Energy Research and Development Division
FINAL PROGRAM REPORT

Enhanced Skylight Modeling and Validation

Part of the Evidence-based Design and Operations PIER Program

Prepared for: California Energy Commission

Prepared by: Daylighting Innovations (DI), Architectural Energy Corp. AEC), New Buildings Institute (NBI)

Contact: Cathy Higgins, NBI

MARCH 2013
CEC-500-08-049

The CEC is in the process of reviewing this Final Report

Prepared by:

Primary Research Team:
Zack Rodgers, DI
Judie Porter, AEC
Kosta Papamichael, CLTC
Cathy Higgins, NBI

Contact: New Buildings Institute
1601 Broadway
Vancouver, WA 98663
360-567-0950
www.newbuildings.org

Contract Number: 500-08-049

Prepared for:
California Energy Commission

David Weightman
Contract Manager

Virgina Law
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

The project team would like to acknowledge the work and support of the many individuals and organizations that contributed to the research and results of the Skylight Modeling and Validation Research.

Project 4 – Skylight Modeling and Validation

- Judie Porter Architectural Energy Corporation (AEC) – Project Manager
- Zack Rodgers Daylighting Innovations, Inc. – Lead Researcher
- Kosta Papamichael California Lighting Technology Center (CLTC) – Lead Project Advisor
- Cathy Higgins, New Buildings Institute - Reseach Program Manager
- Luis Lomelino Fernandes and Anothai Thanachareonkit formerly with CLTC – Field Measurements and Analysis
- Bruce Mosher and Velux - Skylight Photometric Facility and Product Support
- Kurt Levens Daylight Technology – Technical Support
- Mark Jongewaard, Calvin Lanpher, Meg Tidd and LTI Optics - Photopia Simulations, Software Access and Technical Support
- Michael Gauvin, Ed Freniere, Dave Jacobsen, and TracePro - Software Access and Technical Support
- Jacob Jonsson LBNL - Goniophotometer Measurements, Data Translation and Support.
- Andy McNeil LBNL; Greg Ward Anyhere Software - genBSDF, BSDF Material, and Radiance Simulation Support
- Barb Hamilton NBI – Final Report Review

For further information regarding the findings in this report please contact Zack Rodgers
zrogers@daylightinginnovations.com

TABLE OF CONTENTS

EXECUTIVE SUMMARY **1**

1. Skylight Testing and Validation **4**

1.1 Background 4

1.1.1 Objective 6

1.1.2 Approach 6

1.2 Outcome and Findings 12

1.2.1 Sky Measurement and Processing 13

1.2.2 BSDF Measurement and Processing 14

1.2.3 Simulation and Modeling 14

1.2.4 Computer Simulation Advantages 14

1.2.5 Photometric Valuation 15

1.3 Market Connections 15

1.3.1 Research Promotion and Outreach 15

1.3.2 Market Standards and Simulation Tools 16

1.4 Benefits to California 17

1.5 Conclusions and Next Steps 19

1.5.1 Next Steps 19

LIST OF FIGURES

Figure 1: Velux Test Facility 7

Figure 2: Skylight Types and Systems Tested 7

Figure 3: Isometric diagrams of the Sunoptics Light Box and the Sun Tunnel Geometric Models 10

Figure 4: Laser Scan 3D Prismatic Lens Material Models 11

Figure 5: Sky Image 9 (top) with Measured Photometrics and Simulated Photometrics (below) by TracePro, Radiance, and Photopia 11

LIST OF TABLES

Table 1: Potential Annual Energy Savings and Peak Demand Reduction of Greater use of Skylights in New Commercial Building Construction in California 18

EXECUTIVE SUMMARY

This Project Report (Final Report) summarizes the findings for the Skylighting Modeling and Validation project within the *Evidence-based Design and Operation* research program (Program) led by New Buildings Institute (NBI) and its subcontractors for the California Energy Commission's Public Interest Energy Research (PIER) program. The research period was October 2008 through March 2013 and included studies on an evaluation methodology for skylight system and materials performance using computer simulation.

A fully detailed technical report on the research is available at www.newbuildings.org/pier-research.

NBI was the prime research investigator for the Evidence-based Design and Operations Program and supported the work of the research team. The Skylight Modeling and Validation research team was led by Architectural Energy Corporation with Daylighting Innovations performing the technical investigation of the modeling validation and the California Lighting Technology Center performing the field measurements.

Objectives. The objectives of the *Enhanced Skylight Modeling and Validation* project (Skylight Modeling Research) were to define, develop and validate accurate computer simulation methods for producing skylight photometric data. This alternative to reliance solely on physical measures to obtain this data would reduce significant constraints on skylight manufacturers who need to deliver performance information on their products and provide Illuminating Engineering Society of North America (IESNA) compatible files that are usable in lighting design software.

Background. Interior lighting accounts for the largest portion of electricity used in California's commercial buildings – almost 30%[1]. Commercial building skylight and daylighting products, integrated with controls that lower electric lights in response to daylight, can significantly reduce lighting energy use. Building and lighting designers are accustomed to using lighting simulation software to review options for lighting a commercial space and meeting code and client requirements. Lighting manufacturers produce photometric files for each of their lamp products (based on an IESNA[2]-standardized format) and supply the files to the designers and software program companies.

However, skylight manufacturers have limited information to provide on product performance. The industry currently relies on taking physical measurements of daylighting systems in photometric labs to obtain performance data. The physical measurement methods are constrained by factors including skylight size, sky opening, photometric resolution and available geographical aspects (solar altitude). These factors consume time and carry significant costs and accuracy concerns. To increase the use of skylights as a daylighting strategy to reduce

[1] *The California Commercial Energy Use Survey (CEUS), Itron, 2006.*

[2] IESNA is the recognized technical authority on illumination in the U.S.

electric lighting, manufacturers need more accurate and affordable methods to produce photometric data.

