



ANALYSIS OF DAYLIGHTING PERFORMANCE AND ENERGY SAVINGS IN ROOF DAYLIGHTING SYSTEMS

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Contents

1. Introduction

Analysis of Daylighting Performance and Energy Savings in Roof Daylighting Systems

- Toplighting has great potentials
  - Reduce 90% of electric lighting use in DL hours
  - Could be installed on 50% area of non-residential buildings (DOE/EIA 1983)
- Roofing systems has potentials for research
  - Architectural realities are ignored in simulation research





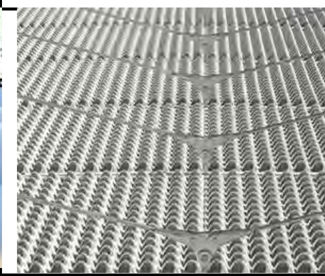
North Carolina Art Museum, Raleigh, NC (2010)
Architect: Thomas Phifer and Partners (local architect: Pearce Brinkley Cease + Lee)
Daylighting system: 362 Horizontal apertures, called "elliptical oculi", which are located in long, parallel, coffered vaults
Daylighting Control System: Curved panels with blades on top of the roof
Climate: Mixed hot and cold

The Rensnick Pavilion (LACMA Expansion), California (2006-2010)
Architect: Renzo Piano
Daylighting system: glazed sawtooth roof facing north and a horizontal layer of translucent glass underneath
Daylighting Control System: large overhangs on the tilted edges of the sawtooth roof
Climate: Moderate marine climate

Expansion of the High Museum of Art, Atlanta, Georgia (1999-2005)
Architect: Renzo Piano
Daylighting system: numerous light scoops creating clear glass shadowed by lipstick shades facing north.
Daylighting Control System: Fiberglass-reinforced molded gypsum shades
Climate: Warm and humid

The Menil Collection, Houston, Texas (1982-1987)
Architect: Renzo Piano
Daylighting system: Multilayer roof composed of exterior tilted glazing connected two by two and giant louvers.
Daylighting Control System: Exterior curved louvers; called "leaves", control daylight from the roof. In the galleries, the curve of the "leaf" blocks direct sunlight and scatters the light reflected off the neighboring leaf.
Climate: Hot and Humid climate

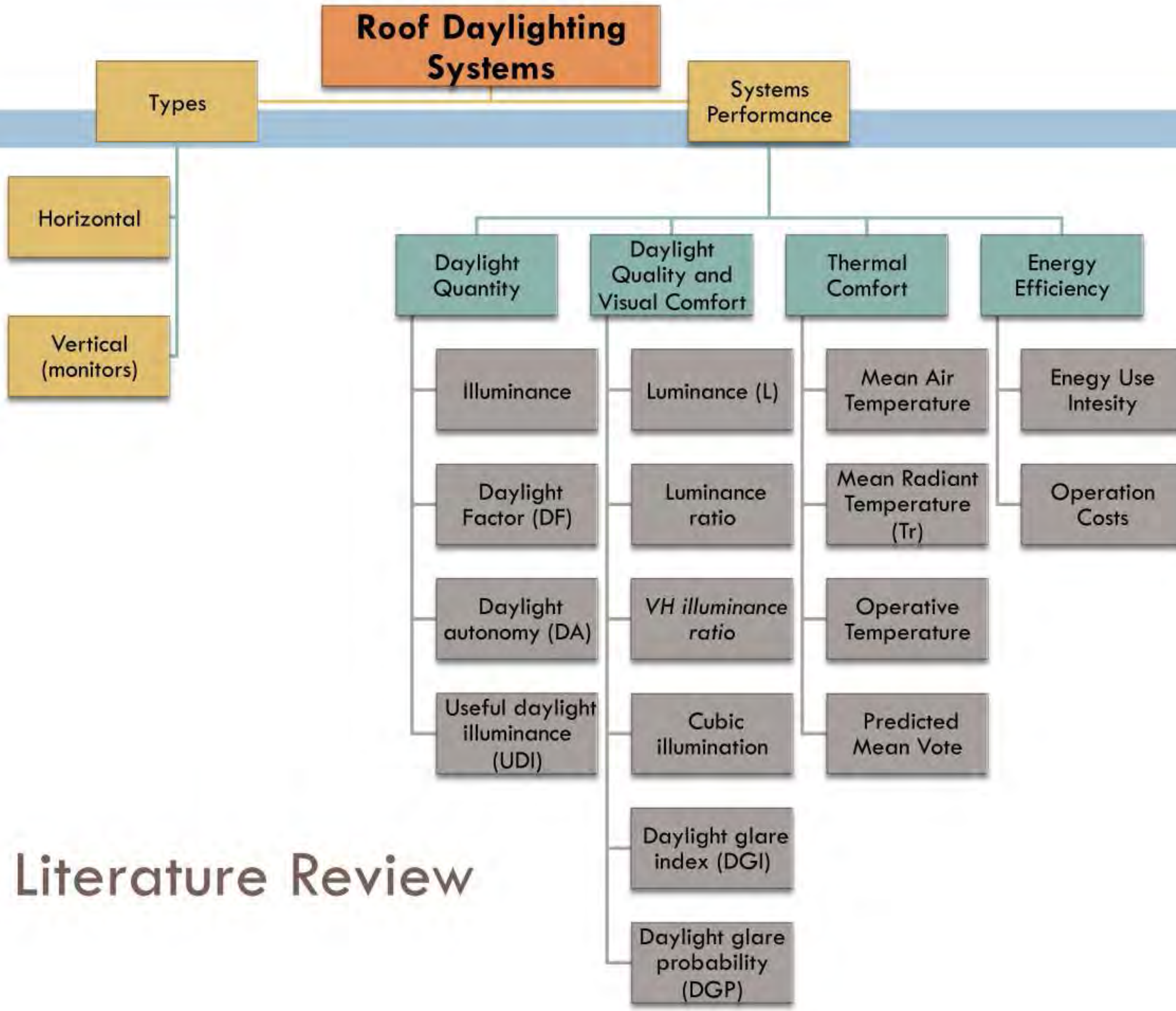
Beyeler Foundation Museum, Riehen, Switzerland (1992-1997)
Architect: Renzo Piano
Daylighting system: Sawtooth louvers facing north built on top of horizontal structural layer of glass
Daylighting Control System: exterior tilted louvers made of translucent laminated glazing material and interior horizontal louvers made of metal mesh frames
Climate: Temperate



Nasher Sculpture Center, Dallas, Texas (1999-2003)
Architect: Renzo Piano
Daylighting system: double-layer roof composed of slightly curved glass vaults with aluminum sunshade panels on top.
Daylighting Control System: cast aluminum sun-shading panels with round holes facing towards north
Climate: Warm and humid climate

		
Harmony Library, Fort Collins, Colorado (1998) *Architect*: David partnership P.C., Architects *Daylighting system*: linear clerestory windows facing north and south *Daylighting Control System*: overhangs on south side *Climate*: Cool and dry (Semi-arid climate)	**Mt. Airy Public Library, Mount Airy, North Carolina** (1984) *Architect*: Edward Mazria *Daylighting system*: sawtooth roof facing south *Daylighting Control System*: vertical baffles *Climate*: mix hot and cold *Average daily sunshine duration*: 7.3 hours *Notes*: Due to evident care in calculation of sunshading at south facing windows and clerestories, there is no observable bright sun or contrast in the reading room. Field tests and occupant surveys confirmed that the daylighting is very well designed	**The Academic Bookshop, Helsinki, Finland** (1969) *Architect*: Alvar Aalto *Daylighting system*: prism-shaped skylights *Daylighting Control System*: Interior pyramidal diffusers *Climate*: Cold semi continental climate
		
The Viipuri Library, Vyborg, Russia (1935) *Architect*: Alvar Aalto *Daylighting system*: conical funnel-like horizontal apertures *Daylighting Control System*: diffuse glazing *Climate*: Cold semi continental climate	**Smith Middle School, Chapel Hill, North Carolina** (2001) *Architect*: Corley Redfoot Zack, Inc. (Daylighting design: Innovative Design) *Daylighting system*: Sawtooth roofs *Daylighting Control System*: translucent fabric baffles *Climate*: Mixed hot and cold	**McPherson Middle School, Clyde, Ohio** (2010?) *Architect/engineer*: FHAI Designer: John McCreery *Daylighting system*: Sawtooth roof *Daylighting Control System*: fabric baffles *Climate*: Cool and humid

		
Arup Campus Office, Solihull, England *Architect:* Arup Associates *Daylighting system:* lighting units designed to capture diffuse north light through an opening towards north and to control south direct light via louvers designed for the units' south surface.	**Heelis Office Building, Swindon, England** (2007) *Architect*: Feilden Clegg Bradley with Max Fordham as M&E consultant *Daylighting system*: A line of north-facing apertures on a side of a gable roof *Daylighting Control System*: none, diffuse light enters the space, ventilation ducts and PV panels cast shadow on some times in a year *Climate*: Mild and humid Notes: Mounting PV panels on the south-facing side and windows on the north-facing side of the roof provides high level of energy efficiency in this building.	**IDeAs office Building, Santa Clara, California** (2007) *Architect*: EHDD Architecture *Daylighting system*: Skylights (tilted by low angles) *Daylighting Control System*: Diffuse glazing material of skylights *Climate*: Moderate marine climate Notes: In a remodeling project, daylighting was added to the building, which was built in1960s. Photovoltaic cells mounted on the roof eliminate provides the remaining power for the building.
		
Gothenburg Law Court Extension, Gothenburg, Sweden (1937) *Architect*: Gunnar Aspuland *Daylighting system*: one large linear sawtooth aperture facing south for brightening the central Great Hall *Daylighting Control System*: *Climate*: Mild climate *Note*: large south facing windows and clerestories could lead to savings in heating energy if night insulation was employed. In addition, no automatic lighting controls exist to respond to natural light. Therefore, this building fails to save energy through its daylighting strategy.	**Spectrum 7 Building, Milton Keynes, Englalnd** *Architect:* ECD partnership, Engineer: Arup *Daylighting system*: 60 degrees tilted apertures in a saw-tooth roofs *Daylighting Control System*: Reflective horizontal surface underneath the aperture.	**Metropoli Fundation Building, Madrid, Spain** *Architect:* Angel de Diego Rica *Daylighting system*: Roof monitors



2. Literature Review

3. Research Design

Research Questions

Independent Variables

Dependent Variables

Research Questions

1. How can each roof daylighting system be optimized to reach the best results in terms of daylighting without creating visual discomfort?

2. How can each roof daylighting system be optimized in terms of energy consumption?

3. What are the potential savings in building operating energy and operating cost that can be achieved by implementing different designs for roof daylighting systems?

