ANALYSIS OF DAYLIGHTING PERFORMANCE AND ENERGY SAVINGS IN ROOF DAYLIGHTING SYSTEMS

LADAN GHOBAD
PH.D. IN DESIGN

COMMITTEE:
WAYNE PLACE
JIANXIN HU
SOOLYEON CHO
STEPHEN TERRY
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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
<table>
<thead>
<tr>
<th>Location</th>
<th>Architect</th>
<th>Daylighting System</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Carolina Art Museum, Raleigh, NC (2010)</td>
<td>Thomas Phifer and Partners (local architect: Pearce Brinkley Cease + Lee)</td>
<td>362 Horizontal apertures, called “elliptical oculi”, which are located in long, parallel, coffered vaults</td>
<td>Mixed hot and cold</td>
</tr>
<tr>
<td>The Rensnick Pavilion (LACMA Expansion), California (2006-2010)</td>
<td>Renzo Piano</td>
<td>glazed sawtooth roof facing north and a horizontal layer of translucent glass underneath</td>
<td>Moderate marine climate</td>
</tr>
<tr>
<td>Expansion of the High Museum of Art, Atlanta, Georgia (1999-2005)</td>
<td>Renzo Piano</td>
<td>numerous light scoops creating clear glass shadowed by lipstick shades facing north</td>
<td>Warm and humid</td>
</tr>
<tr>
<td>The Menil Collection, Houston, Texas (1982-1987)</td>
<td>Renzo Piano</td>
<td>Multilayer roof composed of exterior tilted glazing connected two by two and giant louvers</td>
<td>Hot and Humid climate</td>
</tr>
<tr>
<td>Beyeler Foundation Museum, Riehen, Switzerland (1992-1997)</td>
<td>Renzo Piano</td>
<td>Sawtooth louvers facing north built on top of horizontal structural layer of glass</td>
<td>Temperate</td>
</tr>
<tr>
<td>Nasher Sculpture Center, Dallas, Texas (1999-2003)</td>
<td>Renzo Piano</td>
<td>double-layer roof composed of slightly curved glass vaults with aluminum sunshade panels on top</td>
<td>Warm and humid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exterior tilted louvers made of translucent laminated glazing material and interior horizontal louvers made of metal mesh frames</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>cast aluminum sun-shading panels with round holes facing towards north</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Architect</td>
<td>Daylighting System</td>
<td>Daylighting Control System</td>
</tr>
<tr>
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</tr>
<tr>
<td>Mt. Airy Public Library, Mount Airy, North Carolina (1984)</td>
<td>Edward Mazria</td>
<td>sawtooth roof facing south</td>
<td>vertical baffles</td>
</tr>
<tr>
<td>The Academic Bookshop, Helsinki, Finland (1969)</td>
<td>Alvar Aalto</td>
<td>prism-shaped skylights</td>
<td>Interior pyramidal diffusers</td>
</tr>
<tr>
<td>The Viipuri Library, Vyborg, Russia (1935)</td>
<td>Alvar Aalto</td>
<td>conical funnel-like horizontal apertures</td>
<td>diffuse glazing</td>
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<tr>
<td>McPherson Middle School, Clyde, Ohio (2010?)</td>
<td>FHAI</td>
<td>Sawtooth roof</td>
<td>fabric baffles</td>
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<td>Building Name</td>
<td>Location</td>
<td>Architect/Engineer</td>
<td>Daylighting System</td>
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<td>Arup Campus Office, Solihull, England</td>
<td>England</td>
<td>Arup Associates</td>
<td>Lighting units</td>
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<tr>
<td>Heels Office Building, Swindon, England</td>
<td>England</td>
<td>Feilden Clegg Bradley with Max Fordham as M&amp;E consultant</td>
<td>Lighting units</td>
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<td>IDEAs office Building, Santa Clara, California</td>
<td>United States of America</td>
<td>EHDD Architecture</td>
<td>Skylights (tilted by low angles)</td>
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<td>Gothenburg Law Court Extension, Gothenburg, Sweden</td>
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<td>Gunnar Asplund</td>
<td>Lighting units</td>
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<td>Spectrum 7 Building, Milton Keynes, England</td>
<td>England</td>
<td>ECD partnership, Engineer: Arup</td>
<td>Lighting units</td>
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<tr>
<td>Metropoli Foundation Building, Madrid, Spain</td>
<td>Spain</td>
<td>Angel de Diego Rica</td>
<td>Lighting units</td>
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</table>
2. Literature Review
3. Research Design