Approach. The research had two primary tasks in the development of validated photometric files: measurement and conducting simulations using the measurement data. The measurement task collected real-world skylight system photometric data combined with simultaneous measurement of a variety of sky and solar light conditions. The simulation task used field data from the measurement phase to perform comparable computer simulations of the skylight systems. Measurements were conducted at the Velux[3] daylighting laboratory in South Carolina. Three skylight configurations were selected to test a representative range of different optical complexities and installation configurations. The simulation task developed modeling protocols and simulation methodologies and validated these by demonstrating correspondence with the data provided in the measurement tasks.

The researchers created representative computer models of all aspects of the daylighting system: sky and sun source, skylight system geometry and material characteristics, and near-field meter locations. Three common lighting simulation software tools - TracePro, Photopia and Radiance - were reviewed to ensure modeled results were compatible with these programs. A process of creating detailed reflectance and transmittance information data, known as Bi-Directional Scatter Distribution Function (BSDF), was a key aspect of the research and involved collecting detailed measurements from the main optical surfaces of the skylight products. The research used various simulation settings and methodologies for BSDF for each software tool; final simulation results from each tool were compared to the measured data.

Results. The research team successfully demonstrated the ability to use computer models based on field data to predict skylight systems performance and to produce replicable modeled results. These findings represent new and validated research outcomes that are transferable to manufacturers, researchers and academics.

Some of the findings and conclusions from this research are now being discussed by lighting experts, architects, manufacturers and daylighting designers. Of significant note, these findings demonstrate that the simulated photometric distributions from this research were found to be highly reliable in matching the general shape of the physical measurements for simple to complex optical skylight systems under a range of sky conditions. However, there was a lower reliability in capturing the exact point by point luminous intensity (the level of light at a given point from a source of light). The absence of exact point-by-point luminous intensity data can affect the results of glare analysis but does not reduce the value of the modeled approach for the overall skylight photometrics; rather, it identifies one area for possible reinvestigation. Finally, the research demonstrated that the accuracy and detail of any BSDF measurements used to describe optical materials in the system is critical; the accuracy of the exact system geometry does not appear to be as critical in evaluating systems lighting effectiveness.

[3] Velux is a major U.S. skylight manufacturer and a member of the project advisory team. Testing at the Velux facility was done independently by the research team and included Velux and other manufacturers' products.

Market Connections. The research findings are already being considered for adoption in testing methods by one manufacturer (unnamed) and for inclusion in some existing lighting software programs. Based on the work of this study, research team members will produce a companion document to a key committee (LM-81-10) within IESNA to propose a new "Approved Method: Photometric Testing of Skylights" using computer simulation techniques developed from this research. The team will also encourage IESNA to create a subcommittee to link computer simulation of skylights to physical measurements. IESNA is a critical pathway to moving the modeling method into the simulation tools marketplace. Since the National Fenestration[4] Rating Council (NFRC) is responsible for setting the standards for the measurement and metrics associated with windows and skylights, the researchers will present findings from this work to the NFRC and the idea of system-level BSDFs to NFRC.

[4] Fenestration refers to the design and characteristics of windows and other exterior openings of a building.

1. Skylight Testing and Validation

The *Enhanced Skylight Modeling and Validation* research project (Skylight Modeling Research) aimed to develop and validate computer methods, as a viable alternative to physical measurements, to produce information on the characteristics of the light from commercial building skylight products. This type of information can assist lighting design professionals when considering how and where to use skylights in building design as a strategy to displace electric lighting with natural light (daylighting).

This report is a summary of the findings from Project 3 - Skylight Modeling Research - funded by the California Energy Commission's Public Interest Energy Research (PIER) program within a broader program called Evidence-based Design and Operation. The research occurred from 2010-2013 and was led by Architectural Energy Corporation (AEC) and the California Lighting Technology Center (CTLC). Daylighting Innovations (DI) performed the simulation work and validation analysis and the CLTC was responsible for the physical measurements with support from DI. Other key technical and match contributors included LTI Optics, Velux, Lambda, Lawrence Berkeley National Laboratory (LBNL) and Daylight Technologies. New Buildings Institute (NBI) was the program manager.

An in-depth report titled *Enhanced Skylight Modeling and Validation* (Skylight Modeling Report) was developed[5]. It provides additional details on approach, conclusions and recommendations from this research project.

1.1 Background

Interior lighting accounts for the largest portion of electricity use in California's commercial buildings – almost 30%[6]. The last decade of progress in lamp and ballast efficiency is impressive but it is the integration of daylighting controls – controls that reduce the electric lighting in response to daylight – that is one component to meeting policy goals for zero net energy buildings (ZNE) in new construction.

Daylighting designs, which include skylights and daylighting products that are integrated with controls for the electric lights, are recognized as "best practice" by rating systems such as the U.S. Green Building Council's Leadership in Energy and Environmental Design-[for] New Construction (LEED-NC) and is recognized as important conservation strategy in some State energy codes and standards. For example, California's non-residential energy code - Title 24 part six (Title 24) requires daylighting controls in daylit areas larger than 250 ft^2. The purpose of the controls is to lower electricity use through devices such as dimmers, automatic shading systems, or bi-level lighting switches when sunlight is available as a substitute for electric lighting. LEED-NC states that daylight should be introduced into at least 75% of regularly

[5] http://www.newbuildings.org/pier-research

[6] *The California Commercial Energy Use Survey (CEUS), Itron, 2006.*

occupied building areas. The Advanced Buildings *Core Performance Guide*[7]– used by utility new construction energy efficiency programs across the nation - requires that electric lights in daylit areas be designed with control systems to minimize their use with sunlight is available. Building designers need tools to respond to these best-practice market drivers.