Independent Variables

- **Toplighting Configurations and Design**
  - Horizontal Apertures in Flat Roof (Square and Linear Skylights)
  - Vertical Roof Apertures Facing Two Opposite Directions (Roof Monitors)

- **Buildings Location**
  - Boston
  - Miami

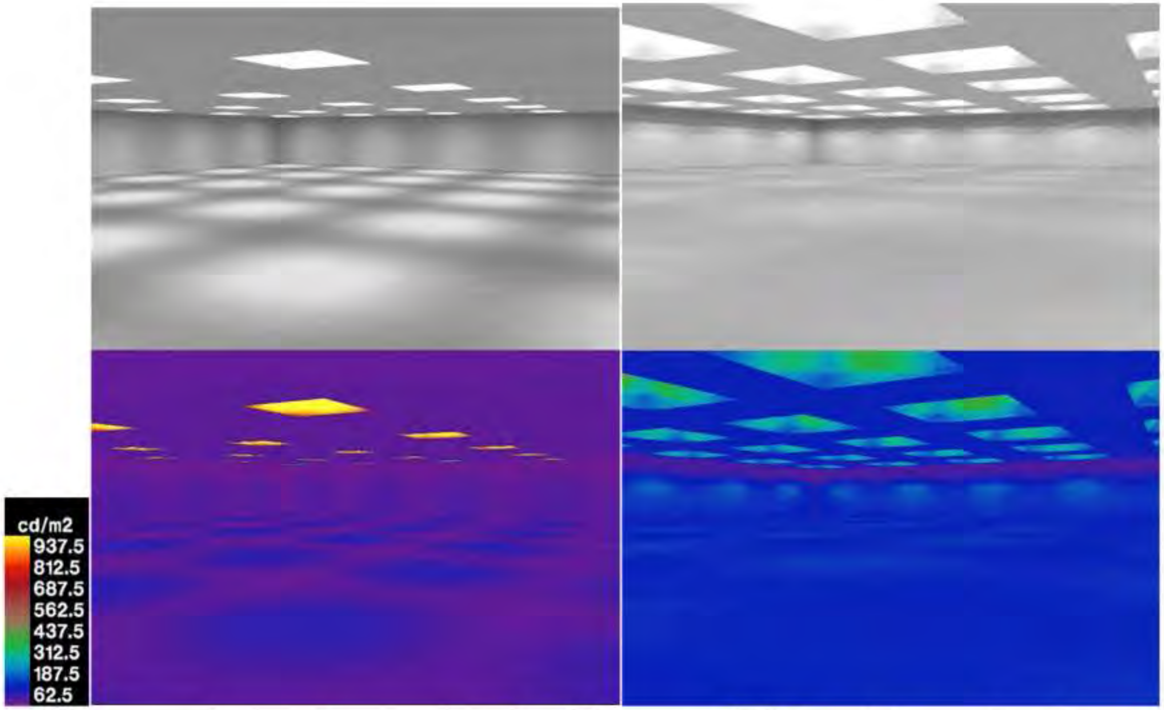
- The **A**perture to **F**loor Area **R**atio (AFR)
  - Skylights: 2% , 3.5%, 5.5%, 7.5%, 10%
  - Roof Monitors: 15%, 20%, 25%

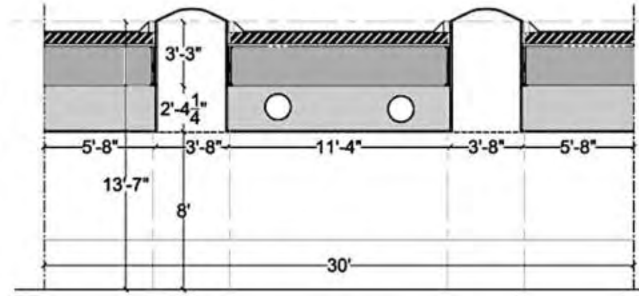
Dependent Variables

- **Lighting Assessment**
  - Quantity of Available Daylight (illuminance)
    - Single-time Spatial Distribution
    - Annual Daylight
  - Monthly Electric Lighting Consumption (kWh)
  - Daylight Glare Probability (DGP)
- **Whole- building Energy Assessment**
  - Monthly Heating and Cooling Energy Consumption (kBtu)
  - EUI (Energy Use Intensity) (kBtu/sqft/yr)
- **Total Operation Costs**
  - Annual Costs ($/yr)
  - Savings ($/yr)

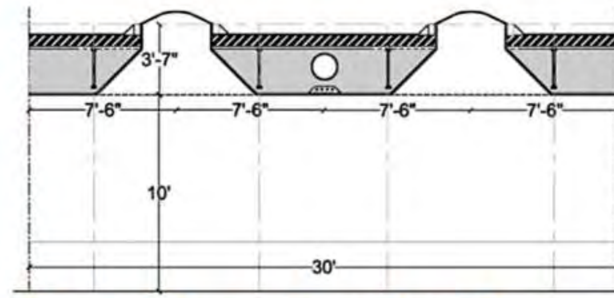
4. Methodology

Skylights

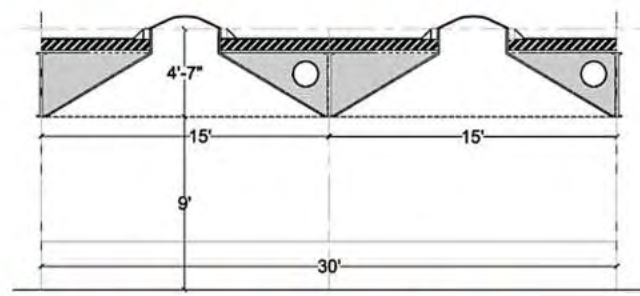




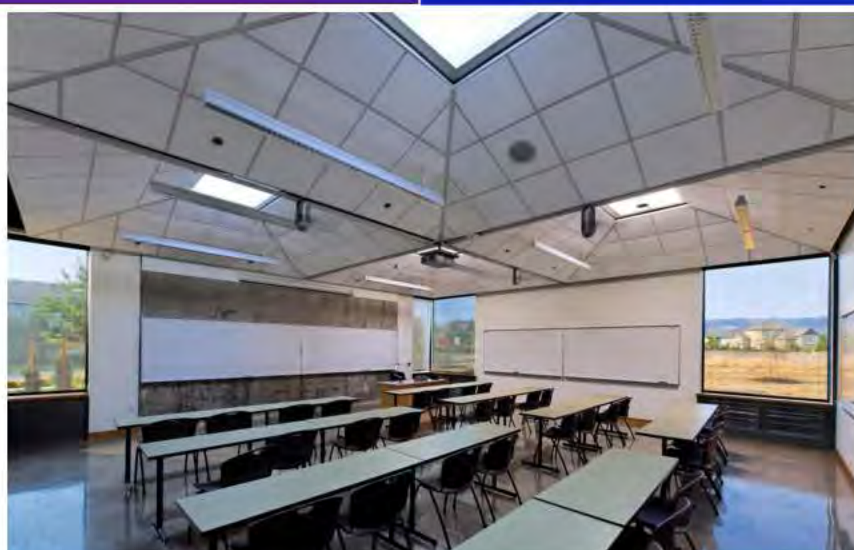
1. Un-integrated Systems, Square Light Well



2. Integrated Systems, Beveled Light Well



3. Integrated Systems, Extended Splayed Light Well



Skylights' Properties

Skylights: Two Lexan plastic sheets

- Thermal Properties
  - U-value: Clear Part: 2.59 $W/m^2 K$
    (Skylight Assembly's U-value is changing)
    Opaque Part: 0.187 $W/m^2 K$ (R-30)
- Visual Properties
  - Skylight Vt= 42%

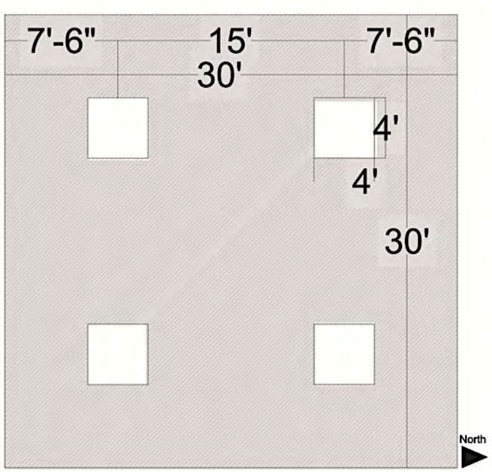
Skylights Glazing Area

Aperture Area to **F**loor Area **R**atio (AFR)

	Floor Area Illuminated		AFR	Number of Apertures	Clear Glazing Length		Clear Glazing Width	
Units	ft^2	m^2	%		ft	m	ft	m
Square Apertures	900	83.6	2	4	2.08	0.63	2.08	0.63
			3.5		2.83	0.86	2.83	0.86
			5.5		3.50	1.07	3.50	1.07
Linear Apertures			5.5	2	30	9.14	0.83	0.25
			7.5		30	9.14	1.13	0.34
			10		30	9.14	1.50	0.46

