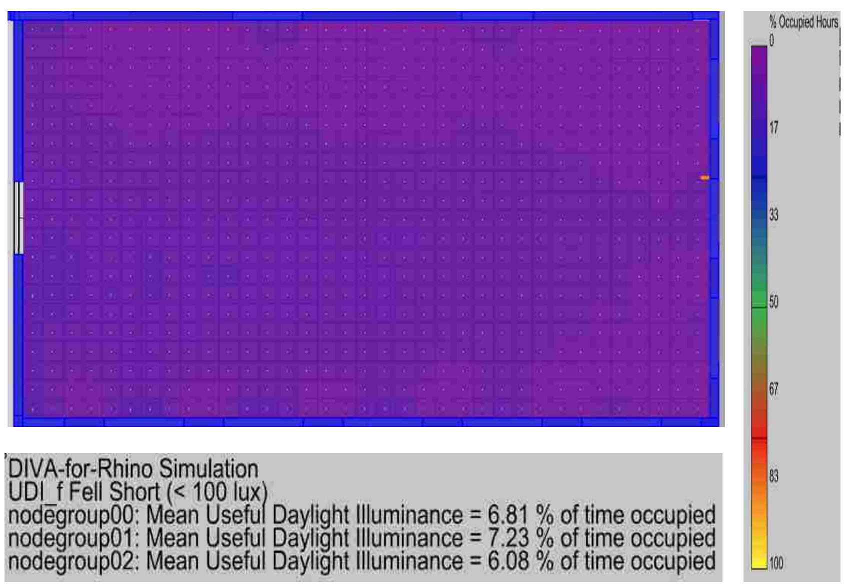


Fig. 36: Plan of east wing shows Useful Daylight Illuminace < 100 Lux

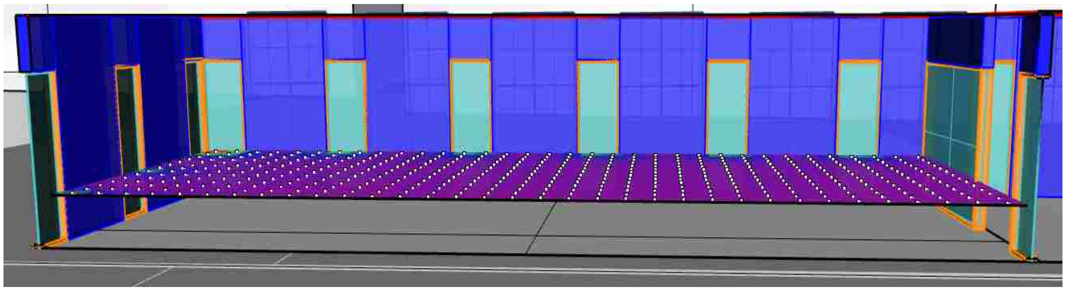


Fig.37: Perspective View of east wing facing South Window

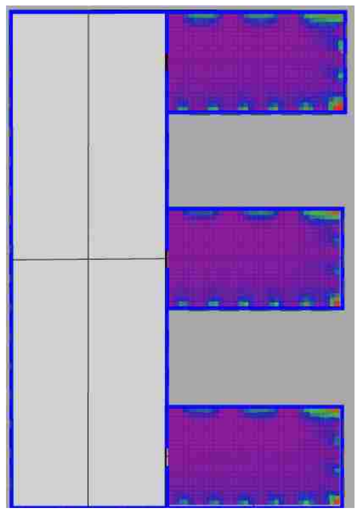


Fig. 38: UDI shows >3000 Lux

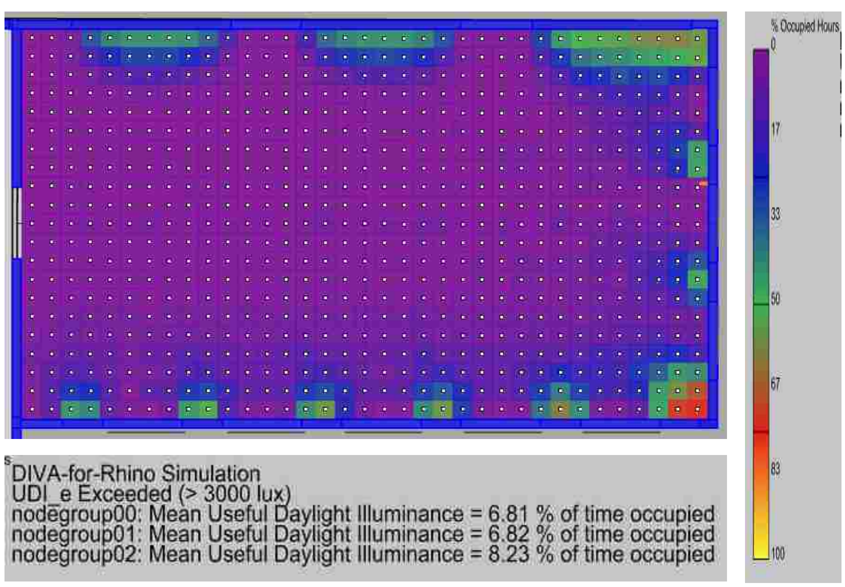


Fig.39: Useful Daylight Illuminace >3000 Lux

The useful daylight illuminance simulation result in figure 39 shows, average 6.5% of the occupied time, illuminance is above 3000 lux in the east wing, which is over lit for the task. All these spaces need manual or automated shading devices.