An office building in Oakland, California, that was studied through this PIER program (see Chapter 2) provides a quick example of the reason for this research which is intended to increase the use of daylighting in buildings. Occupied in 2006, this building met the standard requirement Title 24 for 'installed' lighting of 0.8 watts per square foot of space (W/sf). Yet due to daylighting controls the measured lighting energy use during occupied periods was only 0.33 W/sf – a 59% reduction.

Skylights are an important part of the strategy to accomplish energy reduction through daylighting. Windows by themselves are not always the best source to 'light' the space because daylight quickly diminishes as distance increases away from the window. At least 60% of nonresidential ceiling area in California is directly below a roof that can potentially provide access to daylighting, and 90% of new floor space is single-story construction[8]. Skylight systems, with controlled electric lights, have a significant potential for saving lighting energy.

Lighting manufacturers provide information about the photometric (light) performance of their luminaires (light systems) in the form of candlepower[9] distribution data. This data is delivered in a specific format validated by the industry technical authority - IESNA - that allows it to serve as input to lighting simulation (software) tools. Building and lighting designers are accustomed to using these simulation tools to review the options for lighting a commercial space and to meet the code and client requirements.

In contrast, skylight manufacturers have very limited information to provide to building and lighting design teams in order to assist them with predicting the performance of skylights and specialty daylighting devices. This is due to a variety of technical, time and cost constraints specific to the current approach for determining the lighting performance of skylights. This current determination method requires taking physical measurements for each skylight product in a photometric laboratory setting.

The absence of widespread photometric information on skylight systems makes it very difficult to accurately compare the performance of different products. This information is critical to determining the optimum position and distribution of these devices in a given space and to for predicting year-round performance of skylights and specialty daylighting devices in building projects. Increasing the use of skylights in commercial buildings depends in part on creating

[7] http://advancedbuildings.net

[8] McHugh, 2003. Modular Skylight Wells: Design Guidelines for Skylights with Suspended Ceilings, PIER Report 500-03-082-A-13

[9] Candlepower expresses levels of light intensity in terms of the light emitted by a candle of specific size and constituents and is a common metric in light design.

more replicable, reliable and industry adopted methods that present the lighting performance of skylights in file formats compatible with existing design tools.

1.1.1 Objective

The objective of the project was to define, develop and validate accurate computer simulation methods, as an alternative to physical measurements, for producing skylight candlepower distributions data and useful optical daylighting system (skylight) photometry information in an IESNA compatible format. The candlepower distributions would be applicable for a variety of locations, climates and, provided its material properties are known, skylight types.

This research has the potential to greatly advance both science and technology in the skylight industry by validating a new method for assessing photometric performance that has been slowly maturing over the last 20 years. This method only recently has become realistic and cost-effective due to new measurement and modeling tools. This new method could solve the limitations that exist when relying on physical measurements, i.e., cost, time and technology.

1.1.2 Approach

The project approach was to compare several physical photometric measurements of optical daylighting systems (skylights) to computer models, validating the use of computer simulation to reproduce this photometric information. The project used two main approaches: measurement tasks and simulation tasks.

1.1.2.1 Measurement Task

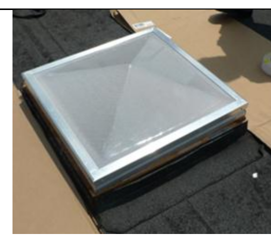
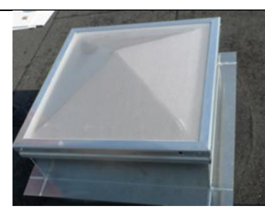
The testing facility for this project was an 18’x18’x18’ building owned by the Velux Company located in Greenwood, South Carolina. Velux, a skylight manufacturer, has developed a unique facility that allows measurement of skylight candlepower distributions under real sky conditions. The building shown in Figure 1 was designed to house a custom-built goniophotometer[10] for measuring the luminous intensity distribution that emanates from a maximum 2’x2’ skylight. The goniophotometer system within the facility is comprised of sensors, data logging equipment and a computer that controls the overall measurement process and capture. Measurements were performed in July because sun angles are high then and the time of year provided a good chance for mixed sky conditions.

[10] A device used for measurement of the light emitted from an object at different angles.

Figure 1: Velux Test Facility

Three skylight configurations were selected for testing to represent a range of optical complexities and different manufacturers. These products ranged from ones with very simple single optics to more complex systems with multiple optical layers. Figure 2 show images of the three daylight systems that were used.

Figure 2: Skylight Types and Systems Tested

Skylight Type	Selected Products	Image
1 – Basic Skylight: Basic skylight: minimal optics, "low" aspect ratio	Sunoptics[11] pyramid skylight Top prismatic lens White diffuse lightwell	
2 - Moderate skylight: dual optics, "med" aspect ratio	Sunoptics pyramid skylight "light cube" Top and bottoms prismatic lens Reflective lightwell	

[11] Sunoptics Prismatic Skylights, an Acuity Company, http://www.sunoptics.com/

Skylight Type	Selected Products	Image
3 - Advanced skylight: multiple optics, "high" aspect ratio	Sun Tunnel™[12] Top clear lens Bottom prismatic lens Reflective tubular lightwell	

For this study, the sky distribution measurements were taken on the roof during the same duration of time that the goniophotometer measurements were done inside the building. The CLTC determined the different measurement devices utilized to accurately capture the sky resource.

Four groups of measurements were taken: Group 1 - sky luminance at zenith; Group 2 - sky luminance mapping; Group 3 - global horizontal illuminance; and Group 4 - diffuse horizontal illuminance. Sky zenith luminance measurements were taken to compare and calibrate the sky luminance mapping. In addition, horizontal and diffuse illuminance measurements were taken to further compare and calibrate the captured luminance maps.

Simultaneous measurements were taken on the roof using the luminance camera, luminance meter and horizontal illuminance meter, and in the interior of the facility using the automated goniometer. The time of each measurement was recorded and referenced to a legal time server. The research team also worked on illuminance meter calibration and captured material reflectance measurements.