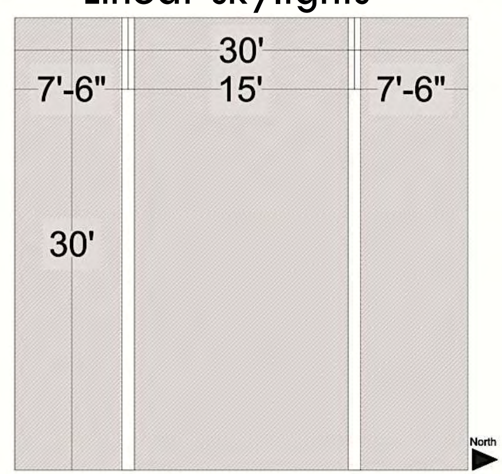
Square skylights

2%
3.5%
5.5%



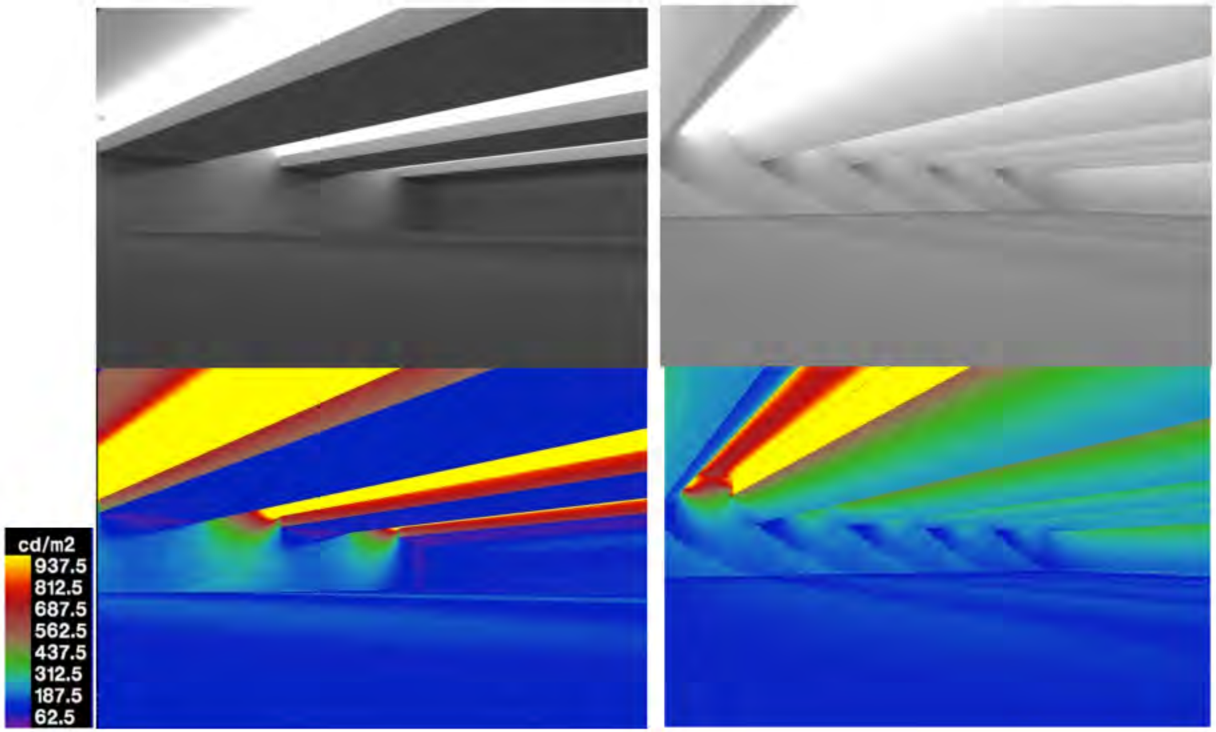
Linear skylights

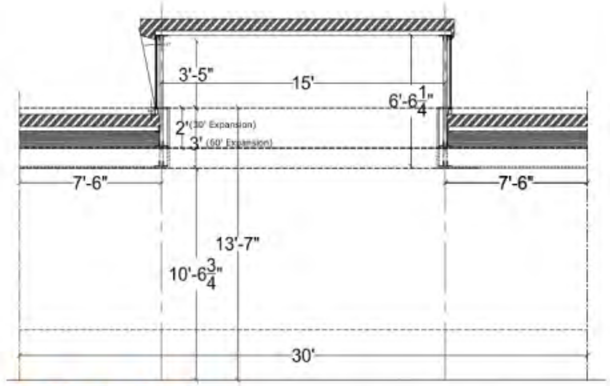
5.5%
7.5%
10%



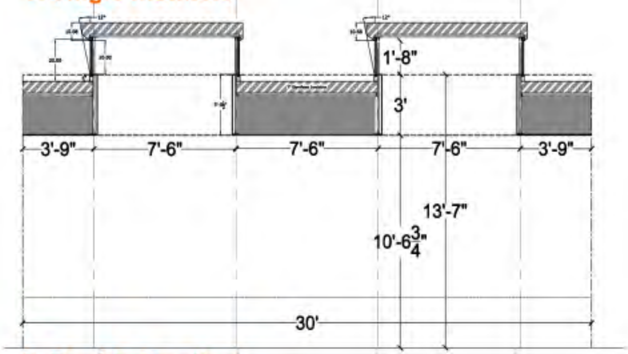
Floor Plans

Roof Monitors

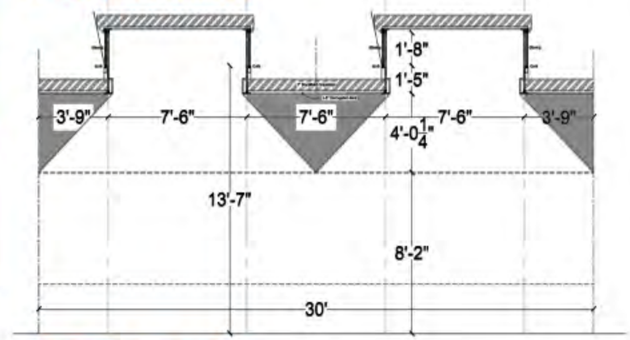




1. Single Monitors



2. Double Monitors



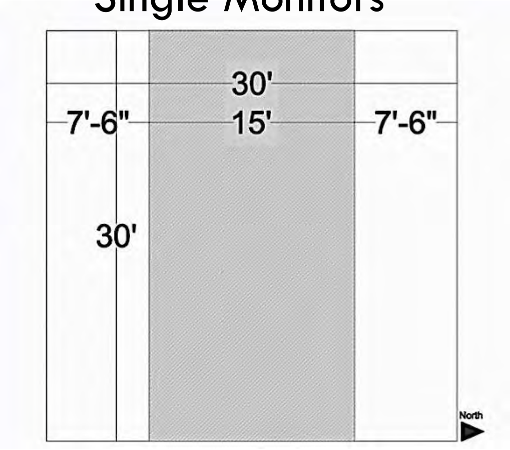
3. Double Monitors
Minimum Light Well

Roof Monitors Glazing Area

Aperture Area to **F**loor Area **R**atio (AFR)

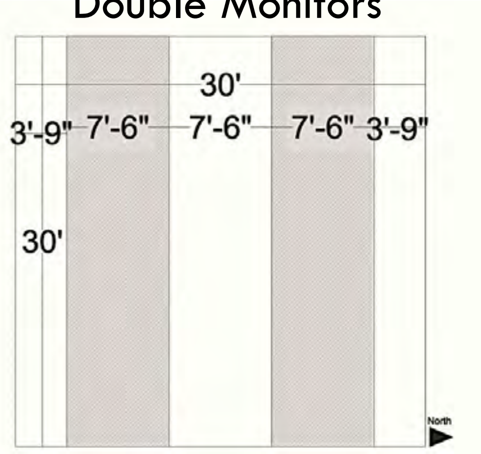
	AFR	Length Of Module		Reduction Factor On The Horizontal Glazing	Effective Horizontal Glazing Dimension		Glass Area In One Panel		Height Of The Glass	
		ft	m		ft	m	ft2	m2	ft	m
Single Monitors (900 ft^2 /83.6 m^2)	0.15	30	9.14	0.9	27	8.1	67.5	6.27	2.5	0.76
	0.20	30	9.14	0.9	27	8.1	90	8.36	3.3	1.00
	0.25	30	9.14	0.9	27	8.1	112.5	10.45	4.2	1.28
Double Monitors (900 ft^2 /83.6 m^2)	0.15	30	9.14	0.9	27	8.1	33.75	3.13	1.3	0.39
	0.20	30	9.14	0.9	27	8.1	45	4.18	1.7	0.52
	0.25	30	9.14	0.9	27	8.1	56.25	5.23	2.1	0.64

Single Monitors



AFRs
15%
20%
25%

Double Monitors



Floor Plans

Roof Monitors' Properties

North-facing Glass: Clear, double layers of glass

- Vt: 65% (accounting for structural members' obstruction)
- U-value (center): 1.42 W/m^2K
- SHGC: 0.312

South-facing Glass: Diffuse, double layers:

1. Velux laminated glass with LoE coating
2. Clear glass

- Vt: 50% (accounting for structural members' obstruction)
- U-value (center): 1.42 W/m^2K
- SHGC: 0.386

Thermal Properties of Glazing Assemblies

Effect of frames and curbs on overall U-values of the glazing

	AFR	Glazing Dimension		U Average of Glazing		Glazing UA	Curb Height		Curb UA	Overall UA (Curb UA+Glass UA)	Average U-value for Assembly	
		m x m	inch x inch	W/m2K	Btu/hr.Ft2.K	Btu/hr. F	m	inch	Btu/hr. F	Btu/hr. F	W/m2K	Btu/hr.Ft2.K
Square Apertures	2	0.64 x 0.64	25" x 25"	3.41	0.60	2.61	0.17	6.50	0.90	3.51	4.59	0.81
	3.5	0.86 x 0.86	34" x 34"	3.20	0.56	4.52	0.17	6.50	1.18	5.71	4.04	0.71
	5.5	1.07 x 1.07	42" x 42"	3.09	0.54	6.66	0.17	6.50	1.43	8.10	3.75	0.66
Linear Apertures	5.5	2.29 x 0.25	90" x 9.9"	3.74	0.66	4.07	0.17	6.50	1.44	5.51	5.06	0.89
	7.5	2.29 x 0.34	90" x 13.5"	3.47	0.61	5.15	0.17	6.50	1.45	6.60	4.45	0.78
	10	2.29 x 0.46	90" x 18"	3.28	0.58	6.50	0.17	6.50	1.47	7.97	4.03	0.71

	AFR	Glass Horizontal x Vertical Dimension		U Average of Glazing		Glazing UA	Curb Height (Curb is composed of		Curb UA	Overall UA for Skylights (Curb	Average U-value for Assembly	
		m x m	ft x ft	W/m2K	Btu/hr.Ft2.K	Btu/hr. F	m	inch	Btu/hr. F	Btu/hr. F	W/m2K	Btu/hr.Ft2.K
Single Monitors (Length 30'/ 9.14m)	15	2.25 x 0.76	7.5 x 2.5	1.86	0.33	6.13	0.25	9.75	2.57	8.70	2.64	0.46
	20	2.25 x 1.00	7.5 x 3.3	1.78	0.31	7.82	0.25	9.75	2.57	10.38	2.36	0.42
	25	2.25 x 1.28	7.5 x 4.2	1.73	0.30	9.50	0.25	9.75	2.57	12.07	2.19	0.39
Double Monitors (Length 30'/ 9.14m)	15	2.25 x 0.39	7.5 x 1.3	2.19	0.38	3.61	0.25	9.75	2.57	6.17	3.74	0.66
	20	2.25 x 0.52	7.5 x 1.7	2.02	0.36	4.45	0.25	9.75	2.57	7.02	3.19	0.56
	25	2.25 x 0.64	7.5 x 2.1	1.92	0.34	5.29	0.25	9.75	2.57	7.86	2.86	0.50

4. Methodology

Building Parameters

Literature Review on Methods

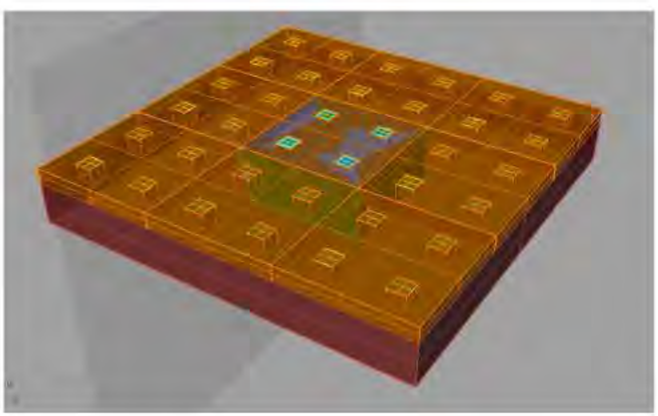
Lighting Assessment

Energy Assessment

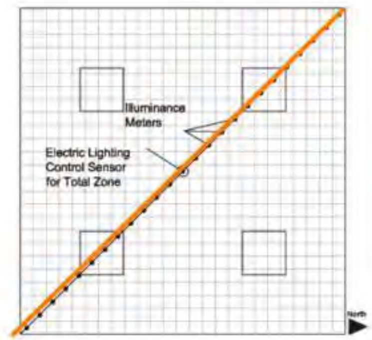
1. Lighting Assessment

1. 1. Single-time Spatial Distribution of Daylighting

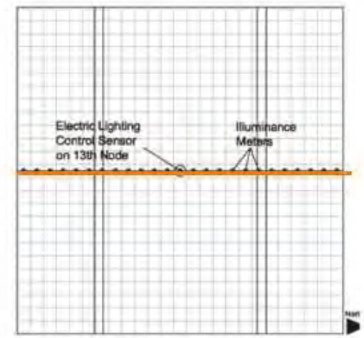
- Tool: RADIANCE, DIVA-for-Rhino plug-in
- Daylight Model:90'x90' floor are composed of 9 identical modules
- Simulation Time: 12 pm, 21 Sept
- Sky Condition: Sunny



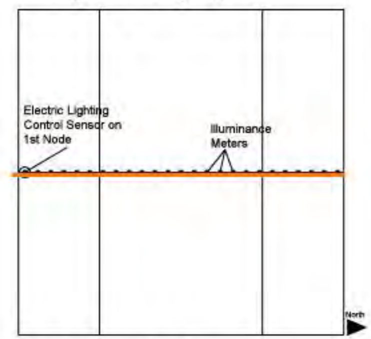
DIVA Daylight Model



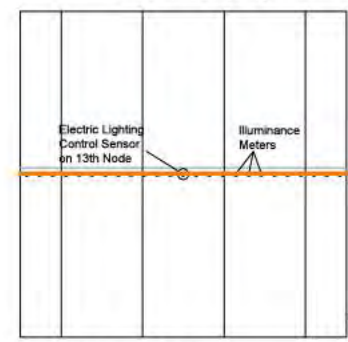
Square Skylights



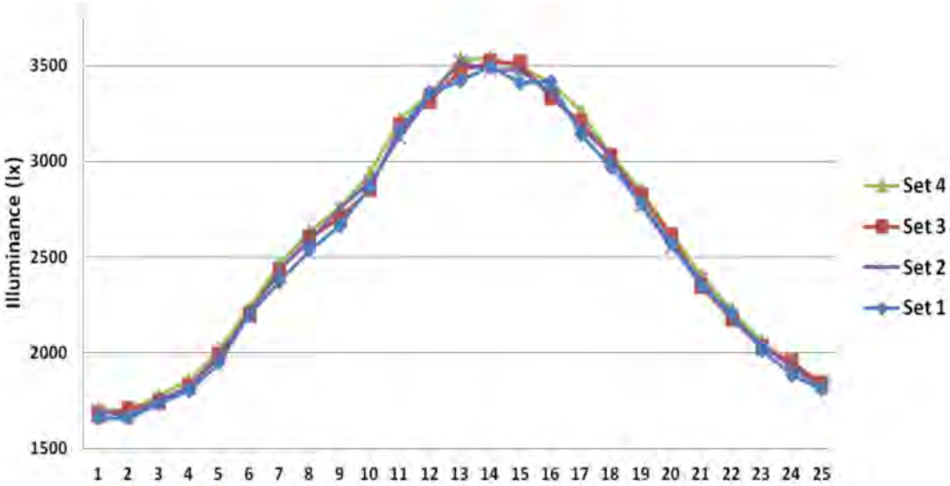
Linear Skylights

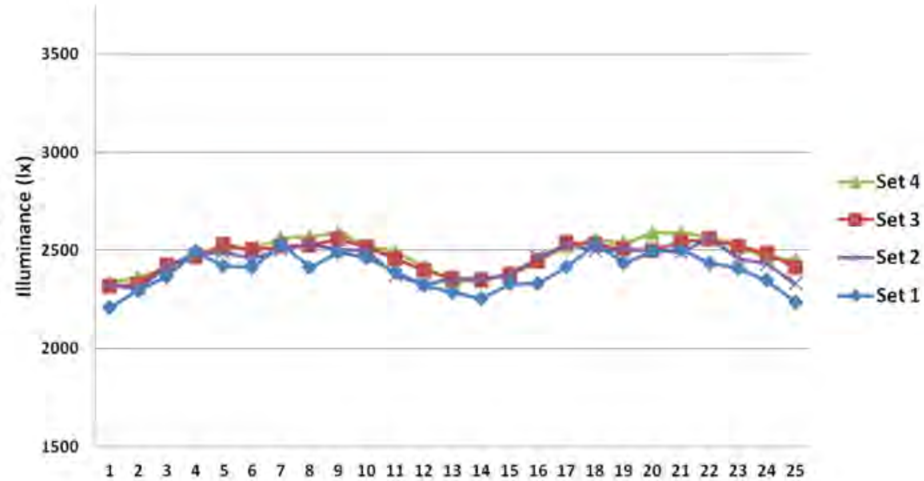


Single Roof Monitors



Double Roof Monitors





	Daylighting Parameters					Minimum Illuminance in Middle Axis at Task Level (lux)		Max Relative Error Compared to the 4th Set (%)	
Vertical Aperture	ab	ad	as	ar	aa	Single Monitor (Minimum occurs at 1st sensor on middle NS axis)	Double Monitor (Minimum occurs at center/13th sensor on middle NS Axis)	Single Monitor	Double Monitor
Set 1	7	2500	625	300	0.05	1660	2284	-3.64	-8.67
Set 2	8	3600	900	600	0.05	1669	2354	-2.98	-4.97
Set 3	8	4624	1156	900	0.05	1673	2359	-2.79	-3.49
Set 4	8	5184	1296	1200	0.03	1703	2342	0	0

