ANALYZING AND REDUCING ENERGY CONSUMPTION ON THE MICHIGAN STATE UNIVERSITY CAMPUS

By

Alexander Renny

A THESIS

Submitted to
Michigan State University
In partial fulfilment of the requirements
For the degree of

Chemical Engineering – Master of Science

2017

ABSTRACT

ANALYZING AND REDUCING ENERGY CONSUMPTION ON THE MICHIGAN STATE UNIVERSITY CAMPUS

By

Alexander Renny

The reliance on fossil fuels to generate most of the world's energy has led to a significant increase in greenhouse gas emissions and the associated negative effects on the climate. The application of energy reducing retrofits allows for significant reductions in total energy use, providing the opportunity to achieve cost savings as well as emissions reductions. Students Planning Advanced Retrofit Technology Applications (SPARTA) was founded to pursue implementation of these retrofits at Michigan State University (MSU). Under this framework, lighting, device, and HVAC retrofits are examined. In commercial spaces, lighting comprises ~17% of total electricity used. The economic viability of retrofitting LEDs in place of fluorescent ceiling fixtures as well as various control methods are determined. The energy use intensity of the average office space on the MSU campus is also analyzed and equipment changes are recommended to decrease the total energy footprint. Conversion from electricity driven cooling to steam driven cooling is evaluated as a method for increasing efficiency of the co-generation power plant and decreasing total fuel consumption. Finally, activities aimed at engaging the public on renewable energy generation are described, which are based on the development of paintable luminescent solar concentrators that combine art and energy. A number of techniques for reducing energy use on the MSU campus have been analyzed which can be applied across a broad spectrum of spaces. Continuing to aggressively pursue the implementation of this framework as well as tracking key economic indicators outlined will ultimately make MSU cleaner and more sustainable.

To my parents, Karen Grady and Craig Renny, for their never-ending love and support.

ACKNOWLEDGEMENTS

I would first like to thank the students of SPARTA – this includes Aryka Thomson, Ben Stephens, Philip Wandor, Bo Li, Lee Padilla, Yuzhu Liu, and Haojun Wang. Without all of you none of this would have been possible. To everyone in the MOE lab – especially Chenchen Yang – thank you for your help in and out of the lab. I would also like to thank Ann Erhardt at Sustainability for championing my cause, as well as Kane Howard, William Lakos, and Jason Vallance at IPF for all of their help. Also, my deepest thanks to Dr. Richard Lunt, my advisor, for helping guide me through SPARTA and graduate school in general. Thank you to Dr. Rebecca Anthony for all of your help co-advising SPARTA. I'd also like to thank Dr. Maddalena Fanelli for serving on my thesis committee.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES x

KEY TO ABBREVIATIONS xii

INTRODUCTION 1

CHAPTER 1: Lighting Retrofits and Control Systems 2
- Introduction 2
- Hallway LED Retrofits 4
  - Rationale for Retrofitting 4
  - Characteristics of Lighting 6
  - Fixture testing 8
  - On-Rate Analyses 11
  - Financial Analysis 15
  - Discussion 20
- Hallway Occupancy Based Lighting Controls 22
  - Rationale 22
  - Available Energy Reductions 22
  - Financial Analysis 23
    - Occupancy Based Lighting Controls Only 23
    - Occupancy Based Lighting Controls Coupled with LED Retrofits 26
  - Discussion 26
- Daylight Harvesting Light Management 27
  - Rationale 27
  - Financial Analysis 28
    - Sensitivity Analysis 30
    - Case Study 31
  - Discussion 33
- Summary 34

CHAPTER 2: Energy Use Analyses 35
- Introduction 35
- Evaluation of Steam Cooling Requirements 36
  - Rationale 36
  - Electricity Use Analyses 37
  - Steam Use Analyses 38
  - Discussion 41
- Energy Use Intensity of MSU Campus Spaces 43
  - Rationale 43

Materials and Methods........ 43
Results........ 46
Discussion........ 48
Summary........ 50

CHAPTER 3: Luminescent Solar Concentrator Outreach Activity........ 51
Introduction........ 51
Concepts of Materials........ 51
Goals of the Demonstration........ 53
Design of Materials and Demonstration........ 54
Hazards........ 59
Discussion........ 59
What Is the Best Color?........ 59
How to Produce a Usable Device?........ 61
Outreach Events........ 62
Conclusions........ 63

SUMMARY AND FUTURE WORK........ 63

APPENDIX........ 66

BIBLIOGRAPHY........ 78

LIST OF TABLES

Table 1: Values used for sensitivity determination. Baseline values are indicated by bold typeface 5

Table 2: Estimated annual hourly light on-rate, Psychology Building [8] 5

Table 3: Illumination levels in specified zones, in ft-candles. Value in parentheses indicates # F32T8 bulbs/fixture. ANSI/IES [7] specify 10-40 ft-candle range and 25 ft-candle average 7

Table 4: Calculated CRI at manufacturer specified CCT and at CCT calculated from spectra. Italics indicate current standard fluorescent lamps 9

Table 5: Illuminance (Lux) and tested power draw compared to manufacturer specified luminous flux (lumens) and power draw. Italics indicate current standard fluorescent lamps. CREE dimming system set at ~50% power. *indicates lumens only provided by manufacturer for single bulb 10

Table 6: Light on-rate for Chemistry Building floors basement and 1-6 14

Table 7: Values used for sensitivity determination in Figure 8. Baseline values are indicated by bold typeface 18

Table 8: Light on-rates for Anthony Hall and Biomedical & Physical Sciences (BPS) measured with an Onset HOBO U12 temp/RH/light/ext logger; PH – Penthouse; B – Basement 23

Table 9: MSU Standards occupancy sensors; Manufacturer: Leviton; Cost includes OSA20-R00 power pack required for operation 24

Table 10: Installed occupancy sensor cost required to achieve financial viability; Manufacturer: Leviton25

Table 11: Installed occupancy sensor cost required to achieve financial viability in conjunction with LED based fixtures; Manufacturer: Leviton 26

Table 12: Costs required to trigger a 5-year payback period for occupancy sensor installation in four MSU buildings. OSC10/OSC20 indicate Leviton occupancy sensor models 27

Table 13: Baseline costs used in DLH system analyses 32

Table 14: Cost of dimmable fluorescent ballast at different electricity reduction rates by DLH system required to trigger a 5-year payback (at $0.07492/kWh) 32

Table 15: Quantity of window mount air conditioning units by building, organized by intensity (units/ft2). Annual energy use for WAC units estimate from US EPA/DOE window air conditioning unit calculator [19] 37

Table 16: Electricity draw at different states of representative devices. All units are in watts (W). Refrigerator energy consumption assumed to US Government Energy Guide value ... 44

Table 17: Estimated annual energy use on a per device basis ... 45

Table 18: Surveyed buildings ... 46

Table 19: Comparison of payback period at $0.05755/kWh electricity purchse rate with installed system lifetime ... 68

Table 20: Agriculture Hall light on-rate ... 69

Table 21: Computer Center light on-rate ... 69

Table 22: Giltner Hall light on-rate ... 69

Table 23: Berkey Hall light on-rate ... 69

Table 24: Trout Food Science light on-rate ... 69

Table 25: Packaging Building light on-rate ... 70

Table 26: Natural Resources light on-rate ... 70

Table 27: Wells Hall (B/C Wings) light on-rate ... 70

Table 28: Engineering Building light on-rate ... 70

Table 29: Bessey Hall light on-rate ... 70

Table 30: Wells Hall (A/D Wings) light on-rate ... 71

Table 31: Chemistry Building light on-rate ... 71

Table 32: Biochemistry light on-rate ... 71

Table 33: North Kedzie Hall light on-rate ... 71

Table 34: Biomedical & Physical Sciences light on-rate ... 71

Table 35: Plant and Soil Sciences light on-rate ... 72

Table 36: Baker Hall light on-rate ... 72

Table 37: Kresge Hall light on-rate ... 72

Table 38: Communication Arts & Sciences light on-rate ... 72

Table 39: Music Practice Building light on-rate 72

Table 40: Student Services Building light on-rate 73

Table 41: Economic metrics at fuel cost of electricity($0.05755/kWh) 74

Table 42: Economic metrics at produced cost of electricity ($0.07492/kWh) 75

Table 43: Economic metrics at delivered cost of electricity ($0.09206/kWh) 76

LIST OF FIGURES

Figure 1: Sensitivity analysis of factors affecting payback period (in years) for LED retrofits targeting three-lamp F32T8 fixtures 4

Figure 2: Measurement locations using Dr. Meter LX1330B, performed at floor level........ 7

Figure 3: Spectral tests for (clockwise from top left) two-lamp retrofit (Precision Paragon TKG24-40XW-EU), three-lamp retrofit (CREE UR2-40L-40K), and standard fluorescent bulbs (Phillips Alto II T8)....... 8

Figure 4: From top to bottom: CREE UR2-48-45L-40K backing with magnetic mounting, CREE front of lamp, PP X-X24-40VW-EU backing with adhesive mounting, PP front of light bar........ 11

Figure 5: Clockwise from top left: Logger installation example; Onset HOBO U12 data logger and placard; measurements of luminous flux and on-rates in the MSU Natural Resources building 3rd floor; basement 13

Figure 6: Annual light on-rates for surveyed buildings on the MSU campus........ 15

Figure 7: Net present value with respect to time, assuming installation date of 10/1/2017. Large drops in NPV indicate end of expected retrofit lifetime and complete replacement 17

Figure 8: Sensitivity analysis of factors affecting payback period (in years) for LED retrofits targeting 2 lamp F32T8 fixtures in the Plant and Soil Sciences Building 18

Figure 9: Payback period for LED retrofits at 19 surveyed spaces on the MSU campus. 19

Figure 10: Return on investment for LED retrofits at 19 surveyed spaces on the MSU campus 20

Figure 11: Survey of office occupants in Psychology Building hallways which had LED retrofits installed 21

Figure 12: Varying hallway widths of MSU buildings; clockwise from top left: Plant and Soil Sciences (10ft); Engineering Building (12ft); Student Services Building (10ft); Biomedical and Phsyical Sciences (6ft) 24

Figure 13: Comparison of payback periods for 6 different lighting configurations to implement DLH systems. Sensor clusters consist of DLH and occupancy sensor 29

Figure 14: Sensitivity analysis variables affecting DLH installation payback. All variables except [expected] electricity reduction apply to both LED and fluorescent variants. Fluorescent electricity reduction refers to both 2/3 lamp and ballast/no ballast addition. LED electricity reduction refers to both 2/3 lamp retrofits. 31

Figure 15: Case study for DLH system installation in Engineering Building room 2250 (two sensor clusters) 31

Figure 16: MSU campus map highlighting (in red) buildings with window AC units 36

Figure 17: Average cooling (left) and heating (right) degree days on a monthly basis. Note differing scales on each plot. A degree day is defined as the number of degrees the average temperature is over/under a base temperature (65°F). If the average daily temperature for each day in November (30 days) was 50°F, the total number of (heating) degree days would be 450. 39

Figure 18: Comparison of HDD, CDD, and total steam consumption for Berkey Hall (WAC cooling) ... 40

Figure 19: Comparison of Berkey Hall and Communication Arts steam use per total degree day scaled by total building area (top) and average values for heating months (bottom), indicated in the top graph by unshaded areas (Oct – Apr) 41

Figure 20: Comparison of Communication Arts (central cooling) and Berkey Hall (distributed/WAC cooling) temperature profiles. Outdoor temperatures are daily averages from LAN (NOAA) 42

Figure 21: Energy use intensity for personal office spaces (total: 539 kWh/yr) 47

Figure 22: Comparison of total office device (not including ceiling fixtures) electricity use to two fluorescent fixtures of different configurations 48

Figure 23: Luminescent solar concentrator schematic 53

Figure 24: Normalized absorption (solid) and emission (dots) spectra of paints used in the demonstration (A). Solar cell module (D). Note that the multiple absorption and emission peaks for blue and green paints stem from two distinct dyes with one dye emitting in the visible and one emitting in the infrared to reinforce absorptive coloring and provide greater power. 56

Figure 25: Sample painted device under direct illumination (left) and ambient conditions (right). Note luminescence along waveguide edge where solar modules are attached during demonstration 57