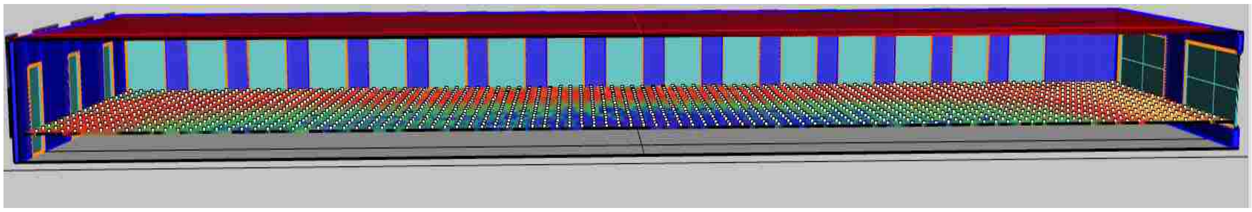


Fig.40: Interior perspective of west wing facing west

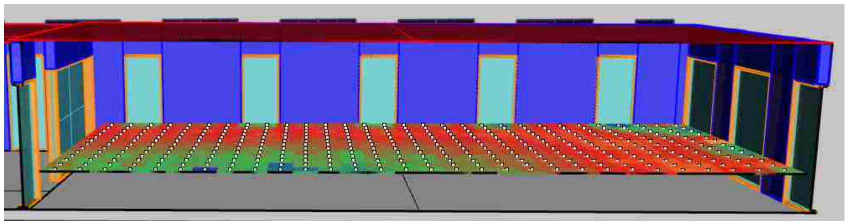


Fig.41: Interior perspective view facing south

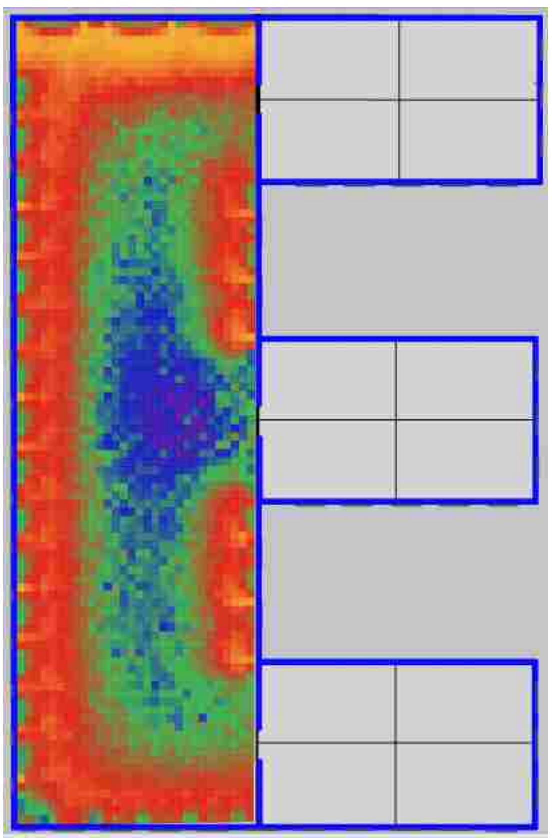


Fig.42: Plan of west wing shows UDI 300-3000

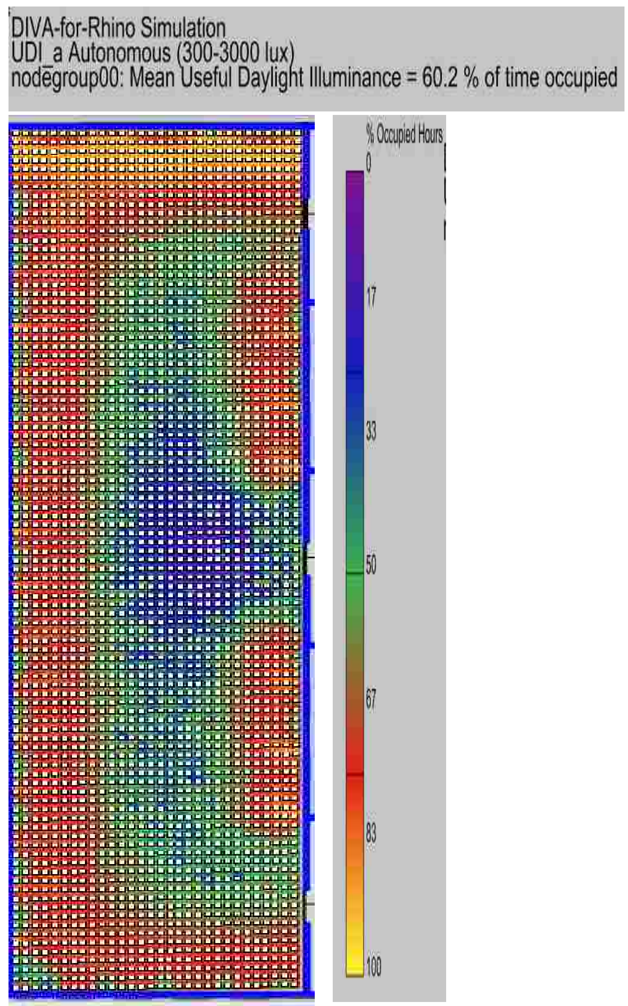


Fig.43: UDI 300 - 3000 Lux

Figure 43 shows UDI of west wing is 60.2% of occupied time with illuminance between 300-3000 lux. The under-lit space needs motion sensor light. Because of BIPV, this is the maximum amount of windows available for daylight harvesting on west side.