Radiance Parameters	ab	ad	as	ar	aa
	8	5184	1296	1200	0.03

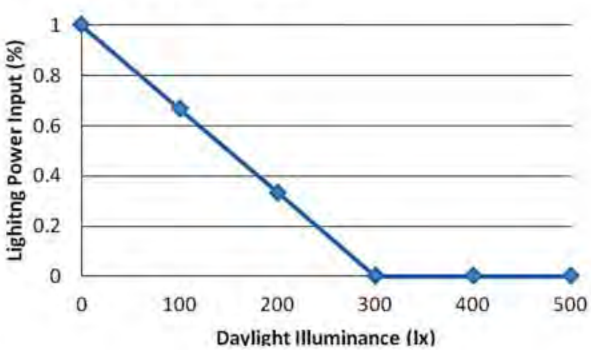
1. Lighting Assessment

1.2. Dynamic Daylighting

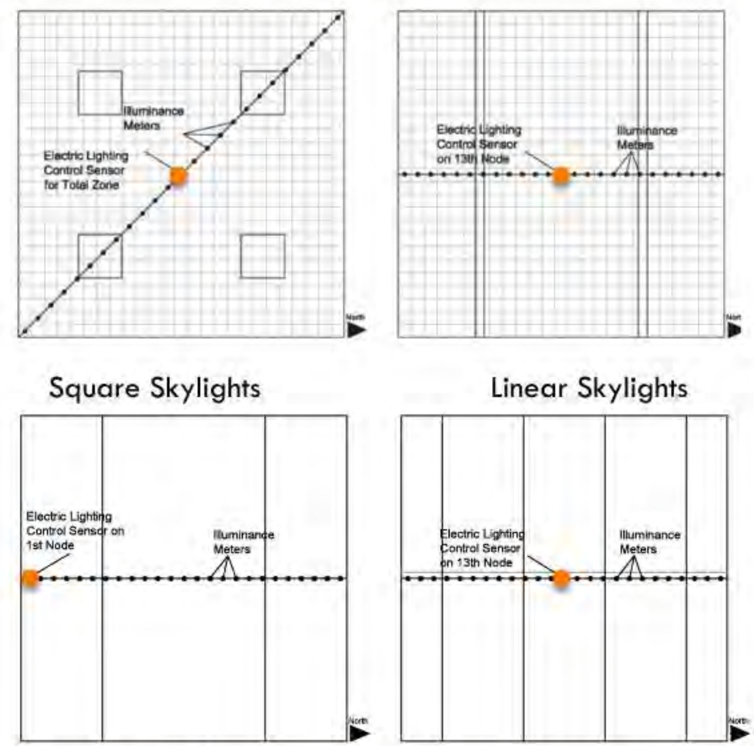
- Tool: DAYSIM, DIVA-for-Rhino plug-in
- Simulation Time: Annual Simulation
- Sky Condition: Weather Data File
- Sensors Location

1.3. Electric Lighting Estimation

- Tool: EnergyPlus
- Electric power input: DAYSIM (CSV files)
- Daylighting Control: Dimming System
- Occupancy Schedule: 9am-5pm weekdays
- Illuminance Target: 300 lx
- LPD: 0.9 W/ft^2



DIVA Daylight Model



Single Roof Monitors   Double Roof Monitors

Radiance Parameters	ab	ad	as	ar	aa
	7	2500	625	300	0.05

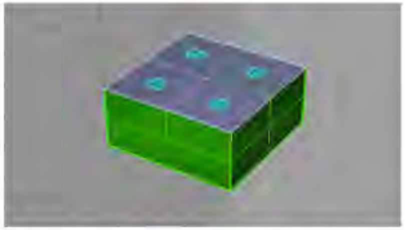
2. Energy Assessment

Tool: EnergyPlus

Energy Model: One thermal Zone

30'x30' module with adiabatic walls

Adiabatic ground



DIVA Thermal Model (Skylights)

2.1. CONSTRUCTION MATERIALS

2.2. INTERNAL LOADS

2.3. AIR CIRCULATION

2.4. HVAC SYSTEM

Cooling System: AC unit (COP 3)

Heating System: Gas Furnace (COP 0.8)