A total of 32 sets of measurements were taken over three days. The goal was to achieve measurements with low, medium and high sun angles and with clear, partly cloudy and overcast skies to obtain a robust data set for thorough validation. Each measurement set yielded a sky luminance map, assembled from 16 hemispherical photographs taken with different exposures. These images were then assembled into a single high-dynamic range (HDR) image, thus providing an accurate luminance map of the scene.

Zenithal sky luminance was measured for each hemispherical image captured, resulting in 16 measurements per test. These showed some variance, particularly for the higher sun angles with a bright zenith, and were averaged for each test. Both global and diffuse horizontal illuminance measurements were taken.

Material measurements were taken for any onsite elements that would impact the optics of the skylight system, particularly for any exposed wood in the roof and skylight framing, the floor and walls of the goniophotometer room.

---

[12] Velux, http://www.veluxusa.com

Photometric files were obtained for 24 out of the 32 tests. The remaining eight tests had faulty or otherwise unreliable data and were not used for further validation. Of these 24 tests, 12 were chosen for final validation with computer simulation: four for each of the three skylight systems. For each skylight system, a test representing a low, mid and high sun angle was chosen under a clear sky and a partly cloudy condition. This set of 12 skies is used to validate the computer-simulated luminous intensity (discussed in the next section).

1.1.2.2 Simulation Task

The simulation task used field data from the measurement phase to perform comparable computer simulations of the skylight systems. The steps included:

- Processing the sky HDR images and recorded diffuse and global illuminance measurements into complete and calibrated sky luminance maps and sun sources.
- Creating ray-sets for use in forward ray-tracing engines from the sky and sun sources as well as developing the skylight geometric models.
- Developing near-field and far-field photometric simulation approaches.
- Performing Bi-Directional Scatter Distribution Function (BSDF) measurements of the skylight materials and developing BSDF models for each critical optical surface.
- Creating the photometric files for the three skylight systems.

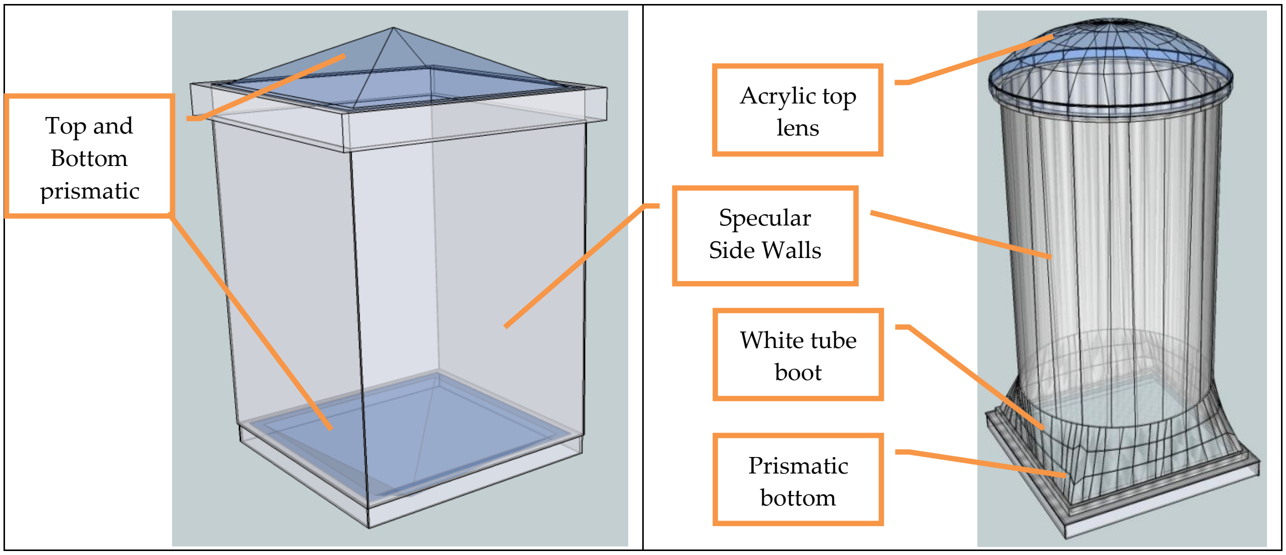
Sky Measurement Processing and Model Creation. Prior to beginning the validation tasks, data from the physical measurements had to be processed into useable forms that represented a hemisphere of sky and that could be incorporated for use in ray-tracing software. To accomplish this, the raw photographs were cropped to represent a perfect hemispherical image with an angular mapping. A negative masking layer was created and applied to the cropped sky and adjusted to match measured sky illuminance. A matching Perez sky[13] was created for the current condition, then adjusted for “sky” shading and applied to a positive masking layer to create a filler patch. Finally, the masked measured and Perez sky models were combined, and a sun definition was added to create a final sky.

Sky Source Ray Set Creation. The research team then took the calibrated sky luminance map and direct solar source and turned it into a form that can be used by the forward ray-tracing programs. Two different approaches were explored in TracePro and Photopia (widely used lighting design software programs): the creation of a continuous ray-set and the application of sky luminance patches to a Tregenza sky patch model.

Geometric Model Development. 3D geometric models were created of the three skylight systems tested (Figure 3). A fairly simple model was created for each skylight system that includes the basic elements as perfect geometric forms (i.e. pyramids, prisms).

[13] A standard used for measured luminance data modeling of the sky named for Richard Perez (University of Albany 1991).