Figure 26: Current-Voltage (IV, left) and Power-Voltage (right) of device (center) with two edge mounted solar modules connected in series and parallel. Multimeter is connected in parallel, reading mV (center)58

Figure 27: Spectrum of sunlgiht, LED lamp, and fluorescent lamp 61

Figure 28: MSU Grandparent's University outreach activity 62

Figure 29: MSU Science Festival student participation 63

KEY TO ABBREVIATIONS

ANSI – American National Standards Institute

BPS – Biomedical and Physical Sciences Building

CCT – Correlated Color Temperature

CDD – Cooling Degree Day

CRI – Color Rendering Index

DOE – US Department of Energy

EUI – Energy Use Intensity

EPA – Environmental Protection Agency

FLCH – Full Load Cooling Hours

HDD – Heating Degree Day

HVAC – Heating, Ventilation, and Air Conditioning

I_{SC} – Short circuit current

IES – Illuminating Engineering Society

IPF – Infrastructure Planning and Facilities

IV – Current – Voltage, used for measuring output of photovoltaics

MPP – Maximum Power Point

MSU – Michigan State University

LED – Light Emitting Diode

LEED – Leadership in Energy and Environmental Design

LSC – Luminescent Solar Concentrator

P_{fluor} – Power draw of fluorescent fixture

P_{LED} – Power draw of LED fixture

PMMA – Poly-methyl methacrylate

PSS – Plant and Soil Sciences

PP – Precision Paragon TKG24-40VW-EU or equivalent Columbia GORK24-40VW-EU LED retrofit kit

PV - Photovoltaic

R – Reflection of front face of waveguide

SPARTA – Students Planning Advanced Retrofit Technology Applications

STEM – Science, Technology, Engineering, and Mathematics

TDD – Total Degree Day

V_{OC} – Open Circuit Voltage

WAC – Window Air Conditioning

η_{Abs} – Efficiency of absorption of luminophore

η_{LSC} – Efficiency of luminescent solar concentrator

η_{PL} – Efficiency of photoluminescence

η_{PV} – Efficiency of photovoltaic

η_{RA}- Efficiency of reabsorption

η_{WG} – Efficiency of waveguiding

INTRODUCTION

The purpose of the SPARTA group is to harness the enthusiasm, energy, and vision of students, faculty and staff to conduct applied energy research while also looking for solutions in novel and impactful arenas. Student members, known as *SPARTA Analysts*, remain driven by the "Spartans Will" mantra to create innovative solutions to advance themselves and their university. SPARTA relies on its Analysts and Faculty Advisers for much of the work within the different project areas, and we are excited to bring in fresh talent with many of our previous analysts graduating last spring. Our undergraduate students, often working on a volunteer basis for long hours, have been highly motivated by and dedicated to energy transition research which provides valuable experience working with software and other tools which are used widely in industry or actively being developed here on campus. It is under this framework that the analyses and outcomes of this thesis have been achieved.

CHAPTER 1: Lighting Retrofits and Control Systems

Introduction

Lighting accounts for around 17% of total electricity consumption in US commercial buildings [1]. Reducing the electricity consumption of lighting through retrofitting is possible with several different emerging technologies which can have few noticeable effects for users of a space. The three technologies which are evaluated in this analysis are Light Emitting Diode (LED) replacements, occupancy sensing controls, and daylight harvesting light management systems.

LED lamps have seen declining costs and increasing efficiencies for the past several years, with trends expected to continue through at least 2030 [2]. LED retrofit kits, units which contain only lamp(s) and a driver (convert high voltage alternating current to lower voltage direct current) which are installed in an existing fixture, are now at a price point which allows for economic viability in many spaces. Commercially available retrofits for 4-foot fluorescent fixtures with three lamps have previously been analyzed for application in the Psychology Building hallways on the MSU campus [3]. This study seeks to expand that previous analysis to the main hallways of other viable buildings as well as determine suitable retrofit options for two-lamp fluorescent fixtures, which make up most ceiling lighting in building hallways on the MSU campus. When retrofitting fixtures there are three key lighting characteristics that must meet or exceed the current fluorescent fixtures which are standards. First is the color rendering index (CRI), a measure of the accuracy of color rendering under illumination by a light source. Correlated color temperature (CCT) is a measure of the color appearance of a light source, with low CCT light sources appearing more orange and high CCT sources appearing more blue. The third characteristic is luminous flux, or the illumination level provided by a light source. A survey of occupants in offices off retrofitted hallways is performed to determine whether the installation had a noticeable impact on occupants. After determining suitable retrofits for two-lamp fluorescent fixtures, economic evaluations are performed to determine viability of installations for nineteen buildings across the MSU campus.

Automatic lighting controls allow for energy use reduction by turning off lights completely or reducing light output levels to match a predetermined setpoint. The use of scheduling is the cheapest method of lighting control, where lights are automatically turned off by central controls based on the time of day. Due to the nature of academic buildings where occupancy by students can often be irregular [4], having lights turn on and off in hallways by a schedule is less feasible without a safeguard such as occupancy sensing systems to override the light off state. Occupancy sensing systems toggle lights on through detection of motion and off after no motion is detected for a user-defined amount of time [5]. While most classrooms on campus have occupancy sensors installed, there are currently only two buildings on the MSU campus which have installed hallway occupancy sensors. A light on-rate analysis is used to determine the energy savings provided by the systems in these two buildings, and this reduction is then used to estimate the required system costs to achieve fiscal viability in the hallways of four buildings with hallway light on-rates of 100%.

A second type of commercially available automatic lighting control are daylight harvesting (DLH) light management systems. These systems are generally used in conjunction with occupancy sensing systems and use light sensors to automatically dim electric lights to balance available daylight and provide a consistent illumination level. The analysis of DLH systems focuses on classrooms and other public areas on campus which have favorable window to wall or footprint ratios. The viability of these systems is evaluated both generally across a wide scale of room sizes as well as a specific room (EB2250) in the MSU Engineering Building using estimated energy reduction values. Fixture modification through reduction of fluorescent bulb count or retrofitting an applicable LED system is included as some spaces on campus have been deemed over-lit by current standards.

Many buildings on campus were initially constructed in the mid-1960s and were therefore built to American National Standards Institute specifications current at that time. By 1982, these recommended lighting levels (ANSI/IES) had decreased by 25-50% across space types of interest [6] and have remained similar through 2017 [7]. Before installing daylight harvesting systems or any other retrofits which target lighting, the possibility of switching to a lower energy consumption lighting system should be evaluated to match current ANSI/IES recommendations for the space type.

Hallway LED Retrofits

Rationale for Retrofitting

With the rising efficiency and falling prices of LED lighting, the replacement of fluorescent fixtures has become a key focus of energy conservation measures. Previous studies by SPARTA [3, 8] found a favorable payback period of 2.9 years for retrofitting fixtures in the Psychology Building on the Michigan State University campus. When performing a sensitivity analysis, light on-rate was determined to be the largest determining factor for the payback period on three-lamp retrofit installations (Figure 1, Table 1).

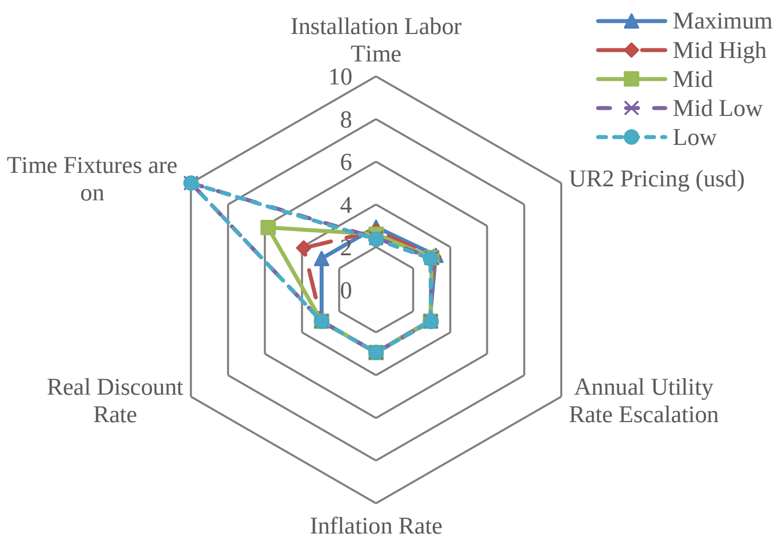


Figure 1: Sensitivity analysis of factors affecting payback period (in years) for LED retrofits targeting three-lamp F32T8 fixtures

Table 1: Values used for sensitivity determination. Baseline values are indicated by bold typeface

	Installation Time (mins)	**Retrofit Pricing (USD)**	**Utility Rate Escalation**	**Inflation Rate**	**Discount Rate**	**Light On-Rate**
High	**60**	$101.32	2.88%	3.48%	7.00%	**100%**
Mid High	45	$96.99	2.16%	2.61%	5.25%	75%
Mid	30	$93.00	**1.44%**	**1.74%**	**3.50%**	50%
Mid Low	15	$92.60	0.72%	0.87%	1.75%	25%
Low	10	**$90.12**	0.29%	0.35%	0.70%	10%

Public hallways were the areas found to be the best targets in these previous studies as they exhibited the highest light on-rates when compared to other building spaces, such as classrooms and offices (Table 2). Across all surveyed spaces, hallway lighting consumed from 0.5% (Computer Center) to 20.8% (Baker Hall) of total building energy consumption. These two factors show the clear benefit of targeting hallway spaces.

Table 2: Estimated annual hourly light on-rate, Psychology Building [8]

	Usage (hours)	
Space Type	**Walk-throughs**	**Metered Data**
Classroom	3830	---
Hallway	8650	8425
Office	5840	---

The economic viability of the installation of retrofit kits was required by Infrastructure Planning and Facilities (IPF), the division at MSU which oversees the installation of any capital projects on campus among other duties. The payback period IPF typically targets must be less than five years for a project to proceed, and recommended kits must also have a warranty of at least five years.

The analysis results for retrofitting fixtures with three F32T8 lamps show very favorable economic returns [3, 8], but these types of fixtures are not common on the Michigan State University campus. After performing walk-through surveys of campus buildings, it was determined that most F32T8 containing fixtures have only two lamps, with the notable exceptions of the Engineering, Psychology, and Chemistry Buildings which have three-lamp fixtures. Because of the reduced number of lamps in these fixtures, retrofits suitable for three-lamp fixtures see a relatively low (31% vs 55% wattage reduction in three-lamp fixtures) reduction in electricity consumption, and therefore cost savings. The increased luminous flux of fixtures containing three lamps instead of two must also be considered. Some hallway spaces on campus are already over-lit [7], so increasing luminous flux through the installation of retrofits suitable for replacing three-lamp installations is not desired. For these reasons, determination of a suitable retrofit solution for fixtures containing two F32T8 lamps was a key step towards translating these potential retrofits across a greater fraction of MSU.

Characteristics of Lighting

Key specifications for determining a suitable retrofit kit for lighting include the brightness (luminous flux), CCT, and color quality (CRI). Evaluation of these measures for selected LED retrofit kits was performed to ensure quality before moving forward with economic analyses and final installation recommendations.

Luminous flux is defined as "[a] measure of the rate of flow of light, i.e. the radiant flux in the wavelength range 380–760 nanometres, corrected for the dependence on wavelength of the sensitivity of the human eye" and is measured in lumens. While lumen specifications are generally provided by manufacturers, specifications for lighting levels are instead measured in lux, or lumens per m^2 (foot-candles in SAE). This measurement is indicative of the total amount of light which reaches a surface. The acceptable range of illuminance for hallways is 10 – 40 foot-candles (107 – 430 lux) with an average of 25 foot-candles, measured at floor level [7]. Illuminance measurements were taken in several buildings targeted for retrofits (Figure 2, Table 3). Wells Hall is consistently over-lit, while the Engineering Building only exhibits levels which exceed recommendations directly under fixtures. This is most likely due to the fact that the Engineering Building had three-lamp fixtures as surveyed.