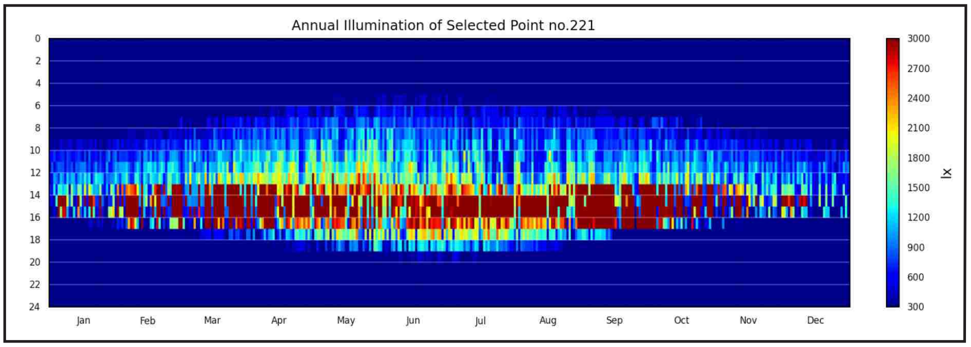


Fig.44: Annual Illuminace of Selected Point shows maximum illuminance intensity

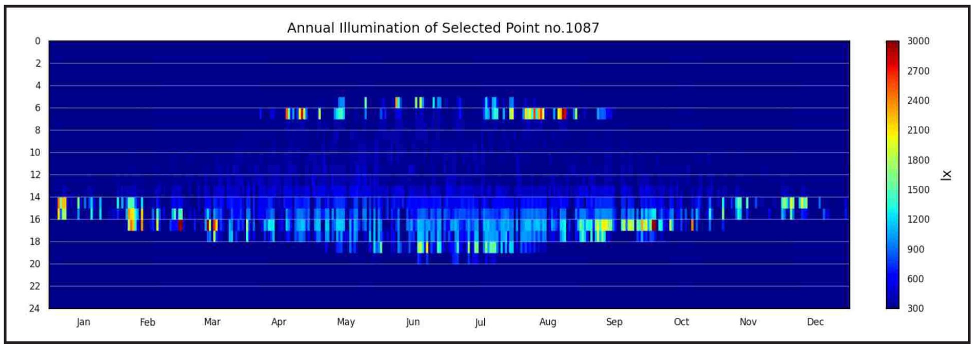


Fig.45: Annual Illuminace of Selected Point shows less illuminance intensity

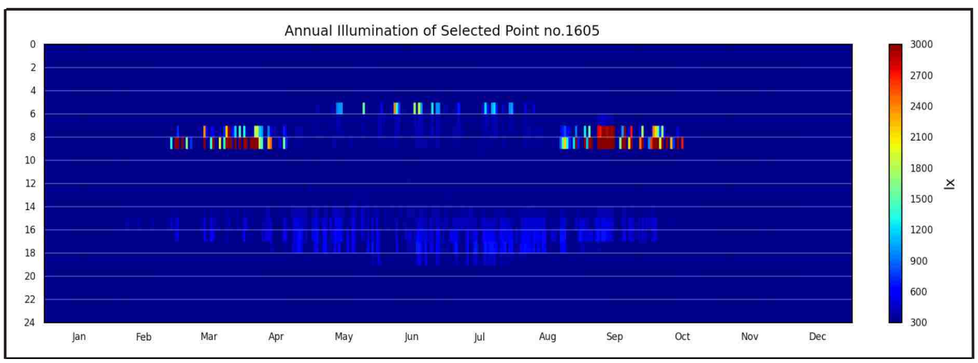


Fig.46: Annual Illuminance of Selected Point shows scattered high and low inten-

Above analysis of annual illuminance of selected point from 1:00pm - 5:00pm. The three results of annual illuminance of selected point shows three different scenarios. In fig.44, when the illuminance on that specific point is above 3000 lux is shown by red color. Figure 45 shows some of the under lit areas and figure 46 identify small scene with scattered intensity of light. During these hours from mid-August till mid-October, the automatic deployment of shading device is suggested when illuminance is above 3000 lux and electrical lighting is suggested when it is less than 300 lux.