2.5. SCHEDULES

Heating Setpoint: 22 C

Heating Setback: 17 C

Cooling Setpoint: 24.5 C

Cooling Setback: 32 C

5. Results Analysis

Daylight Illuminance Distribution

Electric Lighting Consumption

Thermal Comfort

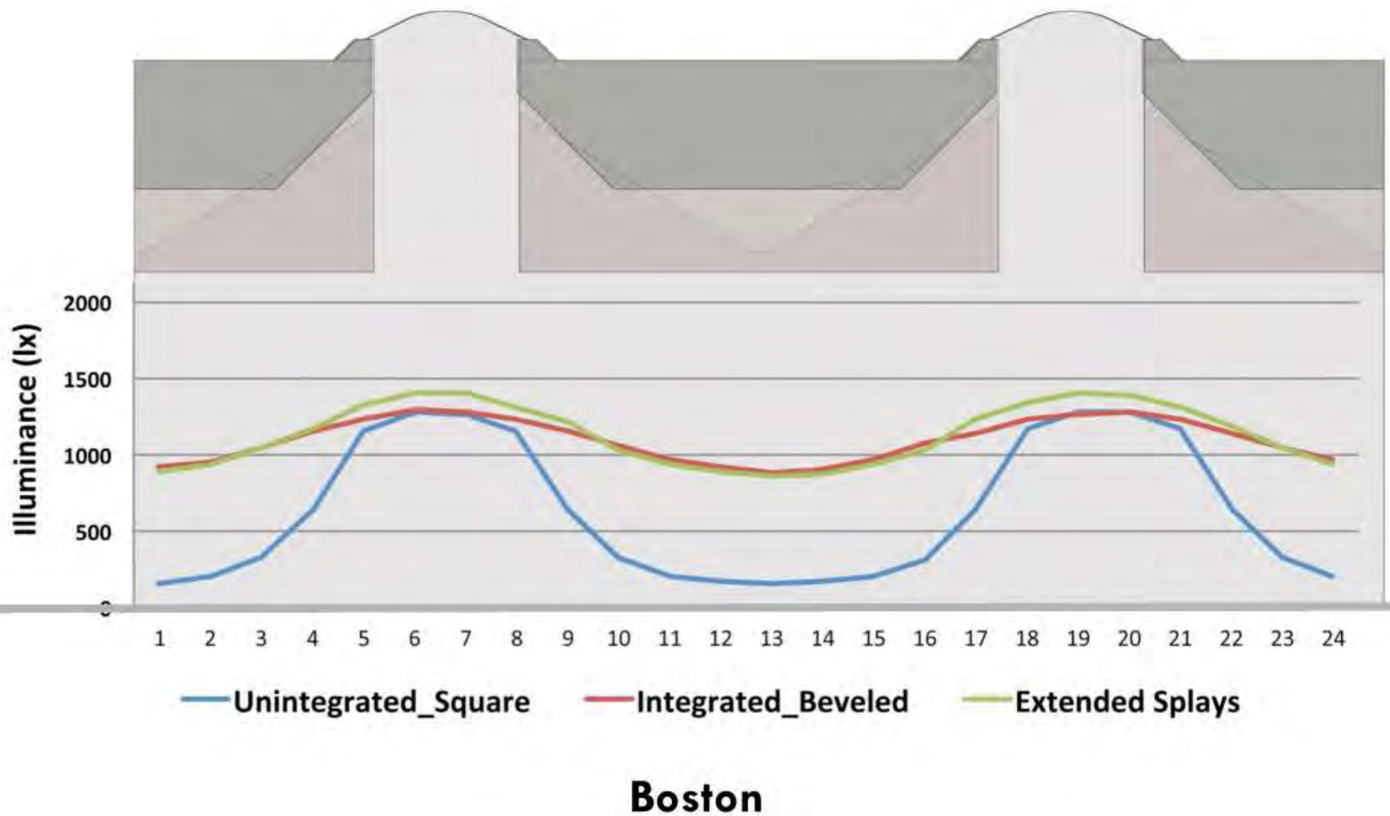
Heating-Cooling Energy Consumption

Energy Use Intensity

Building Operation Costs

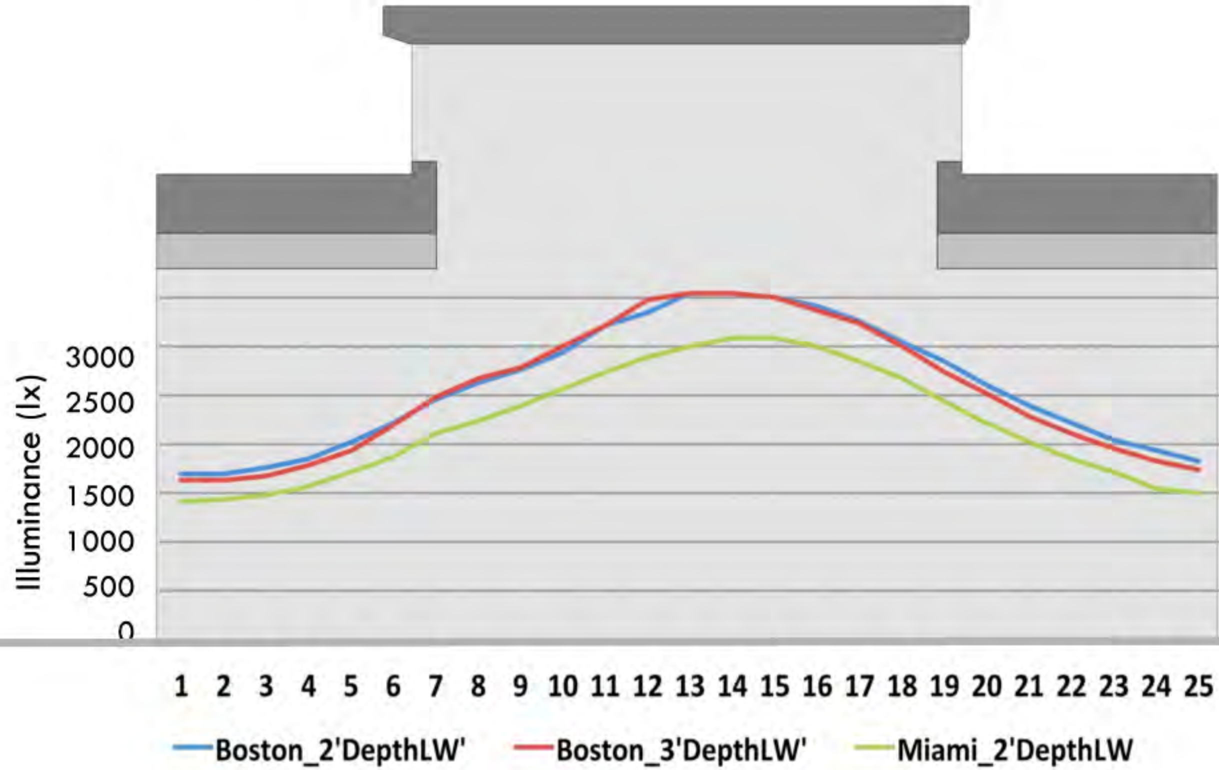
Daylight Illuminance Distribution

Skylights 5.5% AFR



Daylight Illuminance Distribution

Roof Monitors 20% AFR

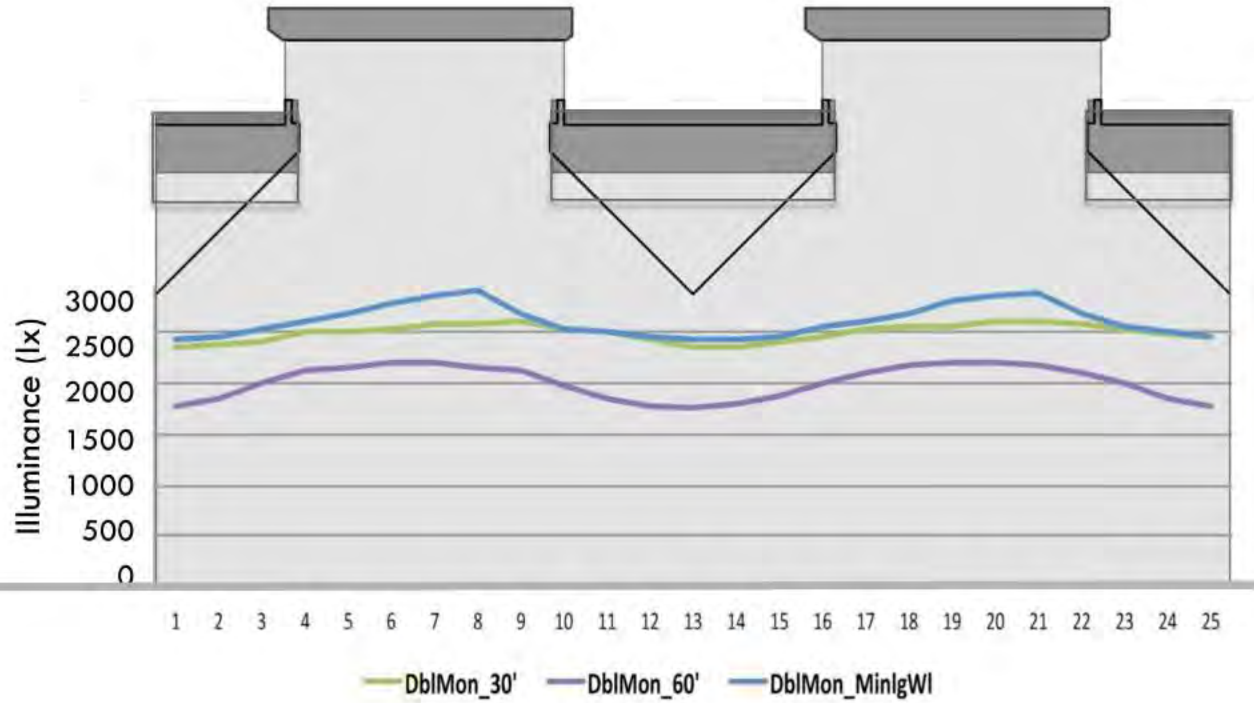


Single Monitors

Boston & Miami

Daylight Illuminance Distribution

Roof Monitors 20% AFR



Double Monitors

Boston

5. Results Analysis

Daylight Illuminance Distribution

↓

Electric Lighting Consumption

↓

Heating-Cooling Energy Consumption

↓

Energy Use Intensity

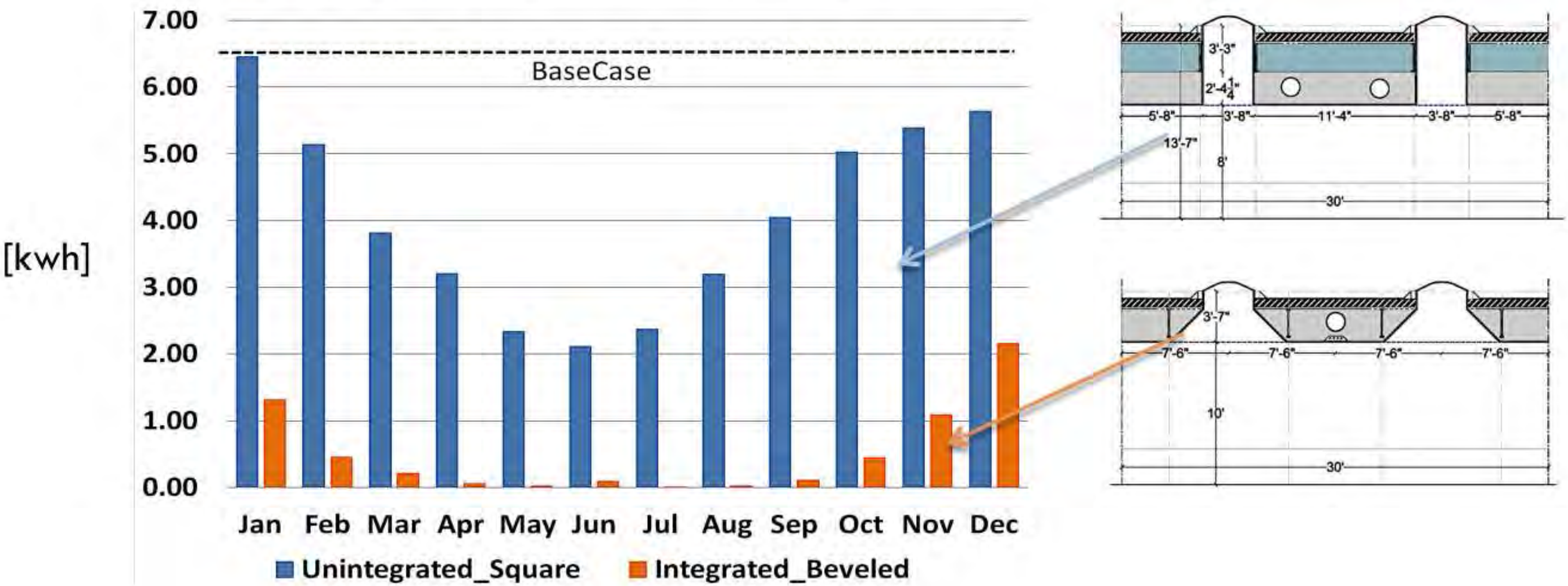
↓

Building Operation Costs

Electric Lighting Consumption

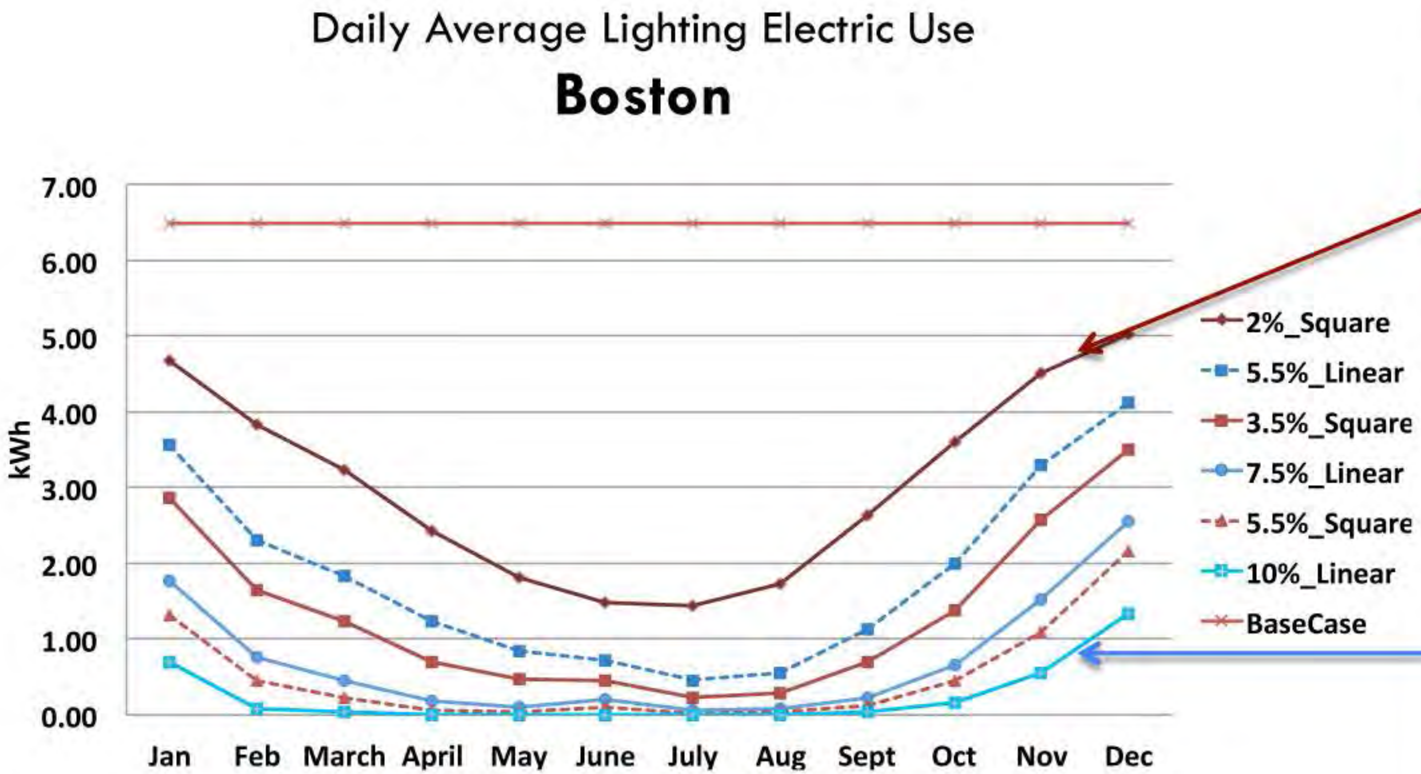
Square Skylights 5.5% AFR

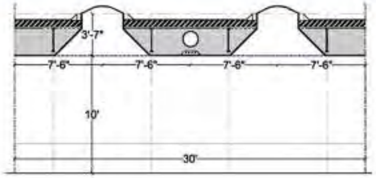
Daily average lighting electric use [kwh] in Boston