1. Centered beneath fixture
2. Along wall beneath fixture
3. Centered between two fixtures
4. Along wall between two fixtures

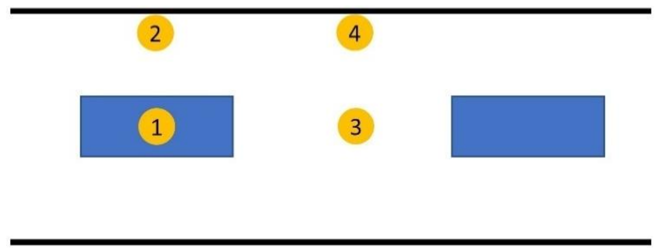


Figure 2: Measurement locations using Dr. Meter LX1330B, performed at floor level

Table 3: Illumination levels in specified zones, in ft-candles. Value in parentheses indicates # F32T8 bulbs/fixture. ANSI/IES [7] specify 10-40 ft-candle range and 25 ft-candle average

Building	**1**	**2**	**3**	**4**
Engineering (3)	54.0	29.4	20.4	14.5
Plant & Soil Sciences (2)	34.8	25.9	15.1	12.8
Wells (2)	49.8	45.4	44.3	42.7
Biomed & Physical Sciences (2)	29.4	25.1	20.4	19.9
Student Services (2)	37.8	28.6	20.8	16.8

The CCT of a light source is the apparent color of that source in relation to a black body radiator and is measured in Kelvins (K). A CCT between 3500K and 4100K, which produces a fairly neutral white light, is recommended by the IESNA for office buildings and schools for daytime use. For reference, there is a strong preference for warmer, lower CCT (e.g. 2700K) for lighting in homes that more closely matches that of incandescent bulbs, particularly at night. The Alto II F32T8 lamps generally installed in hallways and offices on the MSU campus have a manufacturer specified 4100K CCT. The retrofit kits evaluated for this study are all at a manufacturer specified 4000K.

The color rendering index is a scale (0-100) which indicates how accurate a light source is at rendering color when compared to a black body radiator of the same CCT. A higher CRI indicates a better color rendering ability, allowing for greater differentiation between similar colors. Per previous testing by the SPARTA group, the values provided by manufacturers are not always accurate. Therefore, independent testing of selected retrofit kits as well as installed F32T8 lamps are also performed.

Fixture testing

Previous investigation [3, 8] determined that for three-lamp retrofits, the CREE UR2-48-45L-40K retrofit satisfied color temperature and CRI requirements, exceeding the performance of standard fixtures with three Phillips Alto II F32T8 light bars installed. To determine the optimal retrofit kit for two-lamp fixtures, retrofit candidates from four different manufacturers were acquired and both CCT and CRI testing were performed using bare light bars, measured with a calibrated Ocean Optics USB4000 spectrometer. Normalized spectral intensity for the retrofit kit targeting three-lamp fixtures, retrofit kit targeting two-lamp fixtures, and standard fluorescent bulbs were determined using a MATLAB based CCT/CRI calculator (Figure 3).

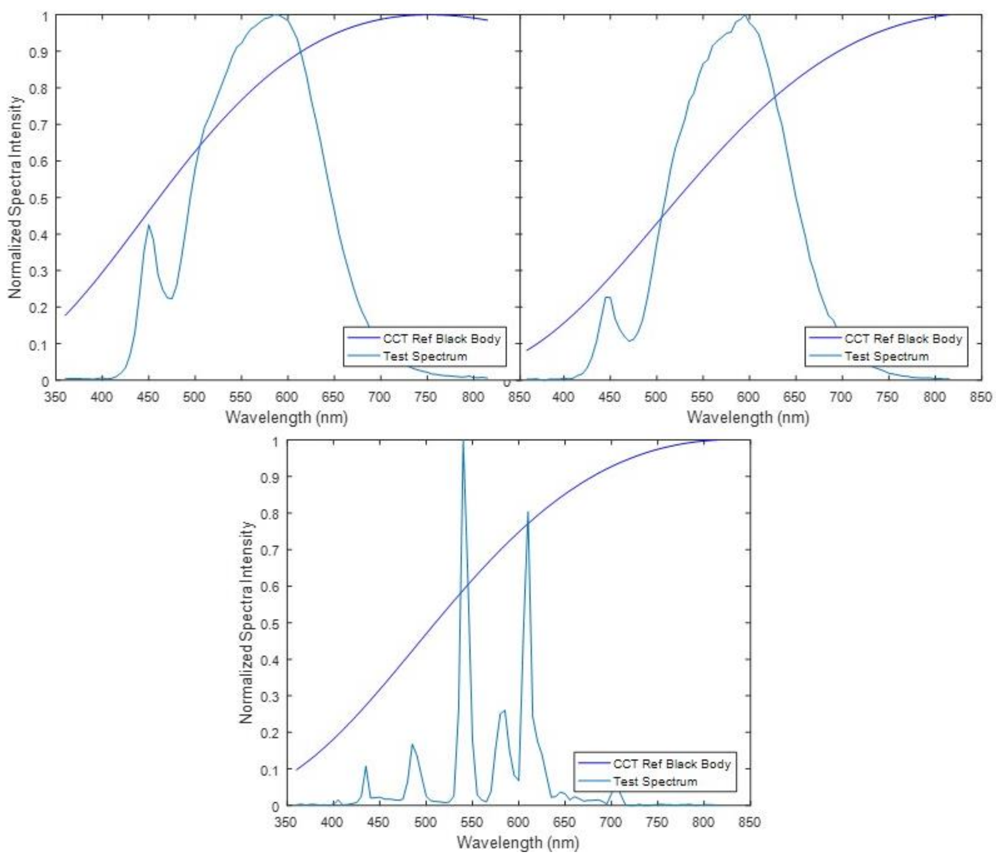


Figure 3: Spectral tests for (clockwise from top left) two-lamp retrofit (Precision Paragon TKG24-40XW-EU), three-lamp retrofit (CREE UR2-40L-40K), and standard fluorescent bulbs (Phillips Alto II T8)

To determine the CRI of the evaluated retrofit kits and fluorescent bulbs, two methods were used (Table 4). First, the CCT was calculated from the measured spectra (Figure 3) and the CRI was then determined at that CCT. In the second method, the CRI was determined with CCT set at the manufacturer specification (4000K for both retrofits, 4100K for fluorescent bulbs). Manufacturer listed CRI values are 78 for Phillips Alto II F32T8 fluorescent bulbs and 80 or above for all tested LED retrofit kits.

Table 4: Calculated CRI at manufacturer specified CCT and at CCT calculated from spectra. Italics indicate current standard fluorescent lamps

		Specified CCT		**Calculated CCT**	
Manufacturer	**Model**	**CCT (K)**	**CRI**	**CCT**	**CRI**
Phillips	*Alto II F32 T8*	*4100*	*76*	*3600*	*75*
Precision Paragon	TKG24-40XW-EU	4000	75	3400	73
Precision Paragon	TKG24-40VW-EU	4000	74	3800	75
Phillips	12T8/40	4000	76	3200	72
Phillips	15T8/40	4000	74	3400	72
CREE	UR-48 [Dimming]	4000	76	3600	75
Columbia	GORK24-40VW-EU	4000	75	3800	73
Columbia	GORK24-40XW-EU	4000	75	3800	73

Luminous flux testing for retrofit kits of interest was then performed using a benchtop test fixture which allowed for a streamlined installation procedure for ballast and lamps to compare retrofit kit illumination levels to a baseline provided by two F32T8 lamps. A Dr. Meter LX1330B Digital Lux Meter was used to measure the luminous flux from the bench top fixture (Table 5) at a fixed position and orientation for all tests. A light diffuser was not installed over the fixture as diffusers in final installation areas vary space to space. Because the retrofit kits will utilize the fixture housing and diffusers which are currently in place, comparison of bare bulbs was determined to be the best method for measuring lighting characteristics. Actual power consumption was measured to compare with manufacturer specifications using a P3 Kill A Watt meter.

*Table 5: Illuminance (Lux) and tested power draw compared to manufacturer specified luminous flux (lumens) and power draw. Italics indicate current standard fluorescent lamps. CREE dimming system set at ~50% power. *indicates lumens only provided by manufacturer for single bulb*

		Specified		Tested	
Manufacturer	**Model**	**Lumens**	**Power (W)**	**Lux**	**Power (W)**
Phillips	*Alto II F32 T8*	---*	*64*	*1230*	*63*
Precision Paragon	TKG24-40XW-EU	2300-2600	22	1350	24
Precision Paragon	TKG24-40VW-EU	2900-3200	27	1420	26
Phillips	12T8/40	1600	24	1020	25
Phillips	15T8/40	2100	30	1330	33
CREE	UR-48 [Dimming]	variable	variable	1220	31
Columbia	GORK24-40VW-EU	2900-3200	27	1430	26
Columbia	GORK24-40XW-EU	2300-2600	22	1330	24

While minimizing the variety of light types was desired for maintenance and inventory reasons, reliability, potential effects on lifetime due to dimming, and long-term quality of illumination were concerns for implementation of permanently dimmed CREE systems. Long term quality evaluations would have to be performed before a recommendation for installation could be provided. However, pricing at the time of the study for CREE UR2-48-45L-40K retrofit kits was not close to providing feasible payback periods of less than five years, so long-term testing was not performed.

The Phillips LED lamps which were tested exhibited an unsatisfactory magenta tint, significant flickering, and very low luminous flux. The Phillips LED lamps closely resembled the F32T8 fluorescent bulbs, with a tubular casing and bi-pin ends. The use of previously installed electrical connection hardware caused reliability concerns and could also increase overall installation time when compared to self-contained units seen on other retrofit kits (CREE, Precision Paragon, Columbia).

LED lamps with internal drivers (driver contained within bulb) were also examined but due to reliability and lifetime concerns due to driver heat production they were not considered for final recommendation. Failure of only one of part of these systems (driver or bulb) will require a complete replacement of the system instead of piecewise replacement available with external drivers. More importantly, bulbs with integrated drivers are often confused for fluorescent bulbs and/or installed incorrectly with old driver ballasts that significantly reduce the overall efficiency.

While all evaluated LED retrofits either met or exceeded warranty requirements from IPF, the Columbia and Precision Paragon models (manufactured by the same parent company) have the best lighting characteristics as well as the lowest power draw of eligible systems (Figure 3). Both retrofit kits will generally be referred to as Precision Paragon (PP) for simplicity. PP retrofit kits not only had adequate CRI at specified CCT (75 at 4000K vs 76 at 4100K for F32T8) but also had the lowest power consumption and overall cost of evaluated retrofits. Coupled with a 5-year warranty and 60,000hr expected lifespan, PP retrofit kits were determined to be the most cost effective, highest quality option. The X24-40VW-EU models of Precision Paragon/Columbia (where X represents TKG/GORK respectively) have a slightly higher energy consumption (2W, ~8%) than X24-40XW-EU variants and are recommended to account for any possible degradation that may occur over the lifetime of the system.

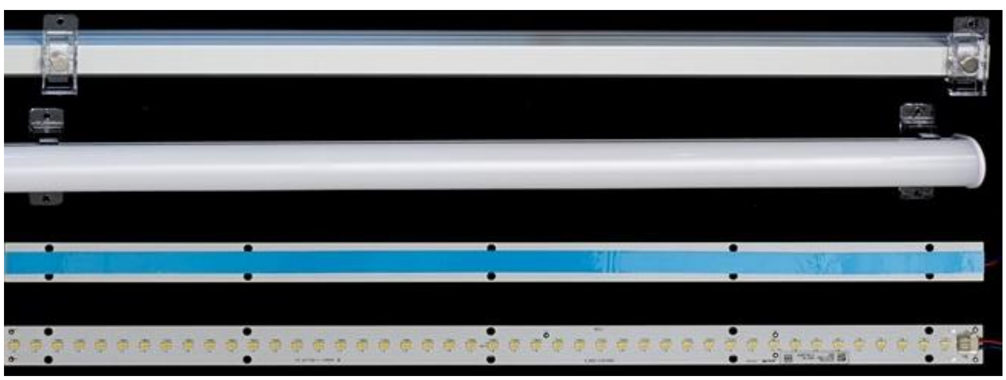


Figure 4: From top to bottom: CREE UR2-48-45L-40K backing with magnetic mounting, CREE front of lamp, PP X-X24-40VW-EU backing with adhesive mounting, PP front of light bar

On-Rate Analyses

The light on-rate is the single largest determining factor for the economic viability of a retrofit installation. For determining the savings afforded by retrofitting fixtures with lower wattage LEDs, the amount of kWh saved each year is first determined by Equation 1 below.

$$kWh\ saved\ annaully = \frac{8{,}760\ hrs}{year} * \%\ On\ Rate * \left(P_{fluor}(W) - P_{LED}(W)\right) * \frac{kW}{1000\ W} \qquad (1)$$

After determining the preferred LED retrofit kit (and accordingly, the power draw), the only variable in the above Equation is the light on-rate. The amount of energy saved is therefore directly proportional to the light on-rate, with 24/7 operation yielding the largest energy savings. Increasing the light on-rate decreases the operational lifetime of installed retrofits, which must be accounted for in return on investment (ROI) determination. With manufacturer specified lifetimes of 50,000 hours for the three-lamp retrofit and 60,000 hours for the two-lamp retrofit, installations at all evaluated electricity costs will pay back the installed cost of the retrofit a minimum of 1.76 years before the end of the specified lifetime (Appendix, Table 19).