5.5 VISUALIZATION | LUMINANCE ANALYSIS

Fig.47: Visualization, June 21st at noon, clear sky condition

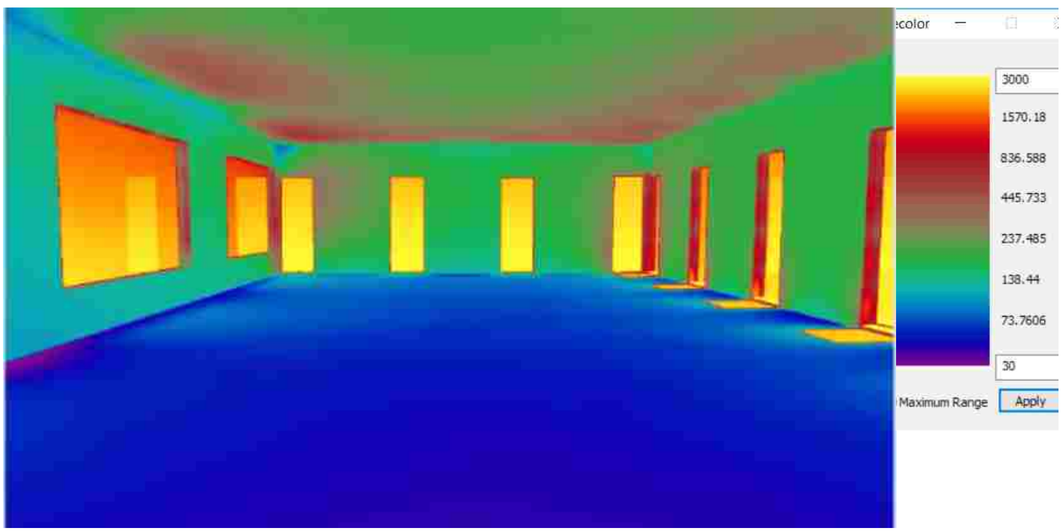


Fig.48: False color on June 21st at noon, clear sky condition

Luminance is the visualization of scene with the amount of light reflected from the material. The unit for luminance measurement is candella/meter square. False color analysis provides luminance threshold for glare inside the interior space. In fig.48, luminance analysis for June 21st at noon shows different distribution of luminance level especially on south windows. Luminance analysis for March fig. 50 and December fig. 52 show different distribution in interior space because during these month sun angle is low which will create glare and over lit areas in the interior spaces. Anything > 3000 cd/m sq. is a source of glare. South windows would need shading device for glare control.