Figure 3: Isometric diagrams of the Sunoptics Light Box and the Sun Tunnel Geometric Models



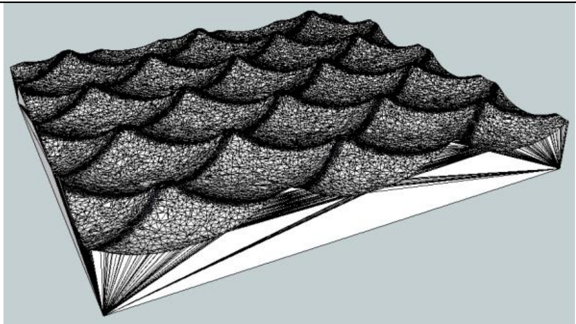
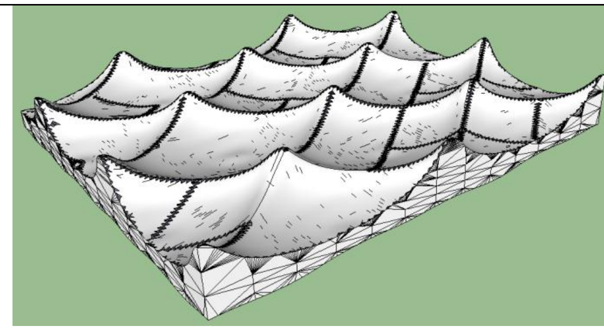
Near-Field vs. Far-Field Comparisons. With performance luminous intensity measurements, it is important to measure the intensity far enough away from the source so it acts as a point source for the given direction. Typically a 5:1 rule (where measurements are taken at least 5x the distance of the maximum dimension of the source) is followed. The physical luminous intensity measurements performed for the skylights are around this 5:1 limit and hence represent more of a "near-field" photometry. The computer simulations have the ability to report absolute "far-field" photometry (measurements are taken at an infinite distance away) as well as near-field photometry.

BSDF Measurements and Modeling. The next step in creating accurate computer models of the skylight systems was to model the optical properties of the surfaces in those systems. Visible reflectance and transmittance measurements were made for any surface that interacts with the optics of the system. Samples of the prismatic lenses were cut from the actual skylights tested and shipped to Lawrence Berkeley National Laboratory (LBNL), LTI Optics and The ScatterWorks for detailed BSDF measurements.

In addition, samples of the Sunoptics box sidewall, Sun Tunnel sidewall and Sun Tunnel boot were measured at LBNL. Samples of both skylight lenses were also sent to a laser scan company, and high-resolution 3D models (Figure 4) were created of each lens, which included many of the minor imperfections in the lens due to the manufacturing process (such as the dimple marks left likely from the injection molding process).

While these various labs and simulation approaches all measured BSDF information, each utilized a different data format and definition standards, thus making comparison and cross use of the data difficult. Due to this, each BSDF generation method was matched with the simulation engine to which it was best suited: Radiance, TracePro or Photopia.

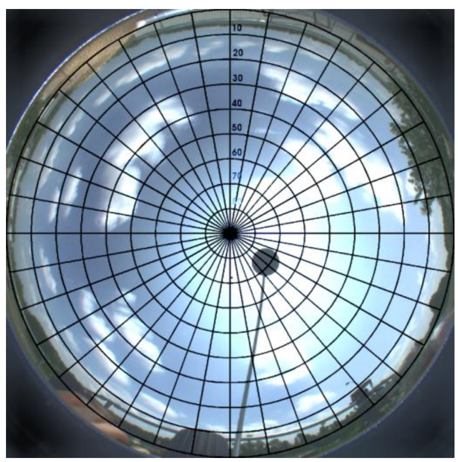
Figure 4: Laser Scan 3D Prismatic Lens Material Models

	
Sunoptics prismatic lens	Sun Tunnel prismatic lens

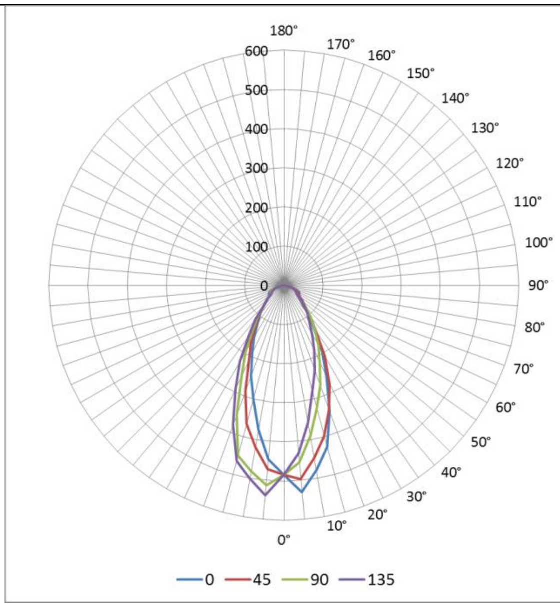
Photometric Creation. The final step was working through various simulation processes and settings using the calibrated sky models and BSDF measurements to create photometric results. This step was done for all three lighting software platforms: Radiance, Photopia, and TracePro.

Figure 5 shows an example of a sky image taken at the Velux facility, the physical measurement photometrics, and the simulated photometrics with each software platform.