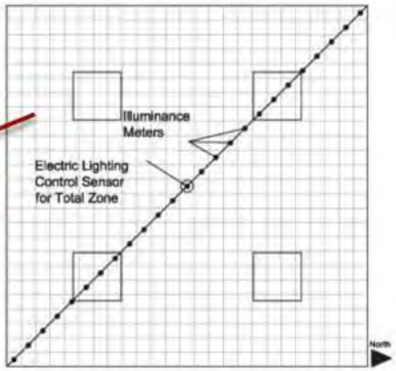


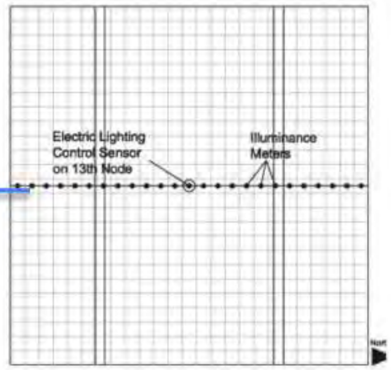
Electric Lighting Consumption

Square and Linear Skylights_ Various AFRs







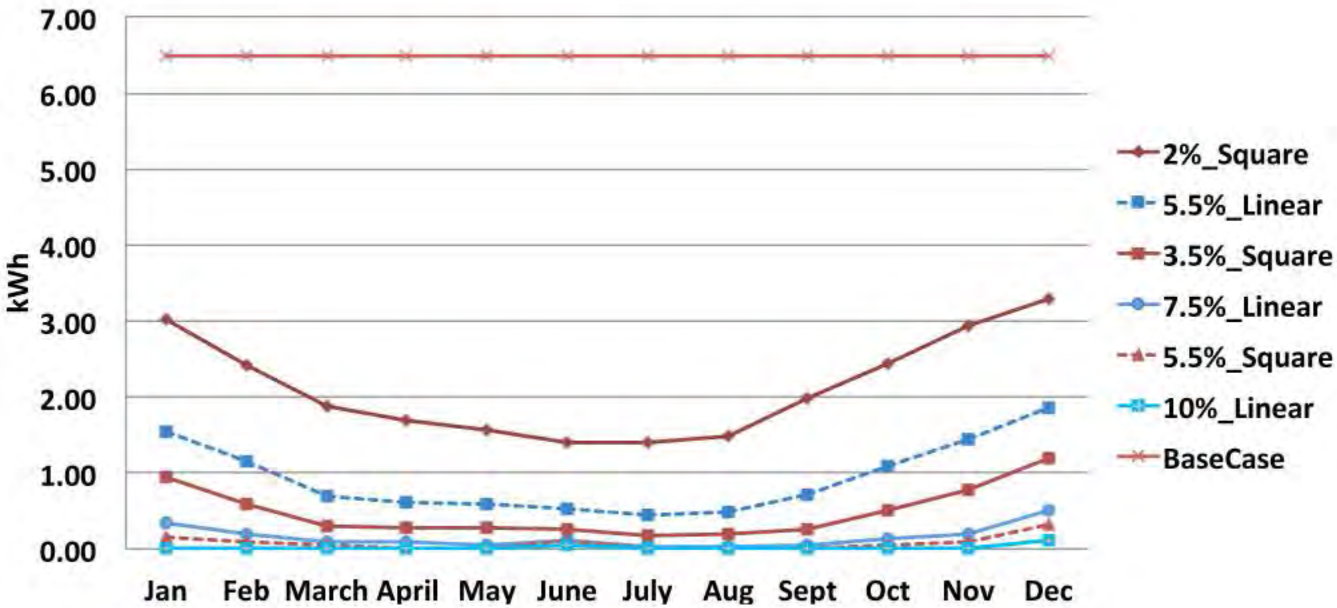


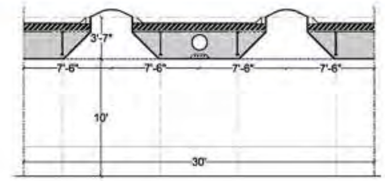
Electric Lighting Consumption

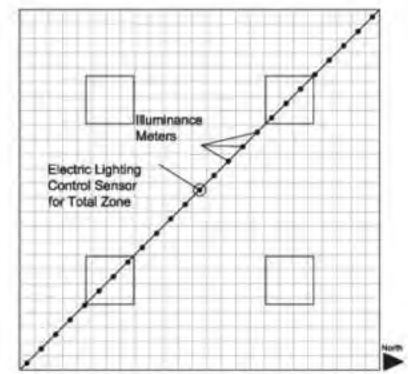
Square and Linear Skylights_ Various AFRs

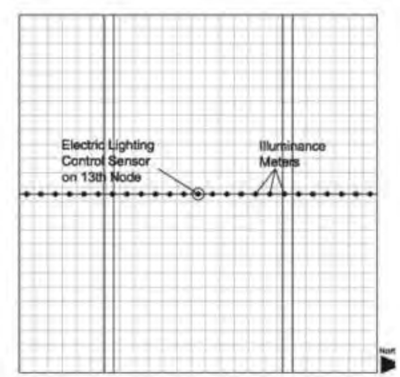
Daily Average Lighting Electric Use

Miami





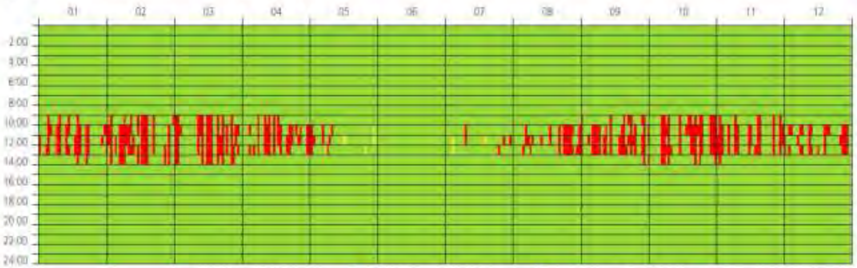




Glare Analysis

1. **Single Monitors**_25%_Diffuse Glazing for South

(Laminated 52% Vt)



Annual glare

2. **Single Monitors with Baffles**_25%

clear glass with LoE , 90% reflectance in baffles

3. **Single Monitor with Banner**_25%

Diffuse Glazing for South (Laminated 52% Vt) with a Banner (white fabric 50% transmittance, 50% reflectance)

1. DGP 49%

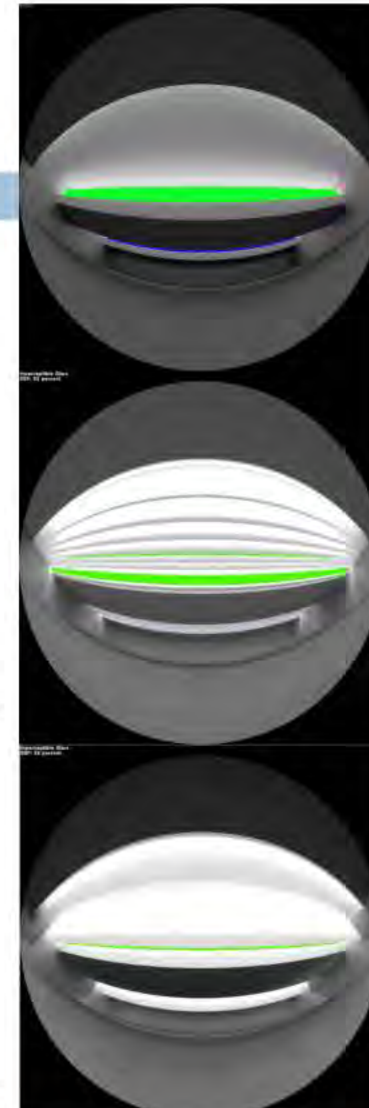
Intolerable glare

2. DGP 33%

Imperceptible glare

3. DGP 32%,

Imperceptible glare



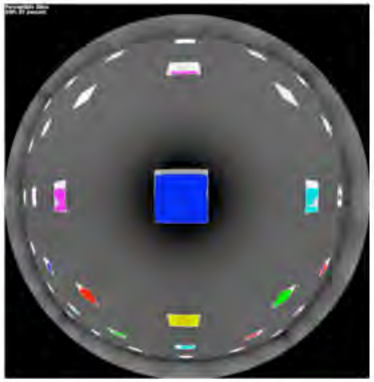
dp	ar	dt	dj	dr	Ir	Iw	st	ps	pj	ab	aa	ad	as
512	128	0	0	2	4	0.000001	0.15	0	0	3	0.1	2048	512