Hallways have previously been determined to have the highest light on-rates in the Psychology Building on the MSU campus [3, 8]. Investigating the light on-rates of the hallways of other on campus buildings was performed to capitalize on these previous findings. To determine the light on-rates in the hallways of other buildings, Onset HOBO U12 temp/RH/light/ext channel data loggers were installed. The loggers were installed on hallway walls ~4ft from the floor under an illuminated light fixture, and the number of strings of lights that were on at the time of installation were noted (Figure 5). This allowed for determination of a baseline lighting level. If the illumination levels dropped below 20 lux, it was assumed that all strings of lights in the hallway were turned off. A middle level indicates that half of lamps in hallway were turned off (a single string). An example of data from loggers is included, including each of the described conditions (Figure 5).

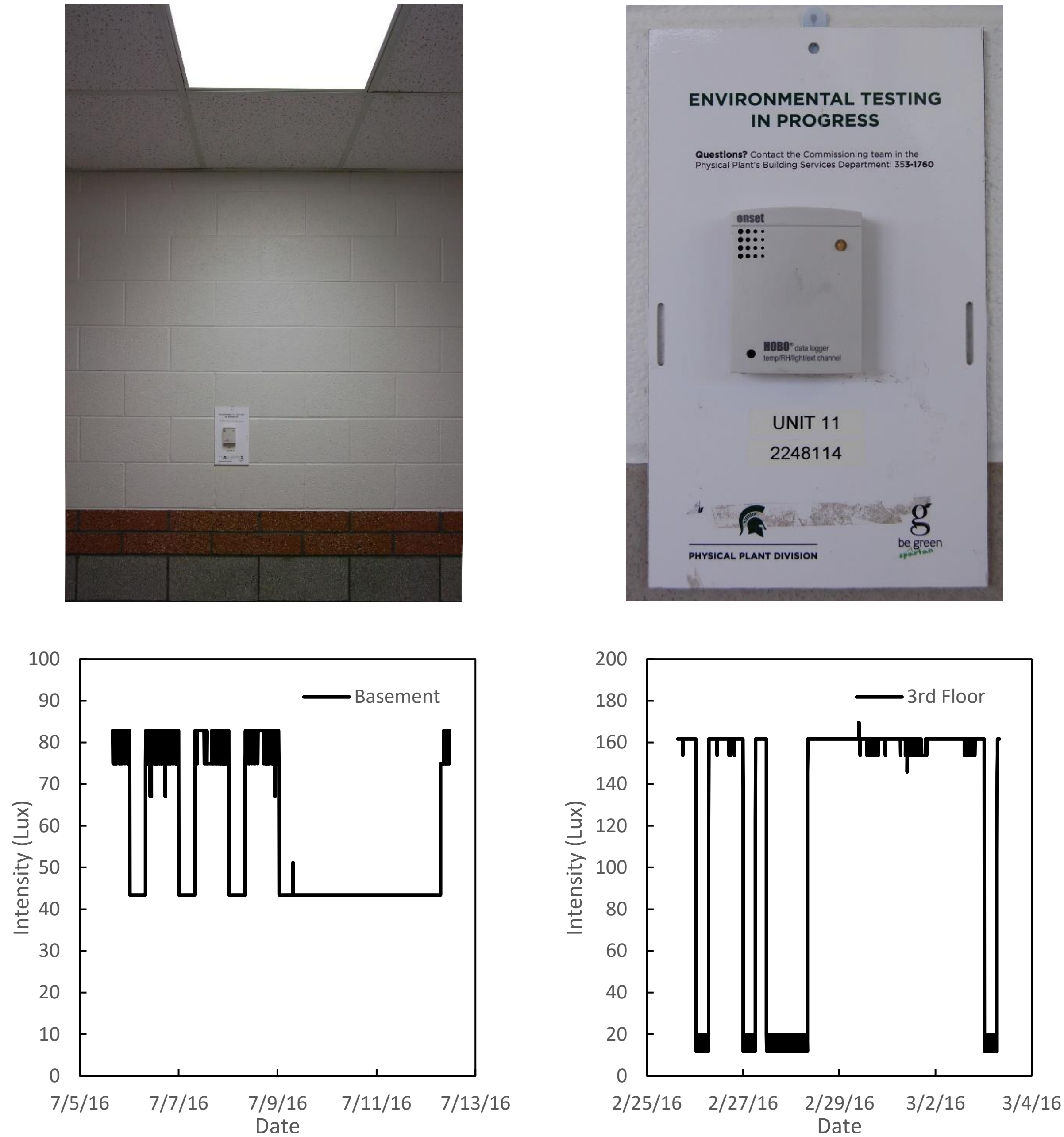


Figure 5: Clockwise from top left: Logger installation example; Onset HOBO U12 data logger and placard; measurements of luminous flux and on-rates in the MSU Natural Resources building 3rd floor; basement

Loggers were installed for one-week intervals and results were categorized by day. Installation was performed on all floors where possible, and if a floor was not surveyed the on-rate was assumed to be the average of similar floors in the same building which were surveyed. On-rates were then assumed to be the same for each day of the week throughout the year. In spaces where hallway lights are not on 24 hours per day, variations exist in the total amount of light on time due to irregular occupant behaviors (Table 6).

Table 6: Light on-rate for Chemistry Building floors basement and 1-6

Floor	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
6	72%	100%	87%	100%	75%	70%	94%
5	65%	69%	68%	72%	77%	100%	77%
4	100%	100%	67%	97%	61%	100%	97%
3	100%	100%	100%	100%	100%	100%	100%
2	66%	100%	67%	100%	0%	0%	1%
1	71%	24%	66%	100%	70%	3%	0%
B	100%	100%	69%	100%	100%	64%	0%

Because weekday and weekend behavior can vary, lower/upper bound on-rate estimations were determined by assuming that each weekday on-rate was equal to the lowest/highest measured weekday on-rate respectively. The same was done for weekends to estimate the variability that is inherent in systems which can be controlled by users. For example, the sixth floor in the Chemistry Building (Table 6) would assume that the total on-rate for Monday through Friday was 72% and for Saturday and Sunday, 70%. This would be taken as the lower bound for the light on-rate. For the upper bound, Monday through Friday would be assumed to have 100% overall light on-rate, and Saturday and Sunday would have a 94% total on rate. The hallways of several academic buildings had 100% on-rates measured (24-hour daily operation) with an average of 83% on-rate across all the buildings surveyed (Figure 6). The combination of occupancy by students and faculty, the scheduling of janitorial staff during night time hours, and concerns for safety are all likely explanations for the high on-rates.

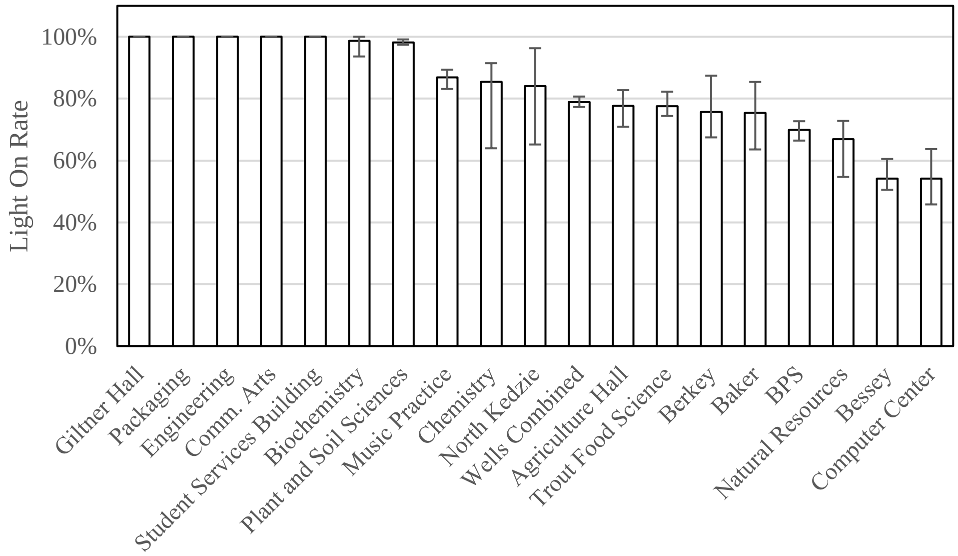


Figure 6: Annual light on-rates for surveyed buildings on the MSU campus

Financial Analysis

Determination of the economic viability and *ROI* for each building/retrofit option was performed. The typical metric used by IPF for determining the suitability of installation for an energy reduction technology is a payback period of less than five years, with a total capital investment (C_0), cash flows (CF), and time (t):

$$Payback\ Period = \frac{C_0}{\sum_{t=1}^{n} CF_t} \qquad (2)$$

C_0 consists of labor cost, retrofit hardware cost, and recycling of fluorescent lamps/ballast. Due to the ease of retrofit installation, expected time per fixture is 25 minutes, and at this rate the capital cost of a single installed retrofit for a two-lamp F32T8 fixtures is $100.53. The capital cost of a single installed retrofit for a three-lamp fixture is $120.12. It is expected that previous fixture hardware including lens, troffer, and wiring, are in acceptable working condition and retrofits can be installed with little to no fixture modification. Due to the mounting hardware on chosen retrofit kits (Figure 4) the previous mounting hardware for attachment of F32T8 lamps can be left within the fixture.

Cash flows consist of energy savings due to electricity use reduction, any rebates, assumed failure rate (1 fixture per 3 months), and replacement of all retrofits at end of usable lifetime. An annual utility escalation rate of 2.23% [12] was used to account for expected changes in the cost of electricity production. In all surveyed cases, the manufacturer specified lifetime of the chosen lamps exceeds the projected payback period. To evaluate the effect of end of life replacement of retrofit kits, the net present value (*NPV*) of the investment is used, with a discount rate of 3.5% (*i*), where:

$$NPV = \sum_{i=1}^{N} \frac{CF_t}{(1+i)^t} - C_0 \qquad (3)$$

The cost at the end of system lifetime is assumed to be the same as the initial C_0. The evaluation of NPV with respect to time is determined for two buildings with similar C_0, Plant and Soil Sciences (98% light on-rate) and Biomedical & Physical Sciences (70% light on-rate) (Figure 7). While the cost of replacement at end of life is significant, a positive return on investment (*ROI*) is realized several years before this end of life replacement point.