- Research Questions
- Independent Variables
- Dependent Variables
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 Aperture to Floor Area Ratio (AFR)**
  - Skylights: 2%, 3.5%, 5.5%, 7.5%, 10%
  - Roof Monitors: 15%, 20%, 25%
3. Research Design

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

- Building Parameters
- Lighting Assessment
- Energy Assessment
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/m² K
    (Skylight Assembly’s U-value is changing)
  - Opaque Part: 0.187 W/m² K (R-30)

- **Visual Properties**
  - Skylight Vt= 42%
Skylights Glazing Area
Aperture Area to Floor Area Ratio (AFR)

<table>
<thead>
<tr>
<th>Units</th>
<th>Floor Area Illuminated</th>
<th>AFR</th>
<th>Number of Apertures</th>
<th>Clear Glazing Length</th>
<th>Clear Glazing Width</th>
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<tbody>
<tr>
<td></td>
<td>ft²</td>
<td>m²</td>
<td>%</td>
<td></td>
<td>ft</td>
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<tr>
<td>Square Apertures</td>
<td>900</td>
<td>83.6</td>
<td>2</td>
<td>4</td>
<td>2.08</td>
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<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td>2.83</td>
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<tr>
<td></td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td>3.50</td>
</tr>
<tr>
<td>Linear Apertures</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
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<tr>
<td></td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
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<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
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</table>

**Square skylights**
- 2%
- 3.5%
- 5.5%

**Linear skylights**
- 5.5%
- 7.5%
- 10%
Roof Monitors

1. Single Monitors

2. Double Monitors

3. Double Monitors
Minimum Light Well
## Roof Monitors Glazing Area

**Aperture Area to Floor Area Ratio (AFR)**

<table>
<thead>
<tr>
<th></th>
<th>AFR</th>
<th>Length Of Module</th>
<th>Reduction Factor On The Horizontal Glazing</th>
<th>Effective Horizontal Glazing Dimension</th>
<th>Glass Area In One Panel</th>
<th>Height Of The Glass</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>ft</td>
<td>m</td>
<td>ft</td>
<td>m</td>
<td>ft²</td>
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<tr>
<td>Single Monitors (900 ft² /83.6 m²)</td>
<td>0.15</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
<tr>
<td>Double Monitors (900 ft² /83.6 m²)</td>
<td>0.15</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>30</td>
<td>9.14</td>
<td>0.9</td>
<td>27</td>
<td>8.1</td>
</tr>
</tbody>
</table>

**AFRs**
- 15%
- 20%
- 25%

**Floor Plans**

**Single Monitors**
- 7'-6" x 30' x 7'-6"
- AFRs: 15%, 20%, 25%

**Double Monitors**
- 3'-9" x 7'-6" x 7'-6" x 7'-6" x 3'-9"
Roof Monitors’ Properties

North-facing Glass: Clear, double layers of glass
- \( \text{Vt: 65\% (accounting for structural members’ obstruction)} \)
- \( \text{U-value (center): 1.42 W/m}^2\text{K} \)
- \( \text{SHGC: 0.312} \)

South-facing Glass: Diffuse, double layers:
1. Velux laminated glass with LoE coating
2. Clear glass
- \( \text{Vt: 50\% (accounting for structural members’ obstruction)} \)
- \( \text{U-value (center): 1.42 W/m}^2\text{K} \)
- \( \text{SHGC: 0.386} \)
### Thermal Properties of Glazing Assemblies