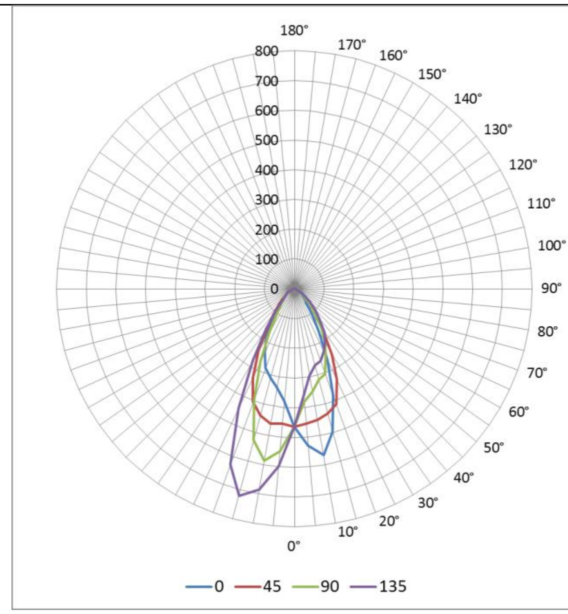
Figure 5: Sky Image 9 (top) with Measured Photometrics and Simulated Photometrics (below) by TracePro, Radiance, and Photopia



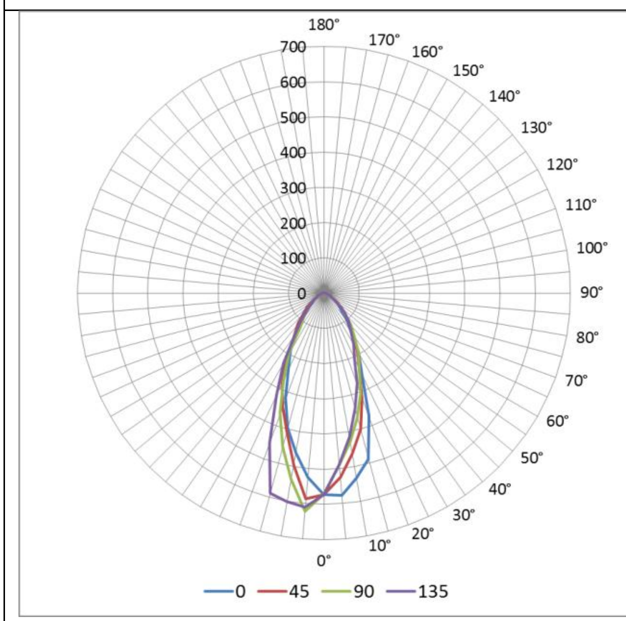
Sky Image 9



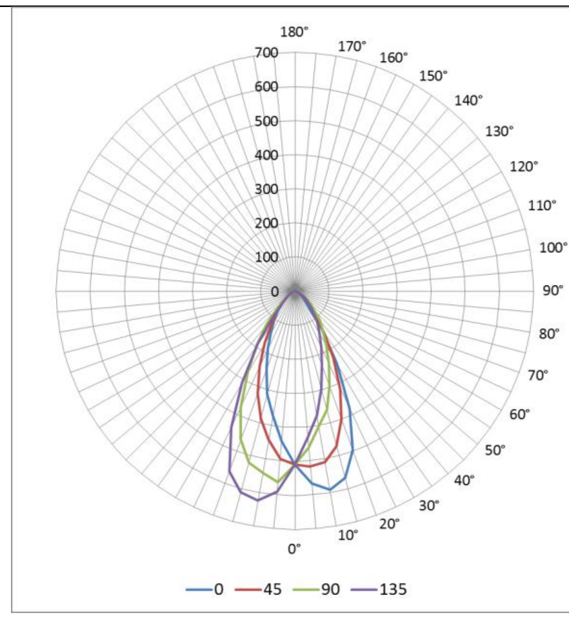
Physical Measurement



TracePro Simulated



Radiance Simulated



Photopia Simulated

1.2 Outcome and Findings

The outcome from the research findings is most significant for skylight manufacturers that use software platforms like Radiance, TracePro and Photopia to simulate the performance of their products and to provide performance data to lighting and daylighting designers. As lighting manufacturers utilize these results and the outcomes become a part of lighting software, building and lighting designers will be able to improve their application of skylights in the built environment, leading to greater opportunities for energy savings. Other audiences include academic institutes (universities) interested in lighting and daylighting analytics and testing methods.

In response to the interests and needs of these audiences, the Skylight Modeling Report, and the section below in this summary report, present the findings organized by the five areas of investigation:

- Sky measurement and processing
- BSDF measurement and processing
- Simulation and modeling
- Computer simulation advantages
- Overall photometric validation

In-depth information on this project's research is in the full technical report referenced earlier - the Skylight Modeling Report. The report provides additional details on approach, conclusions and recommendations for the physical measurements, simulation, and validation tasks for the selected skylight systems noted above. Project research activities and the Skylight Modeling Report received valuable input from a project advisory team (PAC) that included representatives from LTI Optics, Velux, Lambda, LBNL and Daylight Technologies.

1.2.1 Sky Measurement and Processing

The research determined a new method for capturing hemispherical sky images that results in valid and useable sky luminance descriptions. Some key findings regarding this new methodology were that:

- The method requires a digital camera with a hemispherical lens and exposure bracketing ability, a shading disc to obscure the solar disc, and simultaneous global and illuminance measurements to calibrate the resulting HDR image.
- It is important that the shading disc for both the camera and the illuminance meter (for the diffuse measurement) block the same solid angle of the sky.
- The illuminance measurements proved to be more useful for calibration of the skylight measured performance with the modeled performance than the zenith illuminance measurements that were more variable.

The new measurement method for cropping, masking, filling in and calibrating the HDR sky images enabled the creation of a new equi-angular hemispherical luminance map valid for use in lighting software. The method for using the calibrated sky luminance map to generate a set of sky and sun rays useable in forward ray-tracing software resulted in a valid sky and sun ray source adjustable by desired density and resolution.

In all measurements it was important to pay careful attention to the orientation of any anisotropic and/or asymmetric optics as they greatly impact the exact optical performance of the system.

1.2.2 BSDF Measurement and Processing

A variety of different visible reflectance and transmittance measurements were taken to access the properties of the skylight systems and materials. Simulations were performed for the main optical materials in the three systems at different locations and angles. The most important locations were the top and bottom prismatic lenses and the side walls of the skylight systems which are highly reflective.