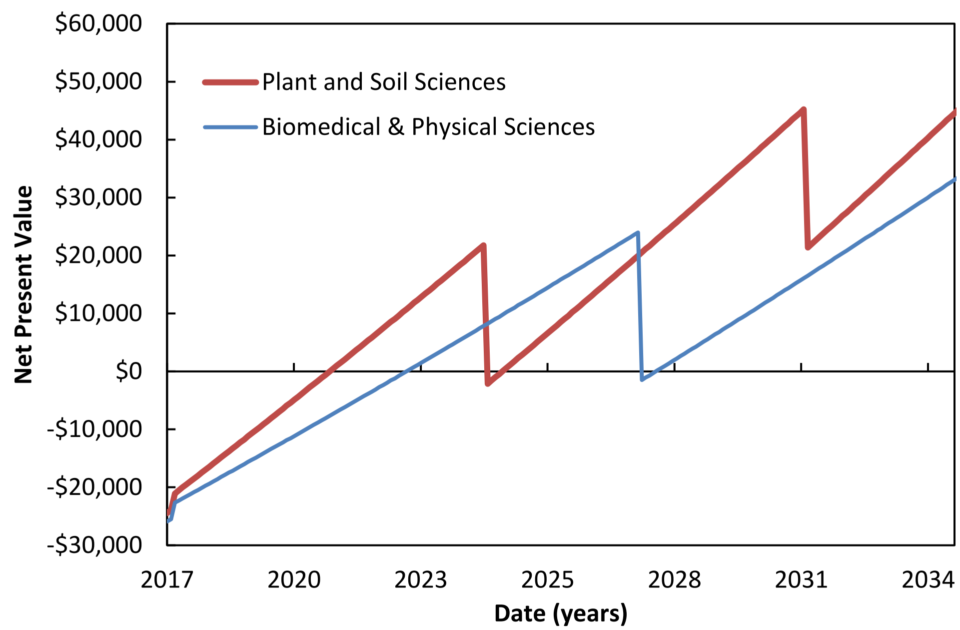


Figure 7: Net present value with respect to time, assuming installation date of 10/1/2017. Large drops in NPV indicate end of expected retrofit lifetime and complete replacement

The *ROI* can be used to normalize profits from an investment C_0 to easily compare the profitability from vastly different C_0:

$$ROI = \left(\left(\sum_{i=1}^{N} CF_t \right) - C_0 \right) / C_0 \tag{4}$$

The two main factors in determination of *CF* due to electricity use reduction for a given building are the total amount of electricity reduced (Equation 1) and the rate at which electricity is purchased. As discussed earlier, the total amount of electricity reduced is dependent solely on the light on-rate in a given building. Because MSU produces most the energy consumed on campus locally at the TB Simon Power Plant [9], pricing of electricity occurs at several rates. These rates are 1) fuel only cost ($0.05755/kWh), 2) produced cost (including operations and maintenance, $0.07492/kWh) and 3) delivered cost (including delivery system operations and maintenance, $0.09206/kWh). The delivered cost is used for buildings under the administration of Athletics or the Residential and Hospitality Services. Unless otherwise specified, following results are evaluated at the produced cost of electricity. The Plant and Soil Sciences Building is used to model the sensitivity of a retrofit installation to five factors (Figure 8, Table 7).

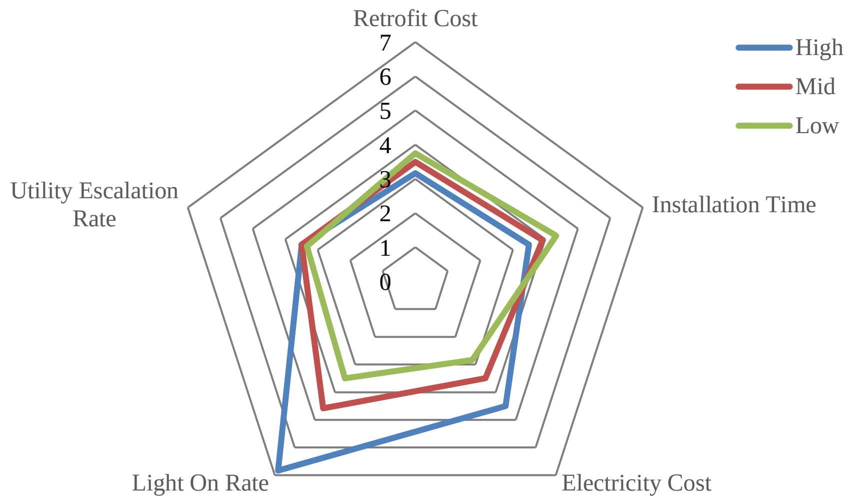


Figure 8: Sensitivity analysis of factors affecting payback period (in years) for LED retrofits targeting 2 lamp F32T8 fixtures in the Plant and Soil Sciences Building

Table 7: Values used for sensitivity determination in Figure 8. Baseline values are indicated by bold typeface

	Electricity Cost	Retrofit Cost	Installation Time	Light On-Rate	Utility Escalation Rate
Low	$0.05755	$63.48	**25**	50%	0.2%
Mid	**$0.07492**	**$70.53**	35	75%	**1.2%**
High	$0.09206	$77.58	45	**98%**	4.2%

Another important factor in the economic viability of LED retrofit installations comes in the form of rebates from energy providers. Currently, MSU purchases approximately 8% of its electricity from Consumers Energy (a utility company). This is because the electricity either cannot be provided by the TB Simon Power Plant or can be purchased at a lower rate than production costs, which can occur during off-peak pricing hours. Subsequently, this still allows the university to take advantage of rebates provided by Consumer's Energy. As of January 2017 [11], the rebate provided for the recommended LED retrofits is $0.25/Watt reduced. With this rebate, two-lamp (PP) retrofit fixtures receive a rebate of $9.25/fixture and three-lamp (CREE) retrofit fixtures receive a $13/fixture rebate. Without rebates applied, the payback period for a given installation can be expected to increase by 11±1%. There is a $2,000,000 annual cap on rebates per facility (...*contiguous property for which a single customer is responsible for paying the Consumers Energy electricity and/or natural gas bill* [10]) so it should be verified that this limit has not been exceeded before applying for rebates.

The payback period at the produced cost of electricity is less than five years for spaces which have an on-rate greater than 70% (Figure 9). Only four of the surveyed spaces do not achieve the desired payback period: the Computer Center (54% on-rate), Natural Resources (67%), Wells B&C wings (67%), and Bessey Hall (54%). It should be noted that when looking at Wells Hall in its entirety, the payback period is less than five years. This is because of the relative scale of the B&C wings to the A&D wings.

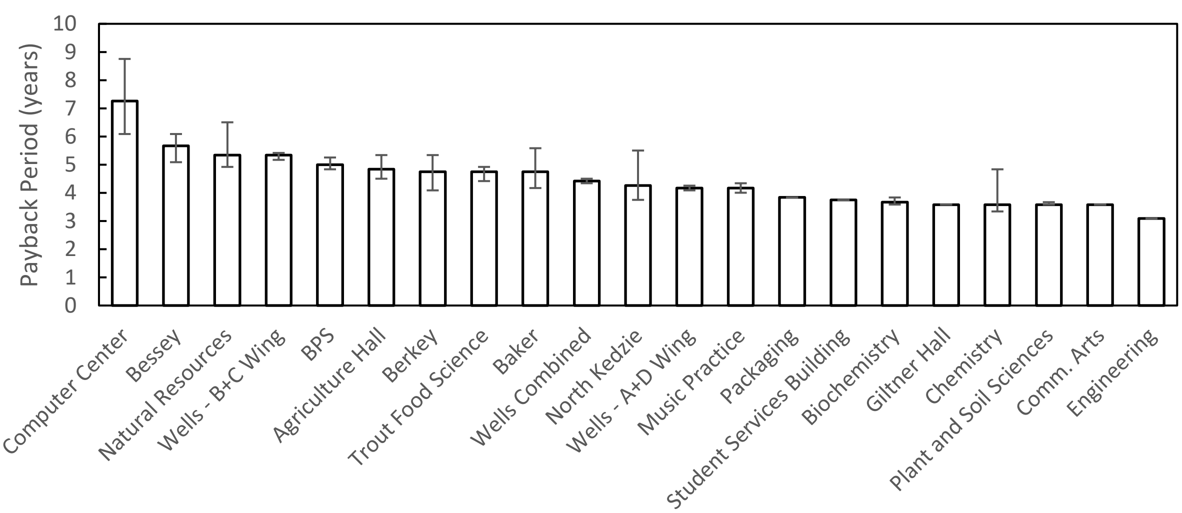


Figure 9: Payback period for LED retrofits at 19 surveyed spaces on the MSU campus.

A positive *ROI* indicates that an investment pays itself back within the specified time range. The *ROI* is evaluated at the end of the lifetime for all installations (Figure 10). While five-year payback periods are not available with all evaluated buildings, the positive *ROI* over the lifetime of the investments suggests that these retrofits are still economically viable over the lifetime of the installation.

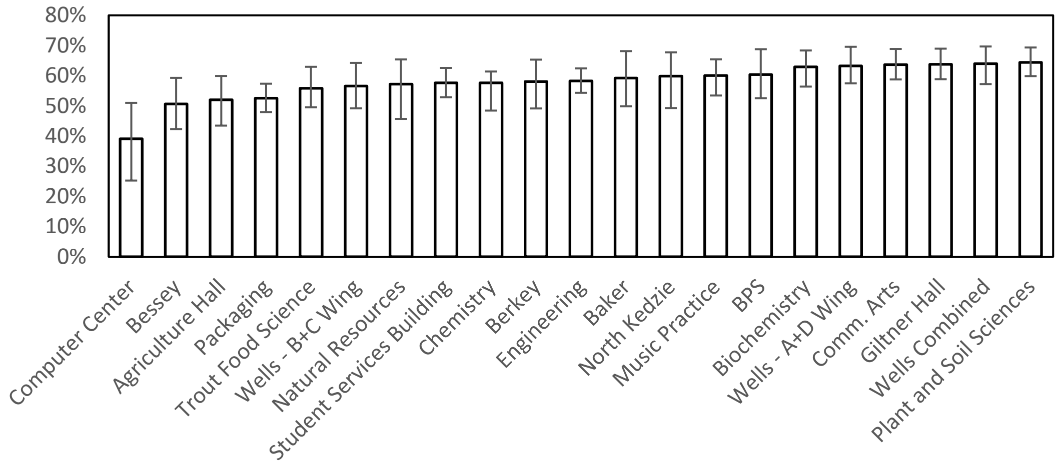


Figure 10: Return on investment for LED retrofits at 19 surveyed spaces on the MSU campus

Discussion

Installation of LED retrofits across all surveyed spaces (19 buildings) would yield an annual reduction of 1.06 GWh of electricity consumption, or ~0.4% of the net annual power delivered to buildings on the MSU campus. Retrofitting fixtures with LEDs is not only economically viable in most spaces, but also requires no behavioral modification and does not have user overrides as seen with lighting controls. A pilot installation occurred in hallways of the Psychology Building using the CREE UR2-48 retrofit. Occupant responses were positive regarding energy efficiency gains and lighting quality of installed retrofits (Figure 11).

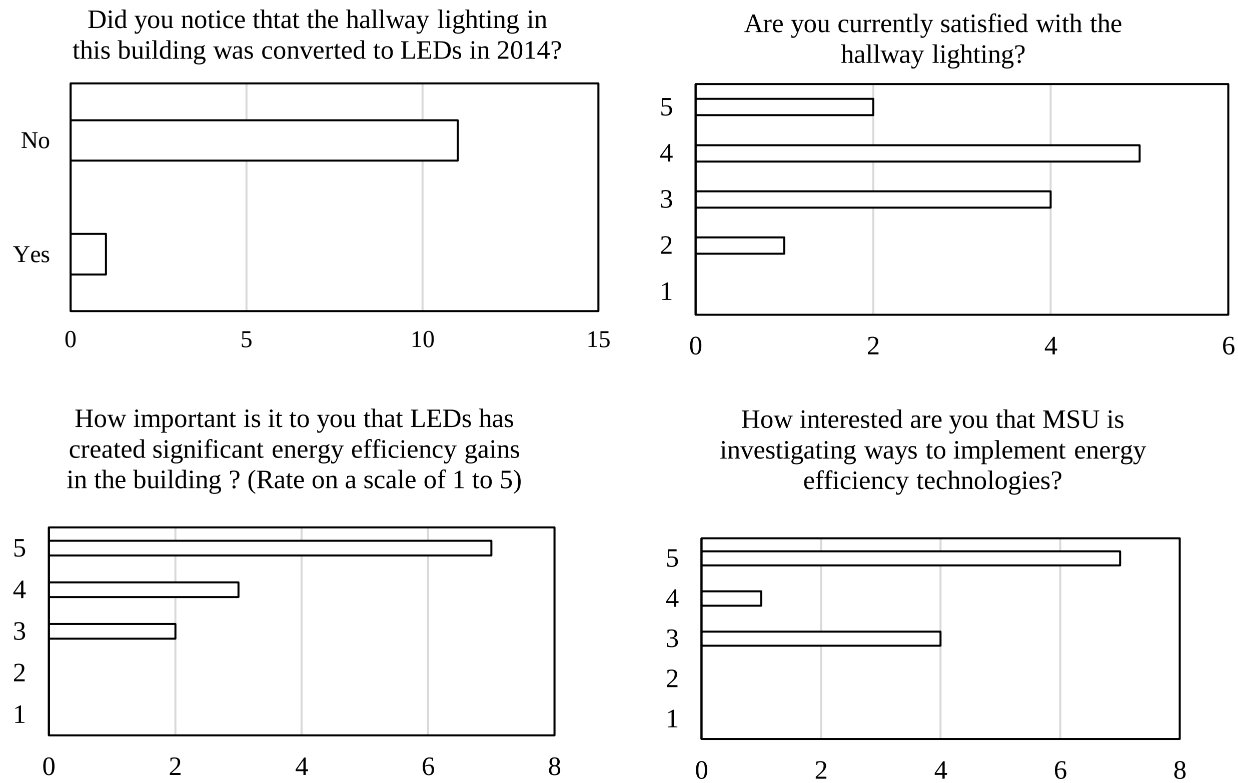


Figure 11: Survey of office occupants in Psychology Building hallways which had LED retrofits installed

Some of the important cosiderations for IPF to consider before implementation of LED retrofits include surveys of current lighting levels to determine which retrofits would be suitable for a space to comply with ANSI/IES standards. As discussed previously, lighting levels are not consistent across building hallways on campus and are not always within acceptable illumination level ranges. Stepping down three-lamp F32T8 fixtures to retrofits specified for two-lamp fixtures can be evaluated dependent on illumination level. Use of lower output X24-40XW fixture could also be examined in hallways with two-lamp fixtures which are currently overlit.