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

<table>
<thead>
<tr>
<th></th>
<th>AFR</th>
<th>Glazing Dimension</th>
<th>U Average of Glazing</th>
<th>Glazing UA</th>
<th>Curb Height</th>
<th>Curb UA</th>
<th>Overall UA (Curb UA+Glass UA)</th>
<th>Average U-value for Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m x m</td>
<td>inch x inch</td>
<td>W/m2K</td>
<td>Btu/hr.Ft2.K</td>
<td>Btu/hr.F</td>
<td>m</td>
<td>inch</td>
</tr>
<tr>
<td>Square Apertures</td>
<td>2</td>
<td>0.64 x 0.64</td>
<td>25&quot; x 25&quot;</td>
<td>3.41</td>
<td>0.60</td>
<td>2.61</td>
<td>0.17</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>0.86 x 0.86</td>
<td>34&quot; x 34&quot;</td>
<td>3.20</td>
<td>0.56</td>
<td>4.52</td>
<td>0.17</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>1.07 x 1.07</td>
<td>42&quot; x 42&quot;</td>
<td>3.09</td>
<td>0.54</td>
<td>6.66</td>
<td>0.17</td>
<td>6.50</td>
</tr>
<tr>
<td>Linear Apertures</td>
<td>5.5</td>
<td>2.29 x 0.25</td>
<td>90&quot; x 9.9&quot;</td>
<td>3.74</td>
<td>0.66</td>
<td>4.07</td>
<td>0.17</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>2.29 x 0.34</td>
<td>90&quot; x 13.5&quot;</td>
<td>3.47</td>
<td>0.61</td>
<td>5.15</td>
<td>0.17</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.29 x 0.46</td>
<td>90&quot; x 18&quot;</td>
<td>3.28</td>
<td>0.58</td>
<td>6.50</td>
<td>0.17</td>
<td>6.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AFR</th>
<th>Glass Horizontal x Vertical Dimension</th>
<th>U Average of Glazing</th>
<th>Glazing UA</th>
<th>Curb Height (Curb is composed of)</th>
<th>Curb UA</th>
<th>Overall UA for Skylights (Curb)</th>
<th>Average U-value for Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m x m</td>
<td>ft x ft</td>
<td>W/m2K</td>
<td>Btu/hr.Ft2.K</td>
<td>Btu/hr.F</td>
<td>m</td>
<td>inch</td>
</tr>
<tr>
<td>Single Monitors (Length 30'/9.14m)</td>
<td>15</td>
<td>2.25 x 0.76</td>
<td>7.5 x 2.5</td>
<td>1.86</td>
<td>0.33</td>
<td>6.13</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2.25 x 1.00</td>
<td>7.5 x 3.3</td>
<td>1.78</td>
<td>0.31</td>
<td>7.82</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.25 x 1.28</td>
<td>7.5 x 4.2</td>
<td>1.73</td>
<td>0.30</td>
<td>9.50</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>Double Monitors (Length 30'/9.14m)</td>
<td>15</td>
<td>2.25 x 0.39</td>
<td>7.5 x 1.3</td>
<td>2.19</td>
<td>0.38</td>
<td>3.61</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2.25 x 0.52</td>
<td>7.5 x 1.7</td>
<td>2.02</td>
<td>0.36</td>
<td>4.45</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.25 x 0.64</td>
<td>7.5 x 2.1</td>
<td>1.92</td>
<td>0.34</td>
<td>5.29</td>
<td>0.25</td>
<td>9.75</td>
</tr>
</tbody>
</table>
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
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/ft²

### Radiance Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ab</th>
<th>ad</th>
<th>as</th>
<th>ar</th>
<th>aa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>2500</td>
<td>625</td>
<td>300</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Tool: EnergyPlus
Energy Model: One thermal Zone
   30’x30’ module with adiabatic walls
   Adiabatic ground

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

DIVA Thermal Model (Skylights)
5. Results Analysis

- Daylight Illuminance Distribution
- Electric Lighting Consumption
- Thermal Comfort
- Heating-Cooling Energy Consumption
- Energy Use Intensity
- Building Operation Costs
5. Result Analysis