Glare Analysis

1. Skylights_Integrated Systems with Squared Lightwells

SFR 5.5%_Diffuse 42%Vt

1. DGP=37%
Perceptible glare



2. DGP=39%
Perceptible glare

2. Skylights_Integrated Systems with Beveled Lightwell

SFR 7%_Diffuse 55% Vt

5. Results Analysis

Daylight Illuminance Distribution

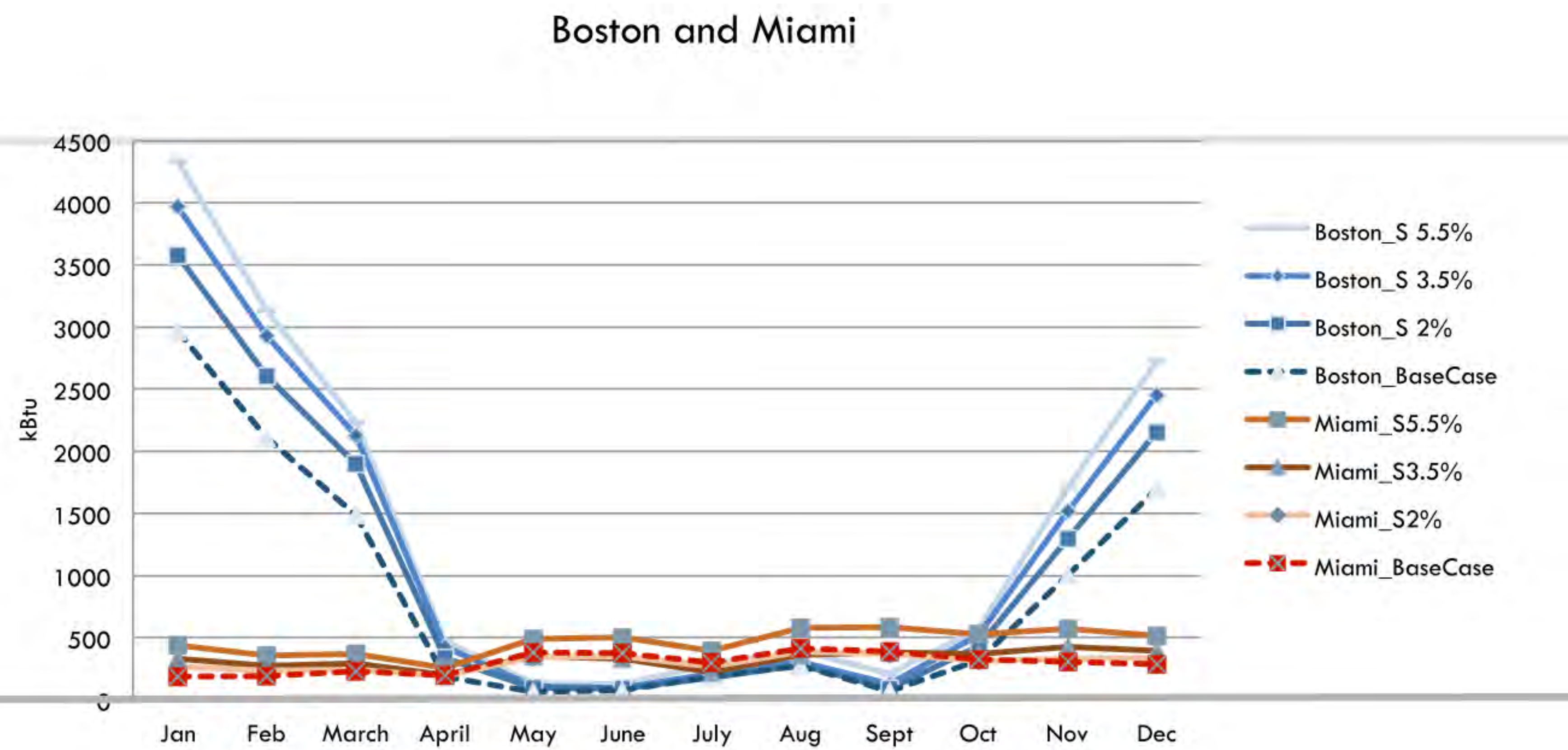
Electric Lighting Consumption

Heating-Cooling Energy Consumption

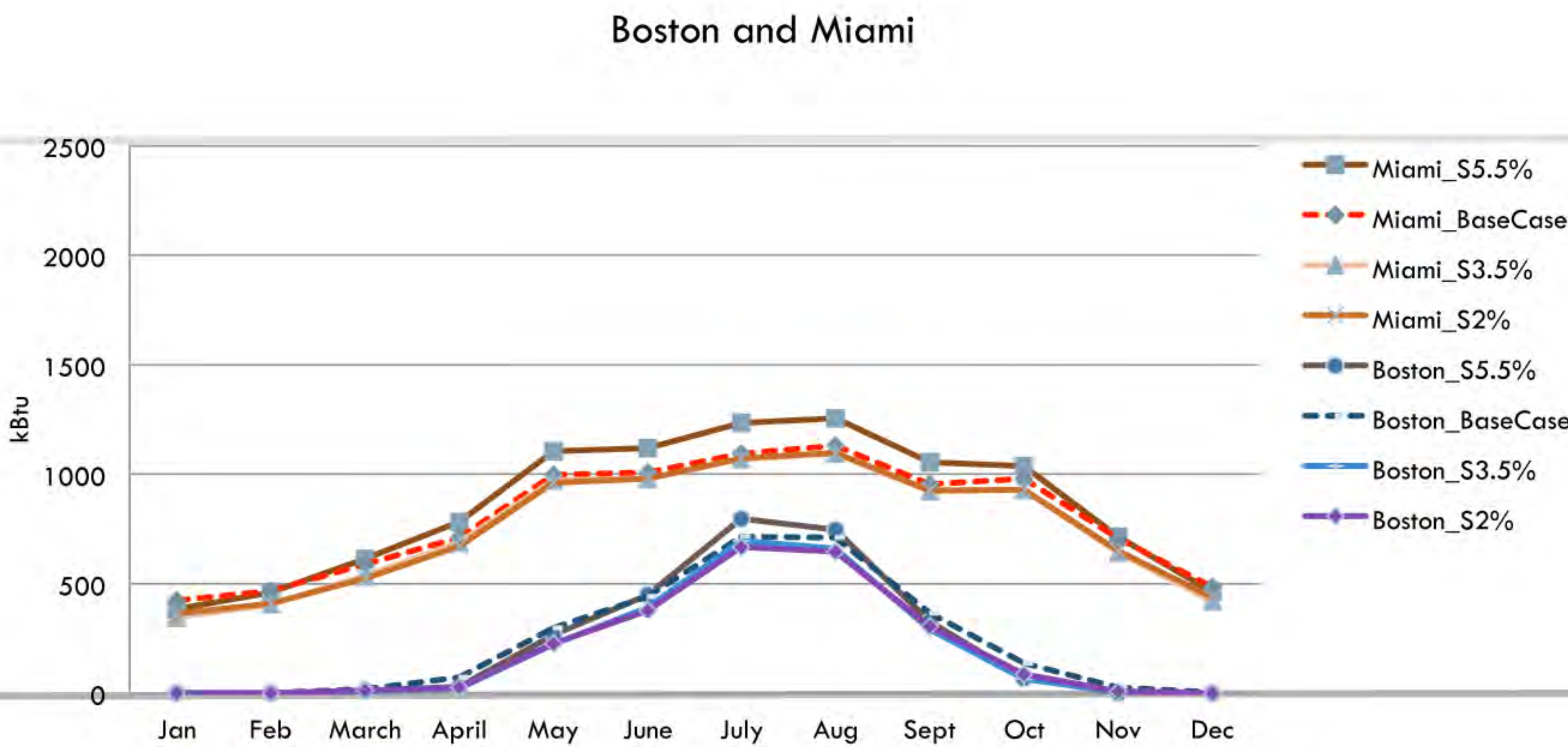
Energy Use Intensity

Building Operation Costs

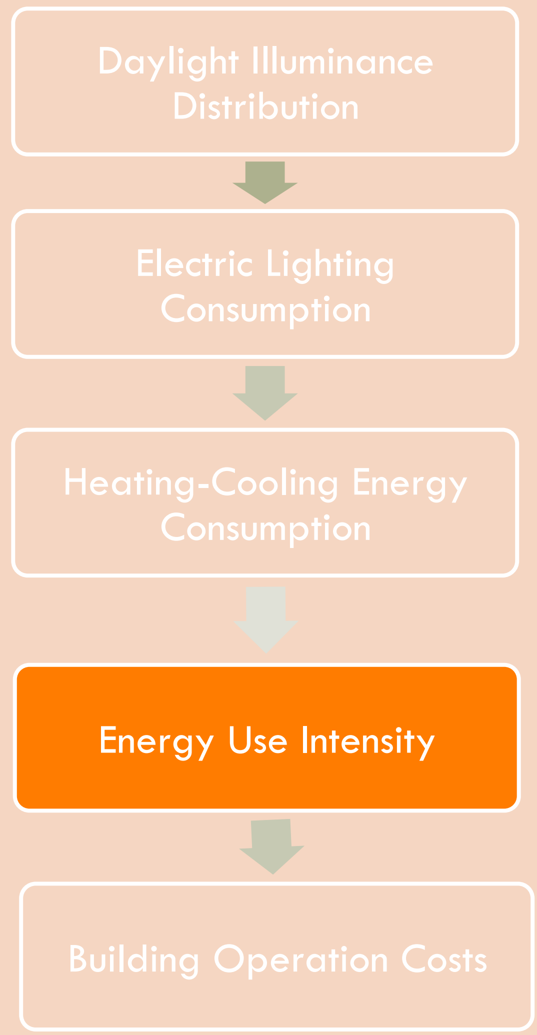
Heating Gas Consumption [kBtu]
Square Skylights



Cooling Coil Electricity Consumption [kBtu] Square Skylights

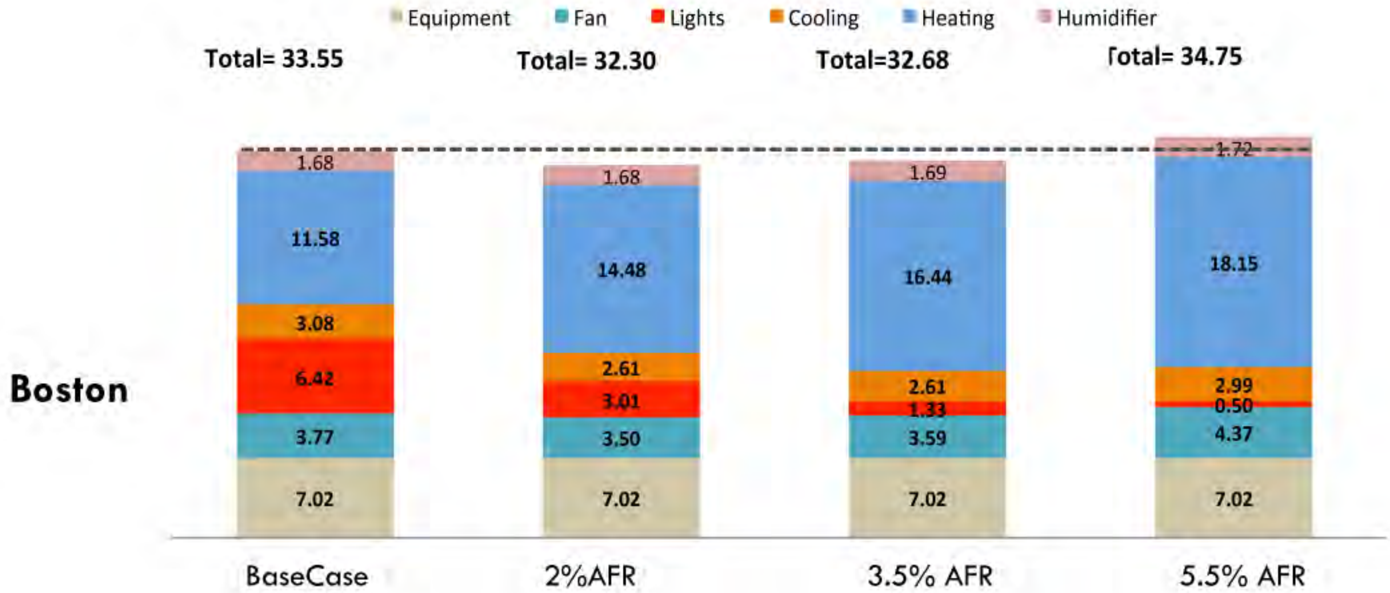


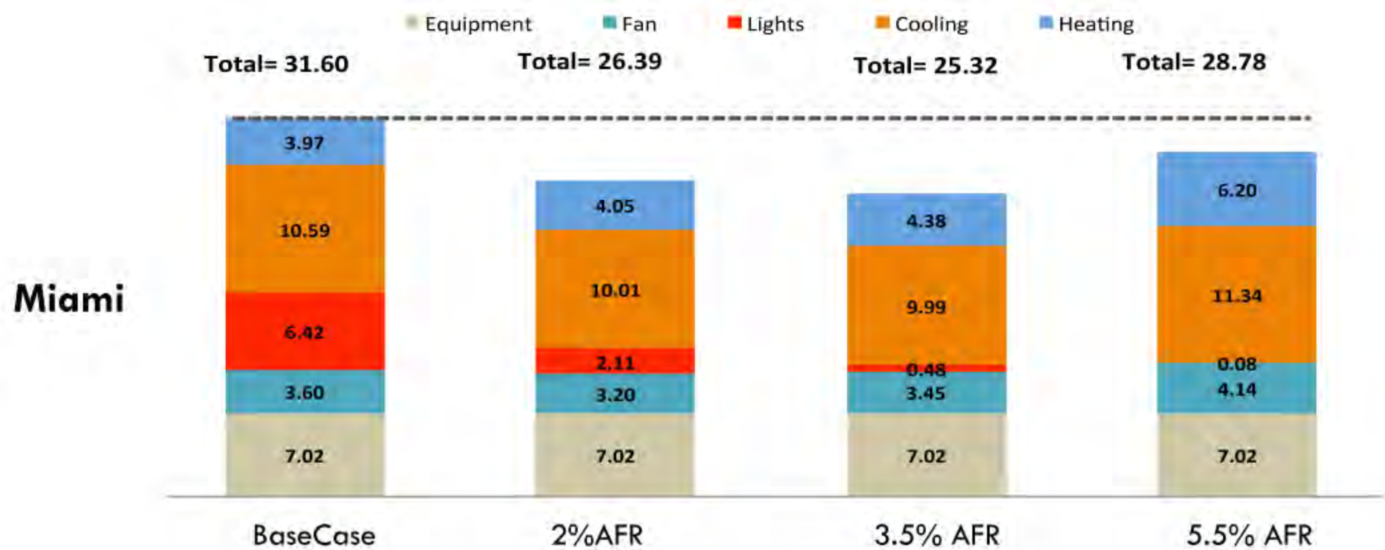
5. Results Analysis



Energy Use Intensity EUI Square Skylights

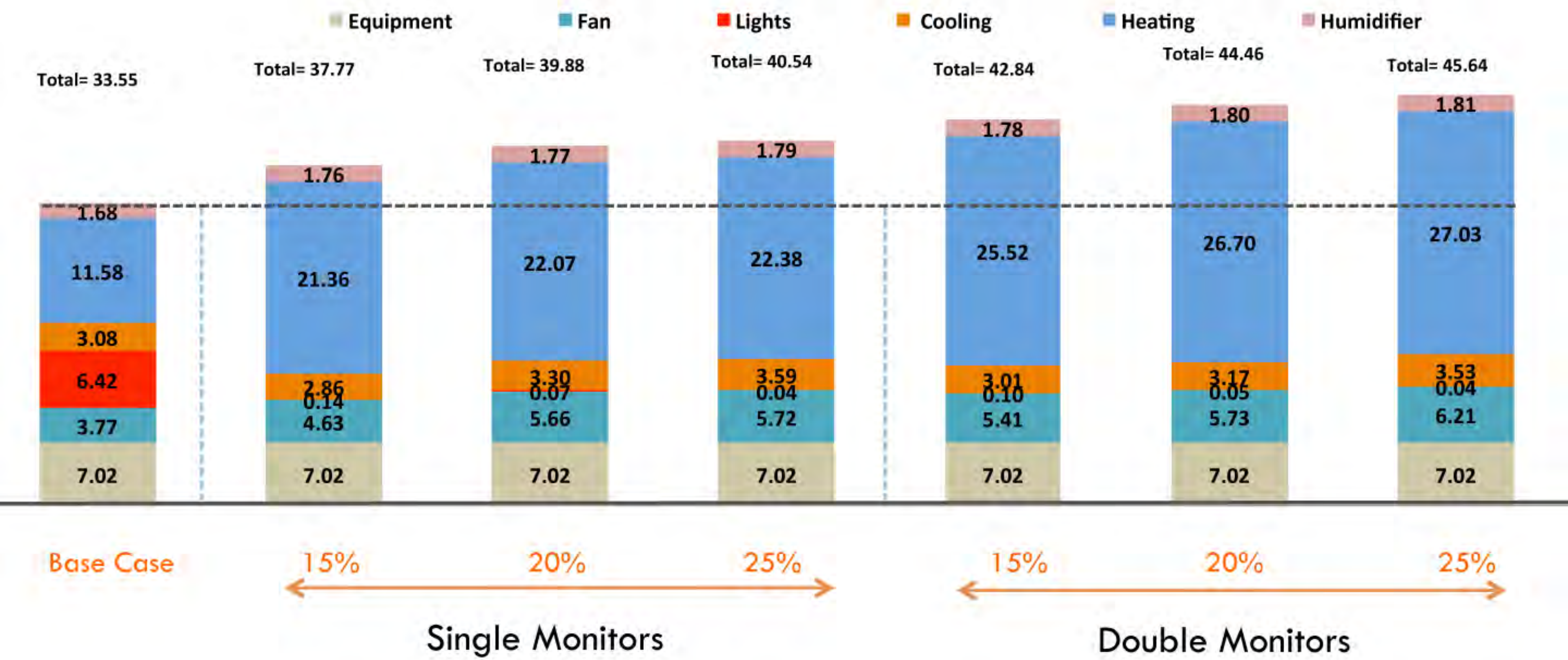
[kBtu/sqft/yr]