The use of different lighting systems adds complication and bulk to the inventory system which would need to be maintained for periodic maintenance and replacement of lamps/drivers which prematurely fail. A final consideration is the overall application lifetime of these systems. With expected system lifetimes ranging from seven (100% light on-rate) to twelve (54% on-rate) years, at the end of life there is no guarantee that these systems will still be available. However, the very positive *ROI* values seen over the lifetime of an installation is significant enough that the investments are still very favorable.

Hallway Occupancy Based Lighting Controls

Rationale

Besides reducing the amount of energy consumed by changing to lower wattage fixtures, a second option for reducing the energy consumed by lighting is reducing the total amount of time that fixtures are powered on. While past efforts (sticker campaigns, recommendations to janitorial staff) have targeted behavioral changes, results from light on-rate analyses in the LED retrofit study indicate that these measures often are less effective. This leads to a significant amount of electricity used at times when lighting is not required – when spaces are not occupied.

Occupancy based lighting controls are systems which are hardwired into lighting strings to toggle lights on and off based on input from occupancy sensors which detect motion [5]. If no motion is detected for a set period (specified by the user on installation) lights are automatically turned off. On sensing motion, the occupancy sensors are triggered which switches paired lighting strings on. Wide ranges of energy savings are estimated to be available, from 15 to 75% depending on the source [5].

The integration of hallway occupancy sensors were studied as a case study in the Biomedical and Physical Sciences (BPS) building and Anthony Hall on the Michigan State University campus. This study seeks to evaluate the energy savings resulting from these installations. These results are then applied to other buildings on campus to estimate the economic viability of further retrofits of occupancy based lighting controls.

Available Energy Reductions

From the light on-rate analyses performed for the LED retrofit study, resultant energy savings from installed hallway occupancy sensors can be observed in both BPS and Anthony Hall (Table 8). Note that occupancy sensors appear to have been deactivated on floors 1 and 2 in Anthony Hall and floor 2 in

BPS. The first floor in BPS contains student study areas, classrooms, and a small convenience store, while all other floors with installed and functional occupancy sensors are in hallways which primarily service office and lab spaces.

Table 8: Light on-rates for Anthony Hall and Biomedical & Physical Sciences (BPS) measured with an Onset HOBO U12 temp/RH/light/ext logger; PH – Penthouse; B – Basement

Floor	PH	6	5	4	3	2	1	B
Anthony	-	-	-	-	40%	100%	100%	-
BPS	19%	47%	50%	61%	61%	100%	81%	37%

With an average on-rate reduction of 52 ± 19% across activated occupancy sensor spaces, realized electricity use reductions are within the expected ranges [5]. Removing spaces which are not regularly occupied (BPS basement, penthouse), regularly occupied floors (BPS 1, 3-6, Anthony 3) saw an average on-rate reduction of 43 ± 14% due to installed occupancy sensor control systems.

While these energy use reductions are significant, results are lower than would be seen through the installation of LED retrofits while maintaining 24 hour on-rates. LED retrofits for two F32T8 lamp fixtures realize a 57% energy use reduction over operating times while retrofits for three-lamp fixtures yield a 54% reduction in energy consumption. Combination of the two technologies (LED and occupancy sensors) would result in an estimated average energy use reduction of 79% with respect to lighting.

Financial Analysis

Occupancy Based Lighting Controls Only

Cost estimations are performed on linear foot basis, as occupancy sensors have a defined distribution and therefore application area size. The light on-rate reduction of 43% ± 14% is used to estimate electricity use reductions from installed systems. The current MSU Standards specified occupancy sensors are highlighted in Table 9.

Table 9: MSU Standards occupancy sensors; Manufacturer: Leviton; Cost includes OSA20-R00 power pack required for operation

Model	Coverage (ft)	Cost	$/ft
OSC05-M0W	23 x 23	$98.46	$4.28
OSC10-M0W	46 x 23	$99.35	$2.16
OSC20-M0W	62 x 32	$103.52	$1.67

Hallway widths in surveyed buildings vary from 6 – 12ft (Figure 12) so hallway length is the primary factor for quantity of sensors installed. Because each sensor can cover at most 62 linear feet, multiple occupancy sensors will need to be installed in any hallway over 62ft in length. Occupancy sensors must be tied into a centralized lighting string controller, so wiring cost will be a function of total hallway length as well. Due to the difficulty in estimating these different conditions, a $/linear foot cost required to reach a five-year payback period is determined instead of estimating the cost on a building by building basis. The total cost can then be compared to the value for economic viability.

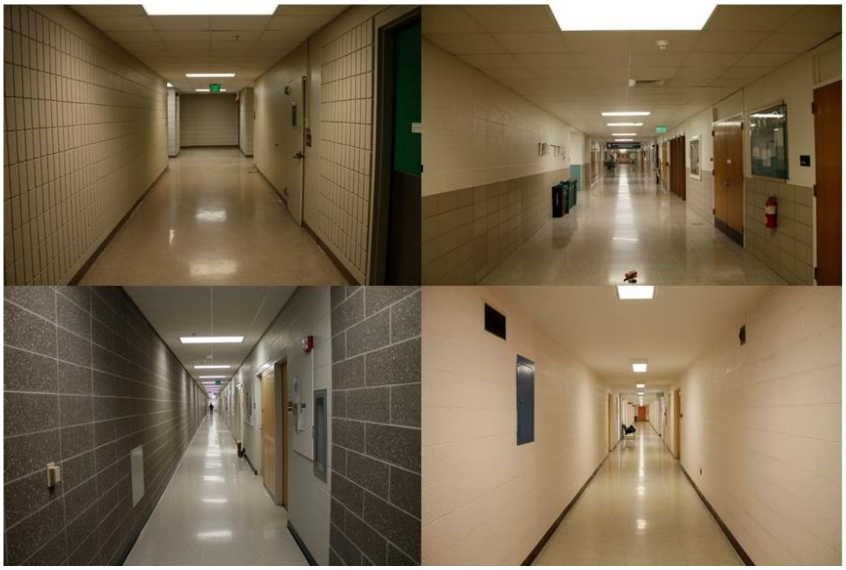


Figure 12: Varying hallway widths of MSU buildings; clockwise from top left: Plant and Soil Sciences (10ft); Engineering Building (12ft); Student Services Building (10ft); Biomedical and Phsyical Sciences (6ft)

Plant and Soil Sciences (PSS) is used as a case study for these estimations as well as for comparison to installing LED retrofits previously described. From the MSU Planning & Budgets *Spartan*

Space system, the total area of public corridors for PSS is 56,000 ft^2 (5,600 linear feet). A total of 256 fixtures in public corridors in the PSS building were on 100% of the time surveyed. Applying the average on-rates seen in BPS and Anthony Hall (Table 8) due to functioning occupancy based lighting controls results in an annual estimated electricity reduction of 60.6 ± 20.0 MWh/year for PSS. At the produced cost of electricity ($0.07492/kWh) this results in annual savings of $4,600 ± 1,500. Over a five-year lifespan, the total expected returns are $23,000 ± 7,500. This equates to $4.1 ± 1.3 per linear foot of hallway.

Per distribution specifications for the Leviton OSC05, OSC10, and OSC20 occupancy sensors (above), it is assumed that spacings between sensors will be 23, 46, and 62 feet respectively. Results are tabulated in Table 10, where viability is defined as achieving a 5-year payback period. The value of required occupancy sensors is the minimum expected value, with more thorough surveying required to determine the exact number of occupancy sensors required.

Table 10: Installed occupancy sensor cost required to achieve financial viability; Manufacturer: Leviton

Model	Required Occupancy Sensors	Cost for Viability
OSC05-M0W	244	$94.3 ± 30.7
OSC10-M0W	122	188.5 ± 61.5
OSC20-M0W	91	$252.7 ± 82.4

With these costs for viability and the very small cost difference between occupancy sensors with vastly different coverage areas, installation of sensors with the largest distribution footprint will provide the highest likelihood of achieving financial viability. Average costs for installation and ancillary equipment for the OSC10 and OSC20 sensors are $89.2 and $149.2 respectively. OSC05 equipment cost exceeds the cost requirements for viability.

Occupancy Based Lighting Controls Coupled with LED Retrofits

For maximizing the savings of occupancy based lighting controls, combination with LED retrofits to reduce electricity use when lights are in the on state is performed. Using the same methodology as above, electricity requirements are reduced by 109.2 ± 8.8 MWh/year, yielding cost savings of $8,180 ± 660/year. With a capital investment of $24,500 for LED retrofits, a total installation cost of $16,400 ± 3,300 is required to achieve fiscal viability of an occupancy sensor installation. This equates to $2.9 ± 0.6 per linear foot of hallway. The costs for viability of the different occupancy sensors are outlined below (Table 11).

Table 11: Installed occupancy sensor cost required to achieve financial viability in conjunction with LED based fixtures; Manufacturer: Leviton

Model	Required Occupancy Sensors	Cost for Viability
OSC05-M0W	244	$67.4 ± 13.5
OSC10-M0W	122	$134.8 ± 27.0
OSC20-M0W	91	$180.7 ± 36.3

Average costs allowed for installation and ancillary equipment for the OSC10 and OSC20 sensors used in conjunction with LED fixtures are $35.4 and $77.2 respectively. OSC05 sensor and power pack costs exceed the minimum cost for financial viability of an occupancy sensor installation.

Discussion

For the purposes of determining when occupancy sensors may be a valid solution for reducing overall electricity consumption, a more in-depth case study must be performed to determine the costs of installation and associated equipment. While the sensors and power pack equipment show favorable comparison on a cost per foot and cost per installed sensor basis, these are only part of the total capital cost of installation. Once an estimate for installation and ancillary equipment is determined, the overall cost of an installed sensor can be compared to on-rate reductions in existing occupancy sensor controlled spaces to determine the viability of an occupancy sensing installation. Cost requirements for viability for four different high (~100%) on-rate buildings are highlighted below (Table 12).

Table 12: Costs required to trigger a 5-year payback period for occupancy sensor installation in four MSU buildings. OSC10/OSC20 indicate Leviton occupancy sensor models

		OSC10-M0W		OSC20-M0W	
	$/ft	Req. Occ. Sensor	Cost	Req. Occ. Sensor	Cost
Engineering	5.4 ± 1.8	156	$246.6 ± 80.3	116	$331.6 ± 108
Biochemistry	7.9 ± 2.6	33	$353.8 ± 115.2	24	$486.5 ± 158.4
PSS	4.1 ± 1.3	122	$186.0 ± 60.6	91	$249.4 ± 81.2
Wells	4.4 ± 1.4	162	$204.5 ± 66.6	121	$273.7 ± 89.1

Daylight Harvesting Light Management

Rationale

Daylight harvesting light (DLH) management systems are used to exert automated control of lighting levels to both maximize usability of a space and to minimize energy consumption of installed lighting elements in areas which contain large windows, especially in south, and to a lesser extent east and west, facing orientations. These systems use sensors which detect illumination levels in a space and automatically adjust dimming levels to match the total illumination detected to a previously programmed set-point. Combining scheduling, occupancy sensors, and daylight dimming controls with an appropriately tuned set point will yield the largest energy reductions [12]. These three separate systems, however, lead to increased cost of installation as well as increasing the likelihood of control issues which arise from a larger number of system inputs. Besides the possibility of significant energy use reductions, greater reliance on daylight instead of electric lighting can see increases in occupant satisfaction with lighting conditions [13,14]. With both occupancy satisfaction and possible energy reductions, the fiscal viability is determined in the following analysis.