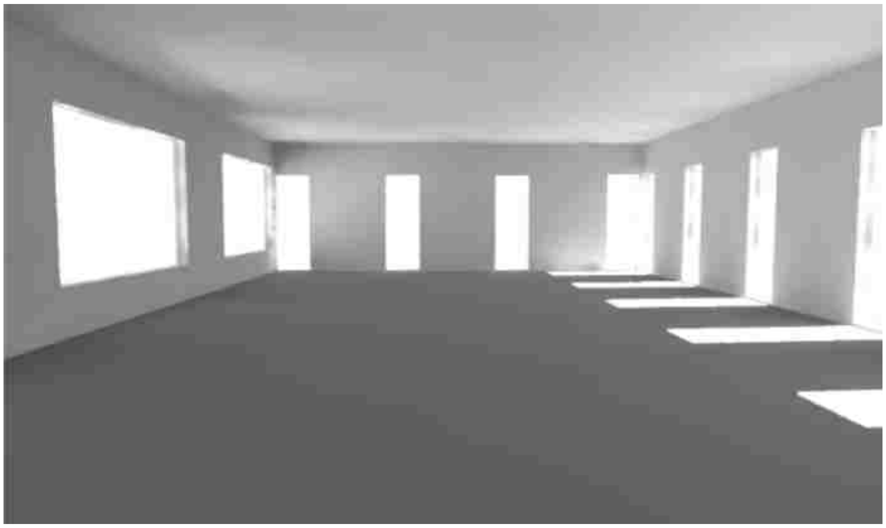


Fig.49: Visualization, March 21st at noon

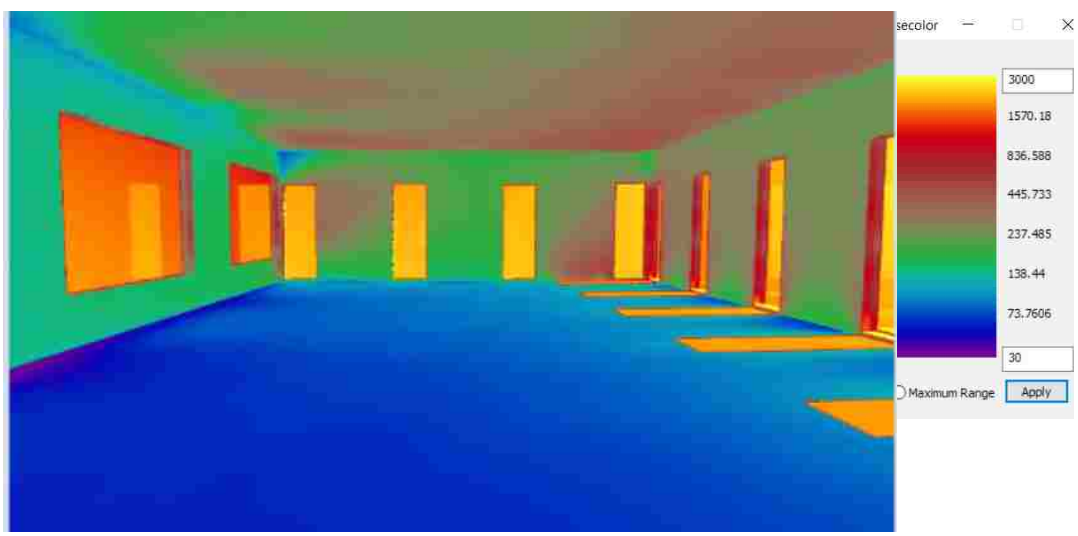


Fig.50: False color on March 21st at noon, Clear sky condition

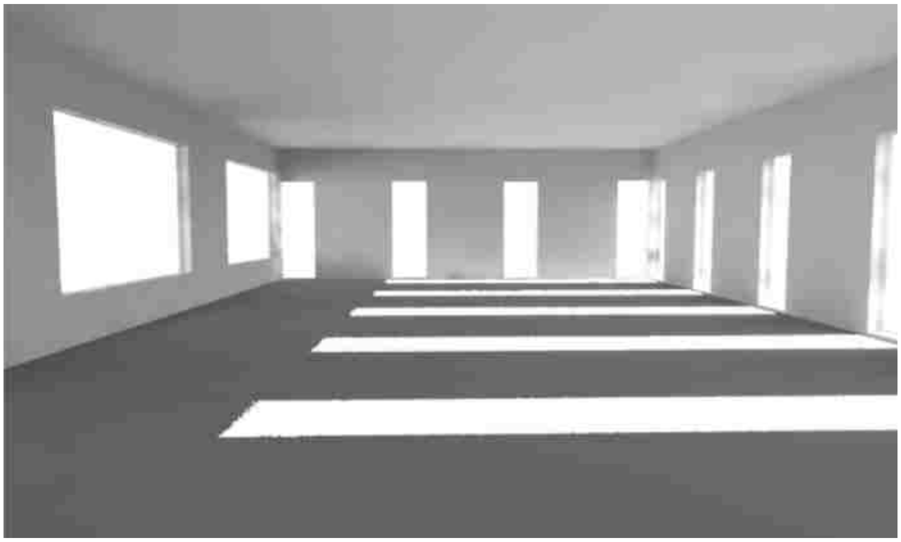


Fig.51: Visualization, December 21st at noon

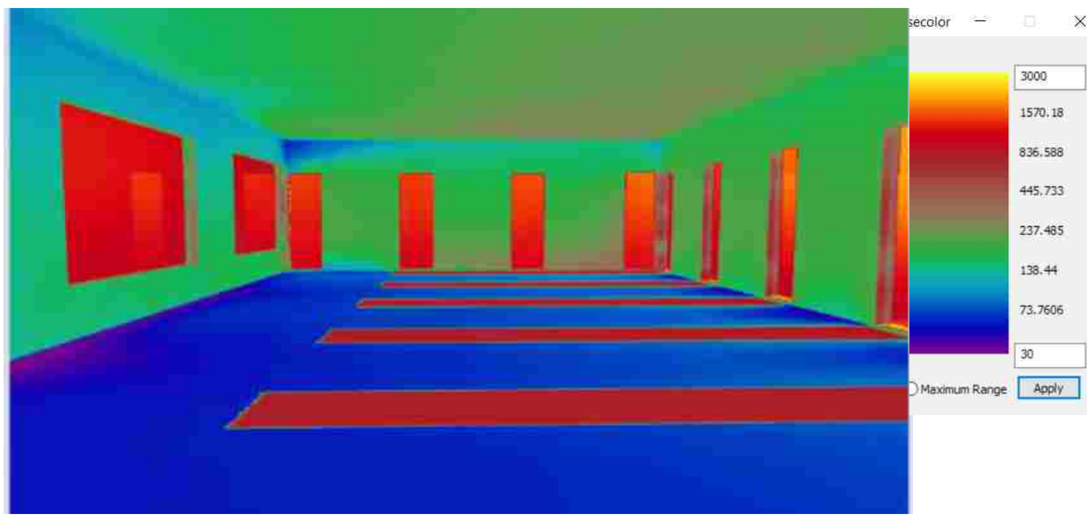


Fig.52: False color on December 21st at noon, clear sky condition

In design case the size of the south windows have been reduced to control glare and heat gain. All those window needs automated shading device during certain time of the year when the sun angle is low. The size of north windows with larger surface area will provide more diffuse daylight in the interior space. There is no need for shading device on the north windows. Anything under 30 cd/m sq. is considered dark. The threshold for glare control is 2000 cd/m sq. for space with side windows only and 3000 cd/m sq. for space with windows in multiple directions.

5.6 COMPARATIVE ANALYSIS |WALL AND WINDOW SURFACE AREA

The intent of this section is to analyze and compare base case with design case. The outcome is thoroughly analyzed by using different charts. The challenges encountered in the base case are then resolved by running iteration with goal of achieving high performance building in design case.