1.2.3 Simulation and Modeling

Various simulation processes and settings were used in creating photometric results using the calibrated sky models and BSDF measurements. Some of the simulation and modeling findings were:

- For the tested skylight products, far-field simulation did not vary much from near-field simulation using TracePro. In forward ray-tracers, far-field simulations and near-field emulators used by Photopia appear to be acceptable alternatives for collecting photometric information.
- An adequate amount of rays is necessary for obtaining smooth and accurate exiting photometrics, particularly using forward ray-tracers.
- For highly specular and reflective systems that exhibit potential for multiple bounces within the system, it is important to simulate adequate bounces.
- Along with a high maximum reflection setting, a low flux threshold setting is recommended to help capture the flux at sharp incoming and exiting angles.
- Using Radiance, adequately high simulation parameters during the generation of both the lens BSDF definitions and system BSDF definitions is critical for accurate tail-end simulations.

1.2.4 Computer Simulation Advantages

Overall, a computer simulation approach avoids the disadvantages of using physical photometric measurements of skylight systems to verify their properties. There are:

- No Size constraints – The simulation methods developed using the three different systems have no size constraints. The daylighting systems could be 1′ to 100′ wide and the software would deal with the simulation equally. Unless optical elements are added to the system, these larger sizes will not significantly impact the simulation time.
- No Sky condition constraints – The simulation methods can use any sky/sun source desired and at any time. Captured sky images can be fed in the simulations or standard algorithmic definitions such as the CIE or Perez standards. Any sky condition can be simulated at any time or any location.

- No Photometric resolution constraints – The simulation methods can produce high resolution photometrics, but not unlimited resolution. The ultimate resolution is dependent on the resolution used in defining all BSDF materials in the systems and on the simulation parameters used.
- Fewer Time constraints – The simulations can be carried out at any time and on any number of computers, drastically improving the accessibility to detailed skylight performance data.

1.2.5 Photometric Valuation

Overall, the simulated photometric distributions matched the general shape of those measured quite well, with the following specific findings:

- The accuracy and detail of any BSDF measurements used to describe optical materials in the system is critical. Isotropic and low resolution representations appear to miss critical optical characteristics of both a single material and an optical system.
- The accuracy of the exact system geometry did not appear to be as critical. This was observed to have a minimal impact on the results where fillets were added to the lens in the Photopia Sunoptics simulations. Also, the tested skylights likely have many imperfections relative to scratches and marks on the lenses as well as dents and marks on the reflective tubes. However, there were no noticeable quirks in the photometric data to indicate any major imperfections in the manufactured geometry.
- All simulation engines (lighting software tools had a limited ability to capture high-angle light leaving the systems.
- All the simulation approaches appeared to adequately describe the general shape of daylight distribution for simple to complex optical skylight systems under a range of sky conditions.
- Time constraints – the simulations can be carried out at any time and on any number of computers drastically improving the accessibility to detailed skylight performance data.

1.3 Market Connections

The market connection work for this project focused on industry players involved in daylighting manufacturing and the design and integration of electric lighting and skylighting systems into the built environment. The following section describes the connections made and those that hold promise for these results to have impact on reducing energy use in California buildings.

The research team shared the results through a variety of promotion and outreach methods as well as through engagement with leading industry and manufactures as described below.

1.3.1 Research Promotion and Outreach

- **Presentations** at various lighting and manufacturer venues will be held in late 2013 and early 2014 by DI and the CLTC.

- **Webinars** were held by AEC and DI with assistance from the CLTC on the results to both the project advisors and the daylighting design community in March 2013. The advisors also joined project webinars in 2011 to review preliminary findings.
- **Industry involvement and articles** citing the results are planned for the *Illuminating Engineering Society of North America*. In particular, Daylighting Innovations and LTI Optics are planning a companion document to the IESNA LM-81-10: "Approved Method: Photometric Testing of Skylights" using Computer Simulation Techniques. It is also planned to encourage IESNA to create a subcommittee with the mission of linking computer simulation of skylights to physical measurements. IESNA is the recognized technical authority on illumination in the U.S. and a critical pathway to the research progress on moving the modeling method into simulation tools.

1.3.2 Market Standards and Simulation Tools

- **Skylighting manufacturers and design teams**. Results from this research are publicly available enabling manufacturers to provide better information about predicted performance to building design teams. In particular, one major skylighting manufacturer – remaining anonymous due to the potential advantage use of these findings may provide - has stated strong interest in funding work to produce this type of data for their spring 2013 product line. This is a major step toward other manufacturers understanding the significance of the research results and getting involved.
- **National Fenestration Rating Council (NFRC)** is responsible for setting the standards for the measurement and metrics associated with fenestration[14] products. Zack Rodgers, research team member from DI, will provide the results of this work to the NFRC in mid-2013 as a reference for the inclusion of daylighting product metrics and the idea of system-level BSDFs.
- **Simulation Software for Daylighting Products.** Three software platforms - Photopia, Radiance, TracePro - provide the ability to simulate skylight performance that generally match physical measurements. Publication of the research results and continued refinement of the validation methodology and BSDF measurements will increase the rigor of these tools as well as encourage the development of other new tools.
- **Other Daylighting Software.** The resulting system BSDF files and design day photometrics can be integrated into many other lighting/daylighting design and analysis software such as AGI32, Visual, SPOT, OpenStudio, DIVA for Rhino, Energy Plus. At least these three ray-trace software can be used to create the data but a number of other software can make use of the data.
- **Utilities.** The results of this research can inform utility program managers for energy efficiency programs focused on electric lighting and daylighting integration as well as

[14] Fenestration refers to the design and characteristics of windows and other exterior openings of a building.

the ZNE initiatives. Outreach in this area beyond exposure of the program-level advisory group to the research objectives and findings did not occur during this research project.

- **Code Governing and Rating Agencies.** Green building rating systems, energy efficiency codes and standards, and ZNE initiatives provide strong market drivers for adoption of tools that improve the integration of quality daylight into the built environment. These should in turn help the manufacturers find a highly interested audience in the design teams responding to these policy factors.