While the previous lighting retrofit (LED, occupancy) analyses have been performed for interior hallways within buildings, the DLH systems being considered in this section focuses on classroom and office spaces. Most hallways on the MSU campus are interior hallways and therefore do not have windows; the majority only experience daylighting in entryway areas. These spaces are therefore untenable for daylight harvesting systems. However, there are numerous office spaces with adequate window area for considering such systems.

Financial Analysis

To determine available savings from these installations, a baseline estimate for energy reduction must first be determined. The US Department of Energy's (DOE) Energy Efficiency and Renewable Energy department provides a Daylighting tool for estimating savings available through the implementation of daylight harvesting light management systems [15]. Minimum illuminance through panels are provided by NREL for a southern angle of incidence under mostly cloudy conditions. Three lamp fixtures output 4500 lumens per previous fixture testing for LED retrofit analyses [3]. With two 20' x 4' windows, the calculated proposed reduction is 85%. This same energy use reduction is estimated for fixture lumen outputs between 3200 and 6200 lumens, so can be applied in determining savings for both two-lamp and three-lamp installations. As shown in the following analysis, however, even these very large reduction estimations provided by the DOE do not provide paybacks of less than 5 years because of the high cost daylight harvesting equipment.

To determine the total cost of installation, an installation time of one hour for user control hardware (Lutron MRF2-F6AN-DV-WH wall dimmer switch), one hour for each sensor cluster, fifteen minutes for dimming ballast installation in fluorescent fixtures, and thirty minutes for LED retrofit installation are assumed. Each sensor cluster (Lutron LRF2-OCR2B-P-WH occupancy sensor, LRF2-DCRB-WH daylight sensor) had a baseline cost of $116.13 and the wall dimmer switch (one per room installation) had a unit cost $105.56. LED retrofits were priced at $70.53 and $90.12 for two-lamp and three-lamp retrofits respectively. The labor rate was set at $60/hour.

The payback period for several different configurations are examined below at different numbers of fixtures per occupancy/DLH sensor cluster. These values are determined for four sensor clusters, where the total number of fixtures covered by a single point is the product of fixtures per sensor cluster and number of sensor clusters.

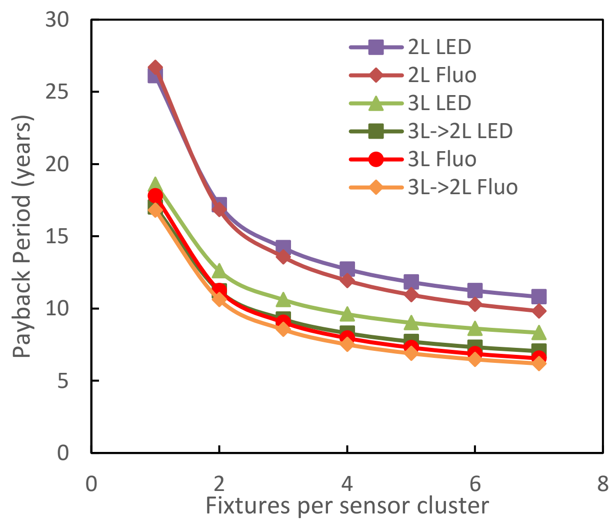


Figure 13: Comparison of payback periods for 6 different lighting configurations to implement DLH systems. Sensor clusters consist of DLH and occupancy sensor

The schemes investigated above in Figure 13 are detailed below:

- *2L LED*: Two lamp LED retrofit (Precision Paragon TKG24 as described in *Hallway LED Retrofits*) with dimming ballast replaces two lamp F32T8 configuration
- *2L Fluo*: Two lamp fixture configurations maintained, existing ballast replaced with dimmable ballast ($62.46/fixture)
- *3L LED*: Three lamp LED retrofit (CREE UR2-48 as described in *Hallway LED Retrofits*) with dimming ballast replaces three lamp F32T8 configuration
- *3L→2L LED*: Two lamp LED retrofit (as above) with dimming ballast replaces three lamp F32T8 configuration
- *3L Fluo*: Three lamp fixture configurations maintained, existing ballast replaced with dimmable ballast ($62.46/fixture)

- *3L→2L Fluo*: Two lamp F32T8 replaces three lamp F32T8 configuration

The replacement of three lamp fixtures with two fluorescent lamps or retrofits specified for replacement of two fluorescent lamp containing fixtures is included to cover areas which may be over-lit. These conditions generally exist because of changes in lighting standards over time [6, 7] which have seen a decrease in recommended lighting levels since the construction of several buildings on campus.

Sensitivity Analysis

Scale dependency (quantity of fixtures for each DLH/occupancy sensor cluster) of DLH installations was described above and highlighted in Figure 13. However, other factors which can have a significant effect on the projected payback period are quantified in Figure 14. Payback periods are most sensitive to the cost of electricity and electricity use reduction (DOE proposed reduction). For the fluorescent fixtures, these two factors show an identical relationship, as both act on a direct kWh reduction basis. Changes in the proposed reduction for LED retrofits see a change in kWh reduction due to a changed baseline fixture wattage from originally installed fluorescent fixtures.

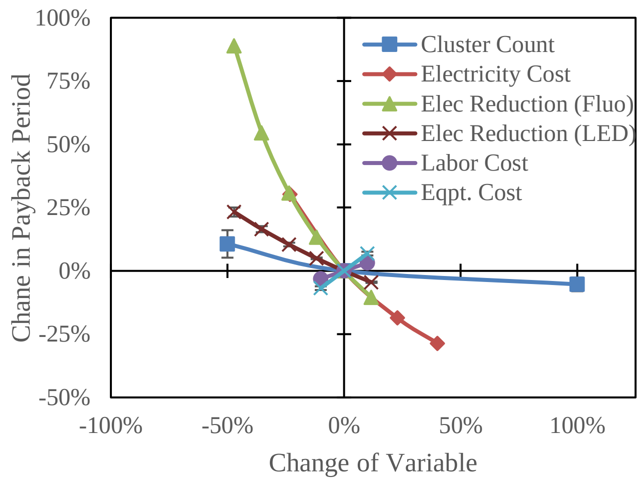


Figure 14: Sensitivity analysis variables affecting DLH installation payback. All variables except [expected] electricity reduction apply to both LED and fluorescent variants. Fluorescent electricity reduction refers to both 2/3 lamp and ballast/no ballast addition. LED electricity reduction refers to both 2/3 lamp retrofits.

Case Study

Room 2250 in the Michigan State University Engineering Building was used as a case study to examine the payback period for an installed DLH system with several different variations on lighting installations accounted for (Figure 15). The four lighting schemes outlined below are described in detail above.

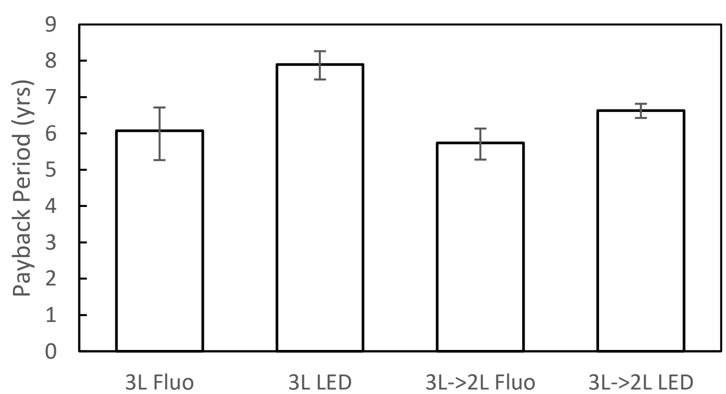


Figure 15: Case study for DLH system installation in Engineering Building room 2250 (two sensor clusters)

The room is 1152 ft^2 (24’ x 24’) and contains 18 three lamp F32T8 fixtures as well as an installed occupancy sensor system. The room consists of an exterior east oriented wall with 176 ft^2 of window space with user operated blinds. The DOE calculator previously described assumes a south facing orientation for estimating illumination from daylight entering a space. Therefore, the upper bound of payback periods indicated by the error bars in Figure 15 above are more likely to represent results from decreased illumination from daylight due to room orientation. For this case study, it is assumed that the blinds remain raised at all times. Equipment costs are included in Table 13. A previously described sensor cluster consists of an occupancy sensor and daylight sensor. These clusters would be utilized in spaces without previously installed occupancy sensing systems.

Table 13: Baseline costs used in DLH system analyses

Manufacturer	Model	Description	Cost/Unit
Lutron	MRF2-F6AN-DV-WH	Dimmer Switch	$106
Lutron	LRF2-OCR2B-P-WH	Occ. Sensor	$50
Lutron	LRF2-DCRB-WH	Daylight Sensor	$66
Lutron	PJ2-3BRL-GWH-L01	Remote (Wireless)	$13

With the results from the EB 2250 case study (Figure 13) and the generalized results (Figure 15) it is difficult to recommend the installation of DLH systems in classrooms or offices. All schemes examined, even with an assumed 85% reduction in electricity use, are unable to achieve 5-year payback periods. The only way that these fast paybacks could be achieved are in spaces which already have dimming ballasts installed in each fixture. In Table 14, the fluorescent dimming ballast price required to trigger a 5-year payback period for the case study area (EB 2250) is highlighted at different electricity reduction rates (assuming occupancy sensor is already installed).

Table 14: Cost of dimmable fluorescent ballast at different electricity reduction rates by DLH system required to trigger a 5-year payback (at $0.07492/kWh)

Electricity Reduction		**39.2%**	**40%**	**50%**	**58.8%**	**60%**	**70%**	**80%**	**90%**
Ballast Cost	**3 Lamp**	$0.00	$0.77	$10.52	$19.11	$20.27	$30.02	$39.76	$49.51
	2 Lamp	--	--	--	$0.00	$0.77	$7.27	$13.77	$20.27

Discussion

The high installation costs for daylight harvesting light management systems are the major obstacle in these retrofit implementations. However, if seeking LEED accreditation through retrofits or for new installations, daylight harvesting is an efficient way to reduce total energy consumption and get LEED points towards certification when cost (and payback period) are less important [16].

Two trial office installations were performed, with a wired sensor in one office and wireless sensor in the second. The wireless system exhibited seemingly random dimming of lights, responding to perceived changes in lighting levels. This continued through swapping out daylight sensors used as well as placement modification. The wired system experienced none of these fluctuations. As has been noted in previous literature [5] the issue of occupancy sensors detecting only major motion sometimes resulted in 'false-off' triggers when the space was occupied but occupants were performing desktop work which resulted in only minor movements. This would in likelihood be mitigated by the larger quantities of occupants if scaled up to a classroom sized installation.

Initial purchase price on a per fixture basis will be less for LED retrofits than DLH installations on fluorescent fixtures at values below five fixtures per sensor cluster (three-lamp retrofit) or twelve fixtures per sensor cluster (two-lamp retrofit). Electricity reductions from these two LED retrofits are 54% and 58% respectively, much lower than the 85% reduction stipulated by the DOE calculator. However, it should be noted that T5 fixtures dimmed to 0% lumen output have been shown to still consume approximately 20% of baseline power [17]. While currently installed fixtures contain T8 lamps, comparable results are likely and would yield lower electricity reduction levels than determined by the DOE calculator.

Because of the footprint of most office spaces (generally one to two fixtures) sufficient payback periods are not achievable with DLH systems presently available. However, installation and monitoring of several case study classroom spaces is recommended to determine actual electricity use reductions due to DLH installation. Different orientations and window to wall ratios should also be tested. Three orientations (E, N, S) and two window to wall ratios, or 6 trial classrooms, are recommended for testing for at least a 6-month monitoring period which can be extrapolated to full year results.