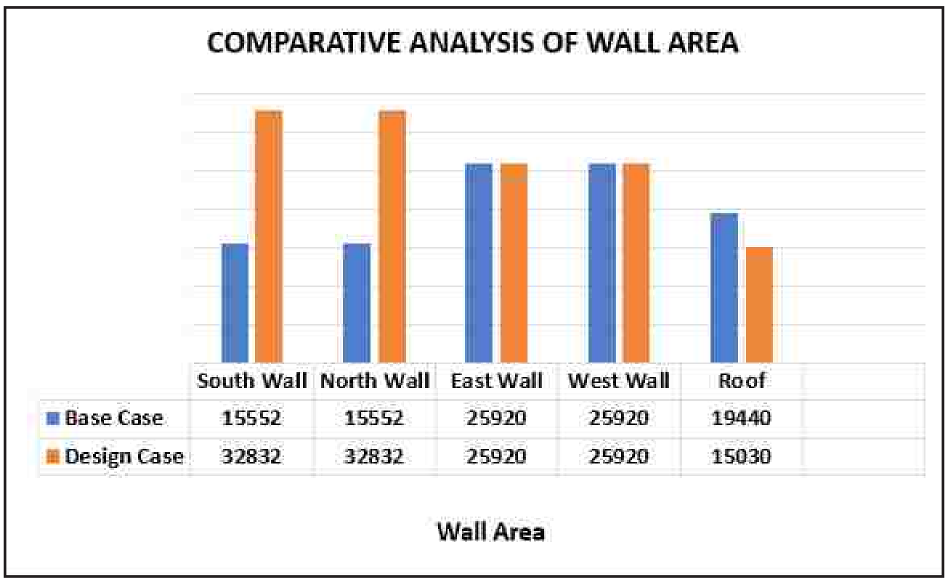


Fig.53: Comparative Analysis of wall surface area

The comparative analysis of wall and window surface area shows a gain of 100% in envelope surface area on the north and south walls from base to design case. East and west side of the envelope surface area didn't change from base case. In the design case there is a loss of 22% roof surface area because of reduction in floor plate. Eighty percent of the roof surface in base case is covered with BIPV and in design case, almost the entire roof surface is covered by BIPV to make up for the loss of surface area.

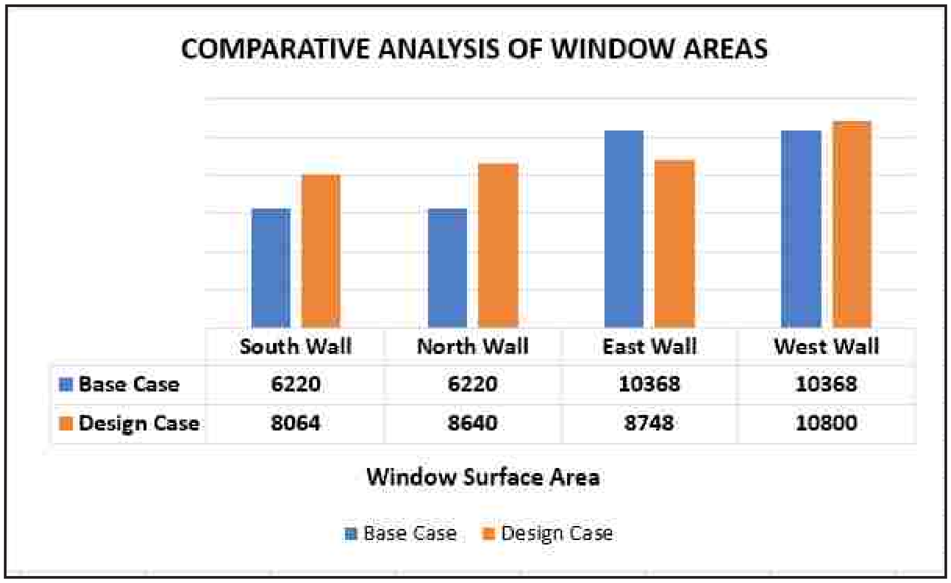


Fig.54, Comparative Analysis of windows areas

The comparative analysis of window areas between base and design case shows increment of window surface area on the north and south envelope. In design case, the south envelope surface area doubled , although window size is smaller there is a net gain in window surface area. The light from north is more diffuse and increase in window surface area on north provides opportunity for maximum diffuse daylight harvesting. In order to encourage maximum diffuse light inside the interior space, the windows on north side are kept large. Although east and west side are same in both cases because of the glare and over lit potential, the windows are kept smaller in size.