Daylight Illuminance Distribution

Skylights 5.5% AFR

[Graph showing variations in illuminance (lx) over time for different types of skylights: Unintegrated_Square, Integrated_Beveled, Extended_Splays. The graph is labeled for times 1 to 24.]
5. Result Analysis

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

- **BaseCase**

- **Unintegrated_Square**
- **Integrated_Beveled**

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tr>
<td>kWh</td>
<td></td>
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</table>

[Graph showing daily average lighting electric use in kwh for different months, with two categories: Unintegrated_Square and Integrated_Beveled.]
5. Result Analysis

Electric Lighting Consumption

Square and Linear Skylights_ Various AFRs

Daily Average Lighting Electric Use

Boston

- 2%_Square
- 5.5%_Linear
- 3.5%_Square
- 7.5%_Linear
- 5.5%_Square
- 10%_Linear
- BaseCase

![Graph showing daily average lighting electric use in Boston for various AFRs](image_url)
5. Result Analysis

Electric Lighting Consumption

Square and Linear Skylights - Various AFRs

Daily Average Lighting Electric Use

Miami

<table>
<thead>
<tr>
<th>Month</th>
<th>2%_Square</th>
<th>5.5%_Linear</th>
<th>3.5%_Square</th>
<th>7.5%_Linear</th>
<th>5.5%_Square</th>
<th>10%_Linear</th>
<th>BaseCase</th>
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<tr>
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kWh
Glare Analysis

1. **Single Monitors**\_25\%\_Diffuse Glazing for South (Laminated 52\% Vt)
   - Intolerable glare

2. **Single Monitors with Baffles** \_25\%
   - Imperceptible glare
   - Clear glass with LoE, 90\% reflectance in baffles

3. **Single Monitor with Banner** \_25\%
   - Imperceptible glare
   - Diffuse Glazing for South (Laminated 52\% Vt) with a Banner (white fabric 50\% transmittance, 50\% reflectance)

<table>
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<th>dj</th>
<th>dr</th>
<th>Ir</th>
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<td>0.1</td>
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Glare Analysis

1. Skylights_Integrated Systems with Squared Lightwells
SFR 5.5%_Diffuse 42%Vt

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
5. Result Analysis

Heating Gas Consumption [kBtu]
Square Skylights

Boston and Miami

Graph showing heating gas consumption [kBtu] for Boston and Miami with different cases and percentages.
Cooling Coil Electricity Consumption [kBtu]
Square Skylights

Boston and Miami

- Miami_S5.5%
- Miami_BaseCase
- Miami_S3.5%
- Miami_S2%
- Boston_S5.5%
- Boston_BaseCase
- Boston_S3.5%
- Boston_S2%
5. Results Analysis

- Daylight Illuminance Distribution
- Electric Lighting Consumption
- Heating-Cooling Energy Consumption
- Energy Use Intensity
- Building Operation Costs
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

<table>
<thead>
<tr>
<th>Location</th>
<th>Electricity (cent per kWh)</th>
<th>Gas (Dollar per therm)</th>
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<tbody>
<tr>
<td>Boston</td>
<td>c5.48 (Oct-May) c8.28 (Jun-Sep)</td>
<td>$0.5732</td>
</tr>
<tr>
<td>Miami</td>
<td>c4.69</td>
<td>$0.3389</td>
</tr>
</tbody>
</table>

#### Graphs

- **Base Case, Boston**: $57, $74, $33, $17
- **Base Case, Miami**: $66, $82, $58, $38, $11

<table>
<thead>
<tr>
<th>AFR</th>
<th>Linear_Boston</th>
<th>Square_Boston</th>
<th>Linear_Miami</th>
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### Building Operation Costs in Roof Monitors
#### Boston and Miami

[$/yr per 900 ft² module$]

<table>
<thead>
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<th></th>
<th>Electricity (cent per kWh)</th>
<th>Gas (Dollar per therm)</th>
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<tr>
<td>Miami</td>
<td>c4.69</td>
<td>$0.3389</td>
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#### Graphs and Data Table

![Graph showing cost comparisons between Boston and Miami](image)

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<tr>
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<td>303</td>
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<td>331</td>
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6. Conclusions
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
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!