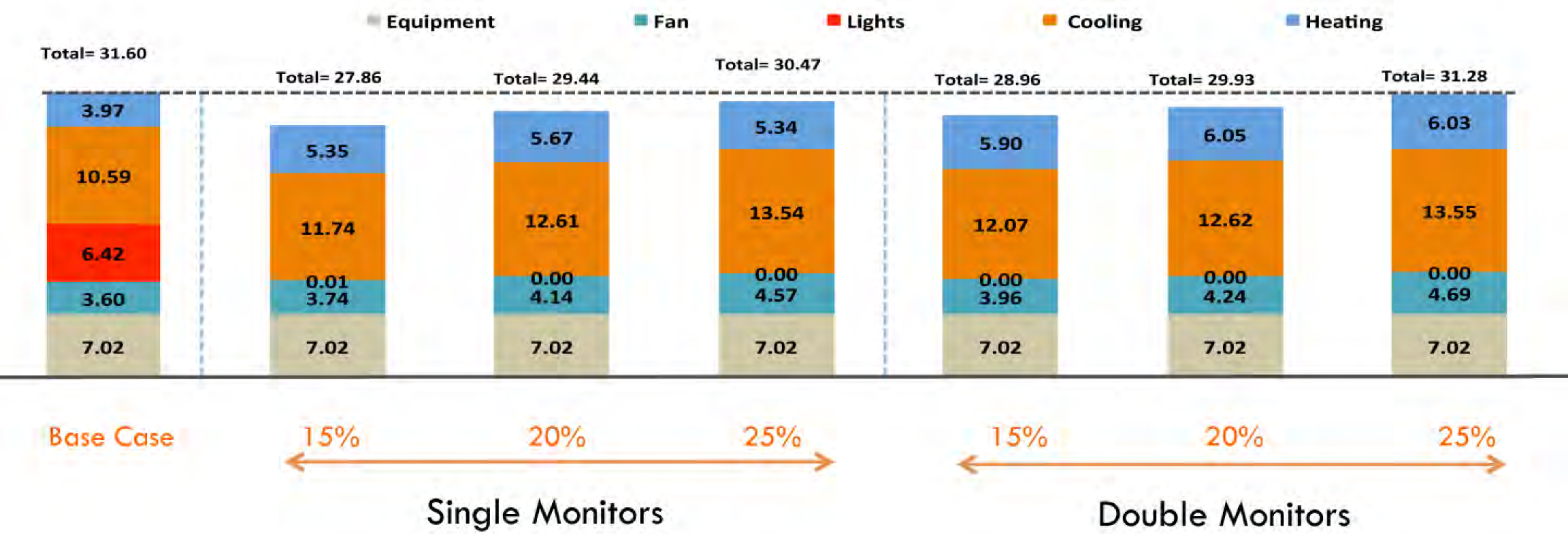
Energy Use Intensity EUI Roof Monitors
Boston

[kBtu/sqft/yr]



Energy Use Intensity EUI Roof Monitors
Miami

[kBtu/sqft/yr]



5. Results Analysis

Daylight Illuminance Distribution

Electric Lighting Consumption

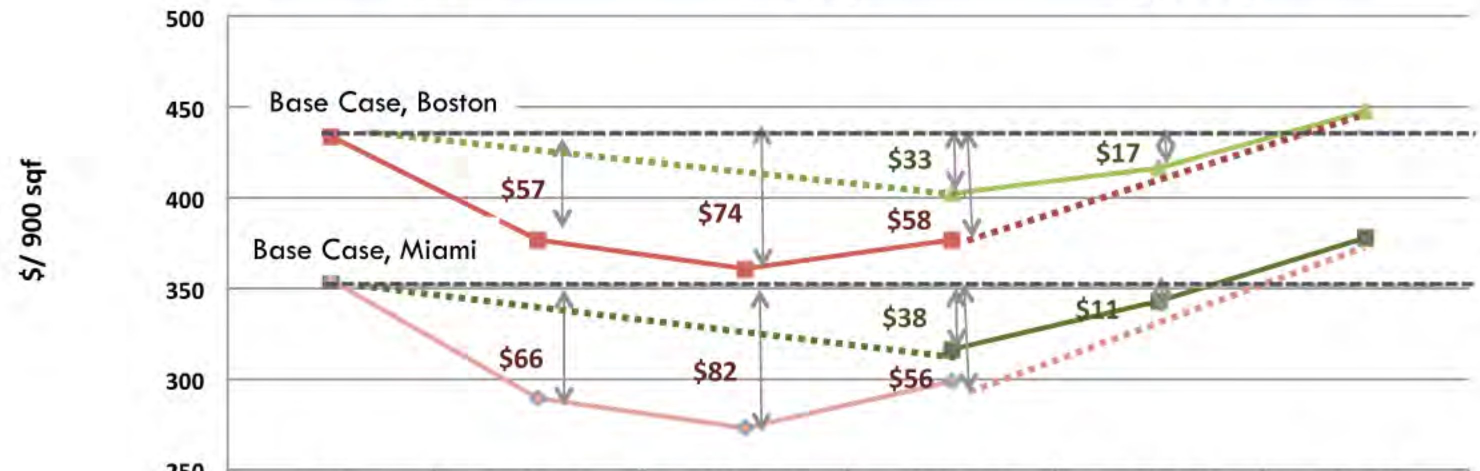
Heating-Cooling Energy Consumption

Energy Use Intensity

Building Operation Costs

Building Operation Costs

	Electricity (cent per kWh)	Gas (Dollar per therm)
Boston	c5.48 (Oct-May) c8.28 (Jun-Sep)	$0.5732
Miami	c4.69	$0.3389

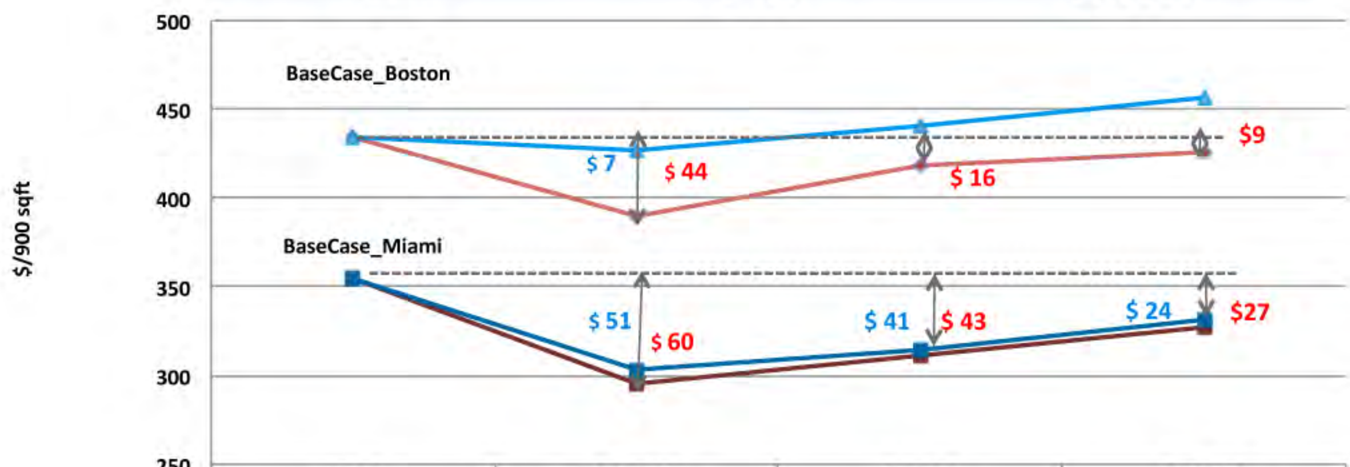


	0 AFR	0.02 AFR	0.035 AFR	0.055 AFR	0.075 AFR	0.10 AFR
Linear_Boston	435			402	417	447
Square_Boston	435	377	361	377		
Linear_Miami	355			316	343	378
Square_Miami	355	289	273	299		

Building Operation Costs in Roof Monitors Boston and Miami

[$/yr per 900 ft2 module]

	Electricity (cent per kWh)	Gas (Dollar per therm)
Boston	c5.48 (Oct-May) c8.28 (Jun-Sep)	$0.5732
Miami	c4.69	$0.3389

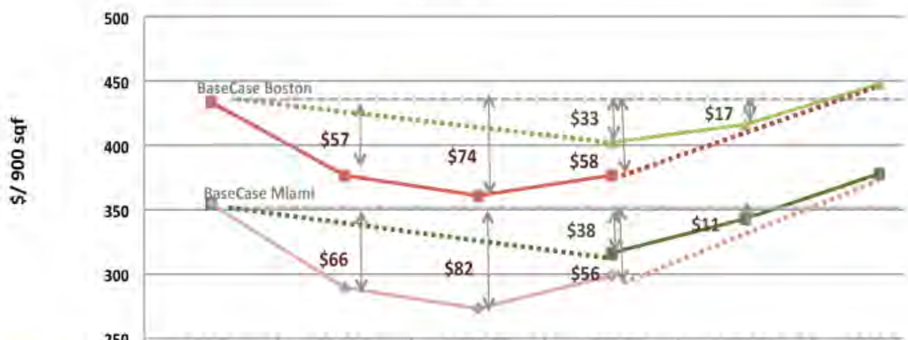


	0 AFR	0.15 AFR	0.2 AFR	0.25 AFR
Boston_Sgl_Mon	434	390	418	425
Miam_Sgle_Moni	355	295	311	327
Boston_Dbl_Mon	434	427	441	457
Miami_Dbl_Mon	355	303	314	331

6. Conclusions

Comparison and Conclusions

Skylights



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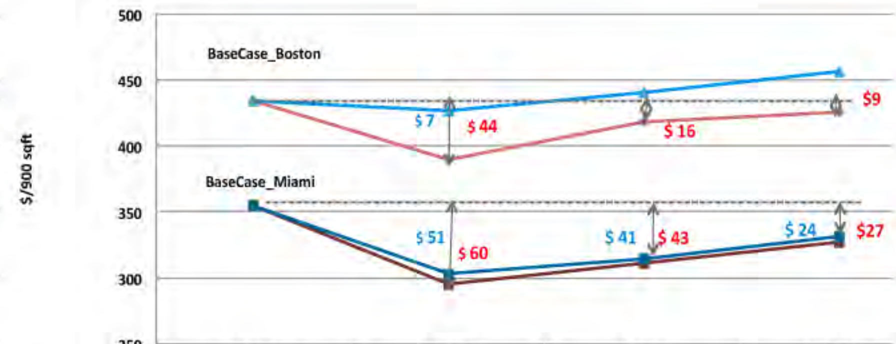
Roof Monitors



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Boston_Dbl_Mon	434	427	441	457
Miami_Dbl_Mon	355	303	314	331

- The maximum energy savings in skylights with 3-3.5% AFR
  - Higher incident illuminance on the skylights reduces the required area of glazing
  - Smaller apertures have thermal advantages

Comparison and Conclusions

- Monitors provide the psychological benefit of less light in the summer when the light tends to be associated with the oppressive heat of the summertime and the psychological benefit of more light in the wintertime, when the lack of sunlight is often a source of depression to people

- Fluctuations in illuminance level in skylight systems can be extreme, causing adaptation issues

Acknowledgement

- Thanks to
  - My PhD committee
  - DIVA group
  - OpenStudio group
  - Jan Weinold

Question and Answers

Thank you!