5.7 COMPARATIVE ANALYSIS | ENERGY PRODUCTION

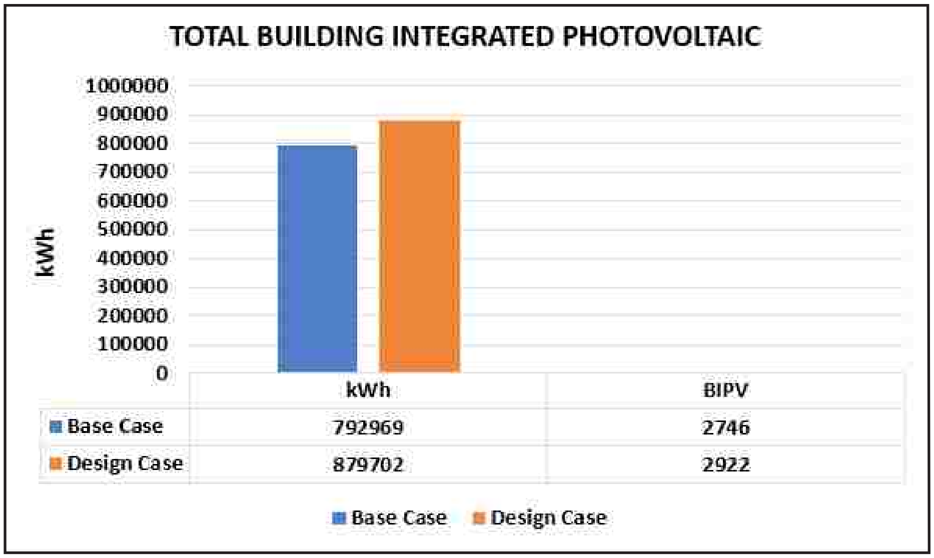


Fig.55: Comparative Analysis of energy production and number of BIPV

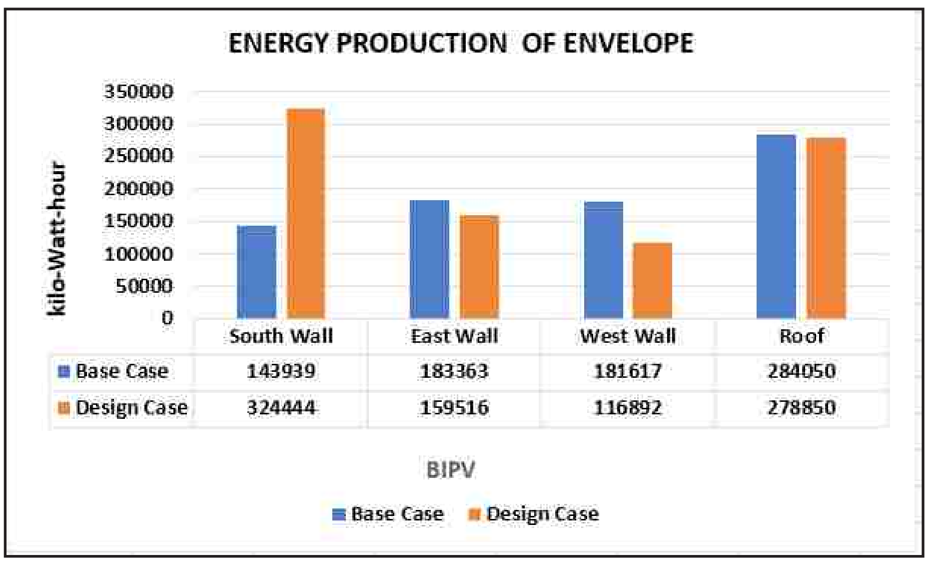


Fig.56:Comparative Analysis of energy production of wall surface

In the comparative analysis of energy production between base and design case, the number of BIPV used in design case is higher than the base case. The gain in energy yield from south wall in design case is the main contributing factor for the increment in overall energy production. Although the overall energy gain is only about 11%, additional efficiency is gained through daylight harvesting. Further is to be noted that design case floor plate is smaller than the base case and its' energy need should be lower.

5.8 COMPARATIVE ANALYSIS DAYLIGHT HARVESTING | UDI

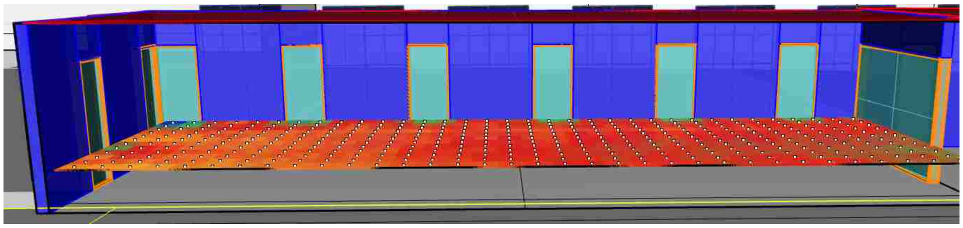
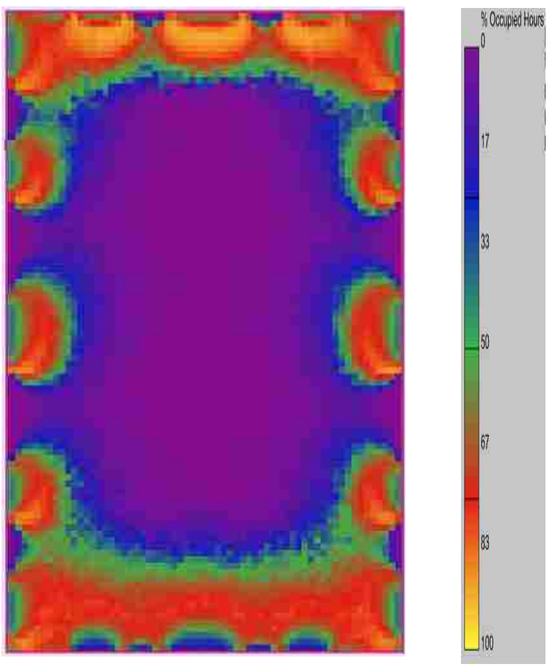