1.4 Benefits to California

The results and methodologies developed from this project provide more accurate information about the performance of skylighting products and specialty daylighting devices to lighting and daylighting designers, energy consultants and building engineers. This will provide the kind of information necessary for design teams to more consistently and successfully integrate daylighting and electric lighting in their projects. California sales of skylights and lighting controls could increase and expand a small niche of work into a larger employment opportunity based on the large amount of commercial floor space eligible for skylight daylighting.

Table 1 presents the estimates for annual energy and peak demand savings potential of a greater use of skylights in new commercial buildings in California.

Table 1: Potential Annual Energy Savings and Peak Demand Reduction of Greater use of Skylights in New Commercial Building Construction in California

Commercial Occupancy Types	**Electricity Consumption Savings**	CA interior lighting electricity consumption for appropriate building segments and end uses (GWh/year)	Savings in electricity consumption from proposed research product (%)	Expected penetration into building segment and end use markets (%)
Large Offices	**5.89**	2,945	20%	1.0%
Small Offices	**2.77**	1,386	20%	1.0%
Restaurants	**1.92**	961	20%	1.0%
Retail	**21.23**	4,246	20%	2.5%
Food Stores	**6.17**	1,233	20%	2.5%
Warehouses	**7.43**	1,485	20%	2.5%
Schools	**2.56**	1,281	20%	1.0%
Colleges	**1.58**	790	20%	1.0%
Hospital/ Healthcare	**2.24**	1,119	20%	1.0%
Hotels/ Motels	**1.89**	945	20%	1.0%
Misc.	**5.75**	2,874	20%	1.0%
Residential	**57.74**	28,870	20%	1.0%
Total	**117.16**	48135		
Commercial Occupancy Types	**Peak Demand Savings**	CA lighting peak demand for appropriate building segments and end uses (MW/year)	Savings in peak demand from proposed research product (%)	Expected penetration into building segment and end use markets (%)
Large Offices	**1.15**	575	20%	1.0%
Small Offices	**0.79**	394	20%	1.0%
Restaurants	**0.35**	174	20%	1.0%
Retail	**3.90**	779	20%	2.5%
Food Stores	**0.89**	177	20%	2.5%
Warehouses	**1.56**	312	20%	2.5%
Schools	**0.84**	418	20%	1.0%
Colleges	**0.35**	177	20%	1.0%
Hospital/ Healthcare	**0.34**	172	20%	1.0%
Hotels/ Motels	**0.30**	149	20%	1.0%
Misc.	**1.18**	591	20%	1.0%
Residential	**6.93**	3464	20%	1.0%
Total	**18.57**	7383		

The energy and peak demand savings represented in Table 1 are estimated based on 20% savings from integrating skylight systems with controls that turn off electric lighting in the occupied space of various California commercial building types. Market penetration is conservatively estimated at between 1% to 2.5% depending on building type. These savings and penetration estimates result in a potential of 117 gigawatt hours of energy and 18 gigawatts of peak energy savings per year in California commercial buildings. Non-energy impacts include increased health and well-being for building occupants and productivity gains. The research results will be in the hands of the daylighting consultants, skylight manufacturers, utilities and policymakers who can make these potential impacts a reality.

1.5 Conclusions and Next Steps

The research team successfully demonstrated and documented the ability to use computer models based on field data to predict skylight performance and produce valid modeled outputs of the performance. Radiance, TracePro, and Photopia were shown to be valid software for simulating the performance of skylight systems given accurate input and careful simulation settings as described in the report.

The research team's engagement with key committees at IESNA and NFRC – the leading organizations responsible for setting the technical standards for lighting and windows/skylights respectively – is a major step toward aligning these standards with the research results. As these organizations adopt the research recommendations, and the photometry files are put to use by skylight manufacturers and through lighting software tools, the use of skylights as daylight strategies to reduce electric lighting will accelerate by design teams.

The simulations can be carried out at any time and on any number of computers drastically improving the accessibility to detailed skylight performance data. Design teams will able to respond to client interest for improved indoor environments and 'green' buildings[15] and help to meet policy drivers in California such as Title 24 and ZNE targets.

1.5.1 Next Steps

Based on the findings from this study the following next steps are recommended.

1. Form an IESNA daylighting sub-committee to develop and publish a companion document to the IES LM-81-10 that outlines an approved method for creating optical daylighting system photometric distributions using computer simulation. The daylighting sub-committee should also develop an approved annual daylight simulation methods that takes into account an optical daylighting systems
2. Coordinate with the National Fenestration Rating Council (NFRC) to expand their rating, certification and labeling efforts to include additional daylighting metrics. Also work with NFRC to implement system photometric information in future daylighting product metric and rating efforts. This is likely an expansion of the Visible Transmittance (VT) metric currently used for fenestration which is a simple measurement of light transmittance at a single perpendicular angle.

[15] By 2015, an estimated 40-48% of new nonresidential construction by value will be green. McGraw Hill, 2012

3. Create an openly available benchmark database with the measured sky and photometry sets for future validation of simulation engines or to validate further refinement of the methods explored in this report. More daylighting benchmarks in general are needed in the daylighting simulation industry to ensure reliable data is being produced and reported to the design industry and this data set could be part of these efforts.
4. Engage and inform daylighting software developers of any daylighting system photometric standard developments and annual simulation standard developments accomplished through activity 1 above. Encourage the adoption and development of software that includes daylighting system photometric data and validated annual calculations. Work with daylight software developers that are already involved in related IESNA daylighting committees.
5. Engage and inform the architectural daylighting design community as to the relevance of having more detailed photometric available when reviewing products and simulating performance. Likely, their main exposure to these advances will be through new labels that reports new daylight metrics on daylighting products and new advances in their lighting software that simply correctly simulates these devices.