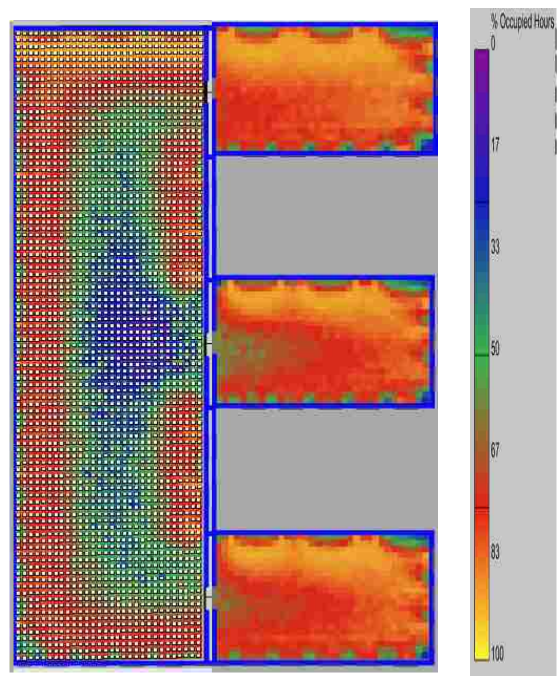
Fig.57: Perspective View facing South shows UDI in Design Case



DIVA-for-Rhino Simulation
Daylight Autonomy (300 lux)
nodegroup00: Mean Daylight Autonomy = 38.59 % of time occupied

Fig.58: Base Case

DIVA-for-Rhino Simulation
UDI_a Autonomous (300-3000 lux)
nodegroup00: Mean Useful Daylight Illuminance = 77.03 % of time occupied
nodegroup01: Mean Useful Daylight Illuminance = 75.11 % of time occupied
nodegroup02: Mean Useful Daylight Illuminance = 78.5 % of time occupied



DIVA-for-Rhino Simulation
UDI_a Autonomous (300-3000 lux)
nodegroup00: Mean Useful Daylight Illuminance = 60.2 % of time occupied

Fig.59:Design Case

Finally in comparative analysis of daylight harvesting between base and design case, there appears to be significant difference in UDI. The UDI in base case is 38.59% of the occupied time when illuminance reaches 300 lux whereas in design case it is 78% on east wing and 60% on west wing the illuminance is between 300-3000 lux. The major factors that made the difference is the width of the floor plate and window size.

5.9 DESIGN CASE CONCLUSION

The base case identified all the challenging elements that has impact on the interior and exterior spaces in terms of renewable energy production and daylight harvesting. The design case attempt to resolve these challenges. The main difference between base case and design case is, that the design case optimized renewable energy production and daylight harvesting. Three major factors involved in the optimization process are listed below:

1. Increase in envelope surface
2. Decrease in floor plate depth
3. Increase in north wall surface area with improved diffuse daylighting

In design case the increment of envelope surface area provides space for more BIPV and increased renewable energy production. Gain in envelope surface area being on south is ideal for renewable energy yield. One of the biggest achievement of design case is optimization of daylight harvesting. This is achieved by reducing the depth of floor plate and modifying window to wall ratio. The envelope of the design case doubled with all gain from north and south side of the building. The gain in surface area on the north side is extremely important as it provided space for large windows aiding entrance of more diffuse daylight inside the interior spaces.

Finally, this thesis suggests additional ways to maximize the potential of high performance building in terms of renewable energy production and daylight harvesting.

CHAPTER 6

CONCLUSION AND FUTURE FRAMEWORK

The intent of this thesis is to find ways to optimize building envelope both in terms of renewable energy and daylight harvesting. The entire thesis project is comprised of two sections. First part is study of base case, that includes preliminary design investigation and identifying the challenges. Second part deals with design case, in which the unresolved challenges and issues of the base case are solved to achieve maximum optimization. This whole thesis is about performative design using different parametric tools for renewable energy and daylight harvesting. The energy and daylight simulation is used on multiple designs to achieve the target goal set after the analysis of base case.

However, one of the most challenging task in this thesis is to keep balance between both renewable energy and daylight harvesting. Assigning of surface area on the envelope and keeping a balance between renewable energy and daylight harvesting is key factor. In conducting base case research the outcome for renewable energy was not optimal but acceptable. On the other hand, daylight harvesting simulations results of the base case was in the lower threshold. This whole project would have not been possible without parametric tools. Multiple iterations were run on several rhino models. As previously mentioned the entire thesis project is performative design base and used different simulations including solar analysis, daylight analysis using Diva Radiance and renewable energy Grasshopper Archsim Energy+.

Designing of energy efficient building has become quite complex and requires analysis of climatic and solar condition. In conducting research for this project, it became clear that these parametric tools are critical for optimization of daylight harvesting and renewable energy production. Analytic methods and parametric tools have become essential for evaluation of energy performance and daylight harvesting of building. The parametric tool takes account of whole year weather condition for daylight harvesting and shadow analysis. In future consolidated parametric tools for both energy performance and daylight harvesting can help and identify the design challenges of maintaining balance between these two elements. Additionally, incorporating thermal analysis in these tools would further improve ability to design building with high energy efficiency that includes all aspect.

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