Summary

Retrofitting fluorescent fixtures with LED in areas with high light on-rates yields very significant reductions in total energy use at a relatively low capital investment. Of the nineteen buildings surveyed, seventeen can achieve payback periods of five years or less by retrofitting fixtures with LEDs. Recommendations have been made to IPF and installation is now planned for the hallways of the Engineering Building, Plant and Soil Sciences, Biomedical and Physical Sciences, and Wells Hall which will yield lifetime energy savings of 3,006 MWh, an ROI of 64%, and lifetime net savings of $98,000. Occupancy sensing was also investigated as a tool for reducing energy use on campus, but further analysis must be done to determine total installation costs which can then be compared to the requirements determined for economic viability. While DLH systems can provide significant energy reductions, the cost of installing these systems does not allow for suitable payback periods, with a best case of 5.3 years without completely replacing the installed lighting systems.

CHAPTER 2: Energy Use Analyses

Introduction

Lighting consumes 17% of the total electricity use in US commercial buildings [1], which corresponds to 14% of total energy use [18]. The remaining 86% of energy used can be split broadly into heating (34%), ventilation (6%), air conditioning (10%) (HVAC, total 50% of energy use), and other equipment (36%; computing, refrigeration, office equipment, etc.). In commercial buildings, office equipment and computing consume 5% of the total energy used in office spaces [18] while space cooling consumes a similar amount of the total energy consumption (10%) [18].

The energy needs of Michigan State University campus are serviced primarily by the TB Simon power plant, a co-generation facility. Since the installation of the power plant, electricity generation has nearly tripled from 120GWh in fiscal year 1965-66 to 347GWh in fiscal year 2012-13 [9]. In this same time frame, steam demand has increased by less than 50%, and excess steam produced is condensed in cooling towers which results in a significantly lower overall process efficiency than at the beginning of the facilities lifetime. Steam is primarily used for heating of campus buildings in the winter and to a lesser extent, cooling in the summer through the use of adsorption chillers.

While steam use for heating is currently at its maximum, increasing the amount of steam used in the summer for cooling is possible with a significant portion of campus currently underserved with respect to cooling. Increasing the summer steam load would increase overall efficiency of the co-generation process by consuming more steam and requiring less electricity. A 630MWh/yr electricity reduction is available by removing all installed window air conditioning units.

Another way to increase the efficiency of the co-generation process is to decrease overall electricity generation at the facility. Purchase of off-peak electricity from an outside provider has driven down total generation to some extent, but decreasing electricity requirements during more expensive peak times can only be done by decreasing the total required load. While lighting was previously discussed, computing and other office equipment uses nearly half of the load required by lighting [1, 18]. By determining the composition of electricity consuming devices in the average office on the Michigan State University campus, recommendations are made for reducing office equipment electricity intensity.

Evaluation of Steam Cooling Requirements

Rationale

Window air conditioning (WAC) units on the MSU campus are present primarily in the older sections of the campus north of the Red Cedar River. While most of the cooling requirements are provided to buildings on campus using steam produced in the on-campus co-generation plant, many of the buildings north of the Red Cedar are primarily cooled using distributed cooling with window air conditioners.

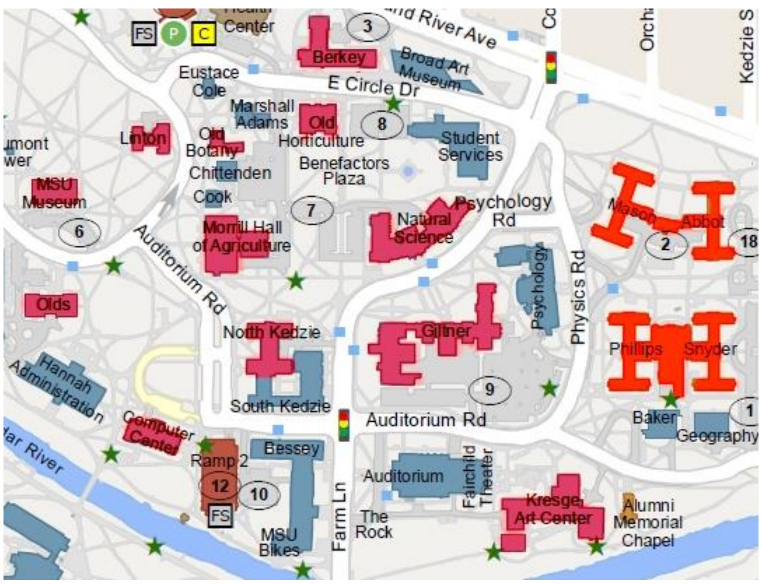


Figure 16: MSU campus map highlighting (in red) buildings with window AC units

It is estimated that these buildings consume approximately 630 MWhrs of electricity annually, which could potentially be offset by excess steam production. Currently no reliable source of hourly steam or electricity production are available to determine actual availability of steam sources. However, steam use for HVAC generally peaks on a per building basis in January for heating and all spaces on the main campus are serviced with steam for heating purposes. With this analysis, the amounts of steam required for cooling these spaces will be determined to be available for reference on verifying quantities of steam available during cooling months (May – September).

Electricity Use Analyses

The buildings with installed WAC units are most easily compared by determining the density of units for a given building floor area (ft^2/unit) (Table 15). Building areas were retrieved from the MSU Office of Planning and Budgets [19].

Table 15: Quantity of window mount air conditioning units by building, organized by intensity (units/ft2). Annual energy use for WAC units estimate from US EPA/DOE window air conditioning unit calculator [19]

Building	# Units	Building Area (ft^2)	Density (ft^2/Unit)	Annual Energy Use (kWh)
Linton	74	32964	445	43660
Old Botany	19	10216	538	11210
Natural Sciences	186	155173	834	109740
Computer Center	75	65076	868	44250
Berkey	122	107273	879	71980
Giltner	208	209084	1005	122720
Agriculture Hall	108	114997	1065	63720
Olds Hall	51	56990	1117	30090
Museum	29	44938	1550	17110
Kedzie	87	137600	1582	51330
Old Horticulture	16	35054	2191	9440
Kresge Art Center	27	79585	2948	15930
Farrall Hall	18	70104	3895	10620
Mason/Abbot	26	165303	6358	15340
Snyder/Philips	23	241074	10481	13570

For estimating annual energy use, the Room Air Conditioner Calculator for consumer grade window AC units from the US EPA/DOE was used [20]. An Energy Efficiency Ratio of 10.8 was assumed as specified within the calculator, as well as 578 full load cooling hours (FLCH) for Lansing, MI. The number of cooling degree days per year (CDD) was 746 ± 166 for 2010 – 2016 in Lansing, MI. Using a design temperature of 95°F, the calculated annual FLCH (Equation 5) is 596 ± 132, in good agreement with the value of 578 provided by the US EPA/DOE calculator [21, 22].

$$FLCH = \frac{CDD * 24}{design\ temp\ °F - 65°F} \quad (5)$$

In total, there were 1069 window AC units counted on these buildings, accounting for approximately 630 MWh/year in electricity consumption. Combined with the inadequate cooling seen in public spaces, determining possible savings from upgrading to steam based cooling will be performed. The electricity consumption outlined can be offset through using of excess steam produced at the TB Simon cogeneration power plant on the MSU campus. Currently there are no estimators for steam requirements for new cooling installation so this analysis proposes a comparative estimating method for determining steam requirements for retrofitting of buildings, which can then be compared against available steam when determining viability of retrofits.

Steam Use Analyses

Determining average steam use for a given building on the MSU campus is difficult due to the high variability of both heating and cooling degree days (HDD and CDD respectively). A heating degree day is the number of degrees below a base temperature that the average daily temperature is. For example, if the average daily temperature is 50°F and the base temperature is 65°F, that day had an HDD of 15. If every day in November had an HDD of 15, then the monthly HDD would be 450. Cooling degree days are determined in the same manner as HDD, but for average temperatures in excess of 65°F. For the purposes of these analyses, 65°F is used as the base temperature for both HDD and CDD determination. Total degree days on a monthly or annual basis have significant variability, seen in comparing CDD for 2016 to both 2015 [22] and the 1981-2010 averages [23] (Figure 17).

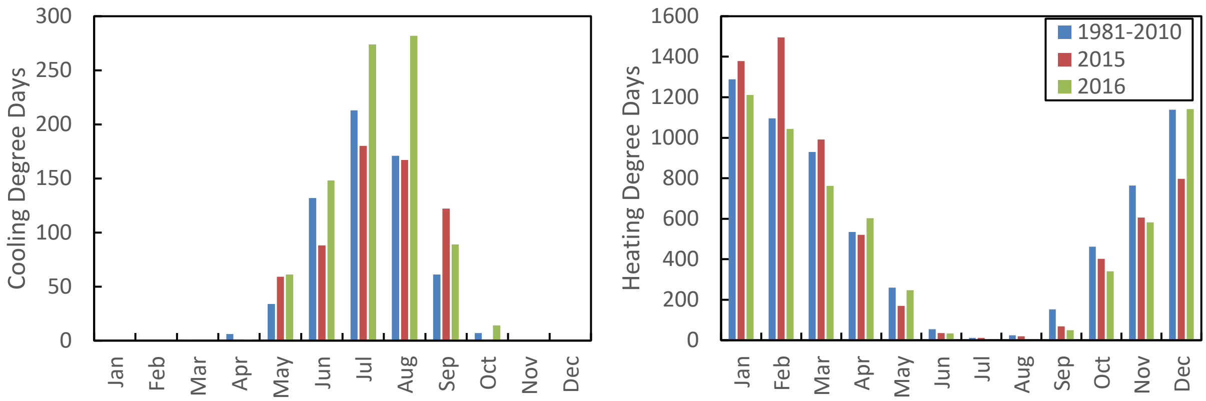


Figure 17: Average cooling (left) and heating (right) degree days on a monthly basis. Note differing scales on each plot. A degree day is defined as the number of degrees the average temperature is over/under a base temperature (65°F). If the average daily temperature for each day in November (30 days) was 50°F, the total number of (heating) degree days would be 450.

This variability in degree days year to year is very important when estimating the potential requirements for steam based cooling in spaces previously cooled using distributed WAC units. If degree day values are not accounted for, rates of steam use can appear to have very large deviations. When plotted against degree days it becomes clear that the large variations in monthly steam use arise from variations in degree days (Figure 18). For example, during the 'heating months' of October – April the average amount of steam used in Berkey Hall during 1/2013 – 12/2016 is $1.02 \pm 0.14 \frac{klb\ steam}{TDD}$, where TDD is the total degree days (sum of CDD and HDD). If the steam use is not related to the total degree days, the average amount of steam used for this date range is $930 \pm 380 \frac{klb\ steam}{month}$. Without accounting for TDD, the standard deviation is 41% of the average, compared to 14% when accounting for TDD.

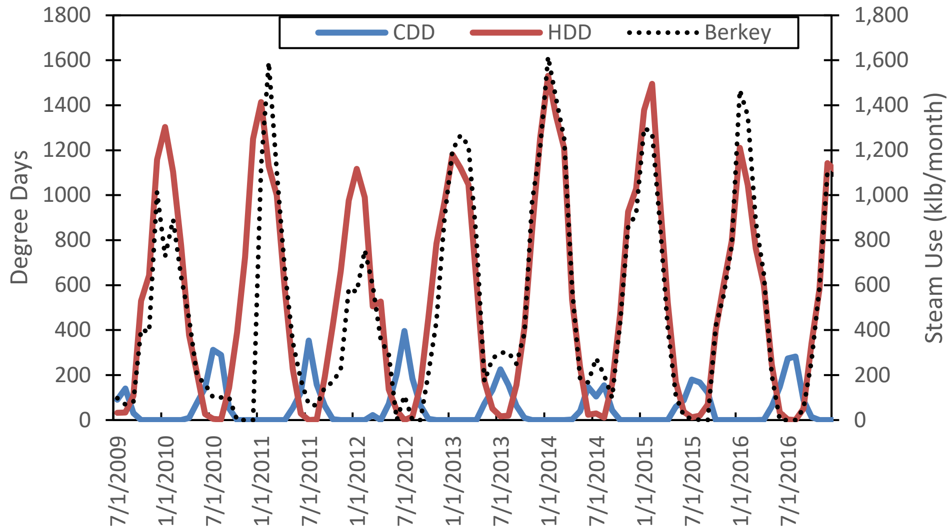
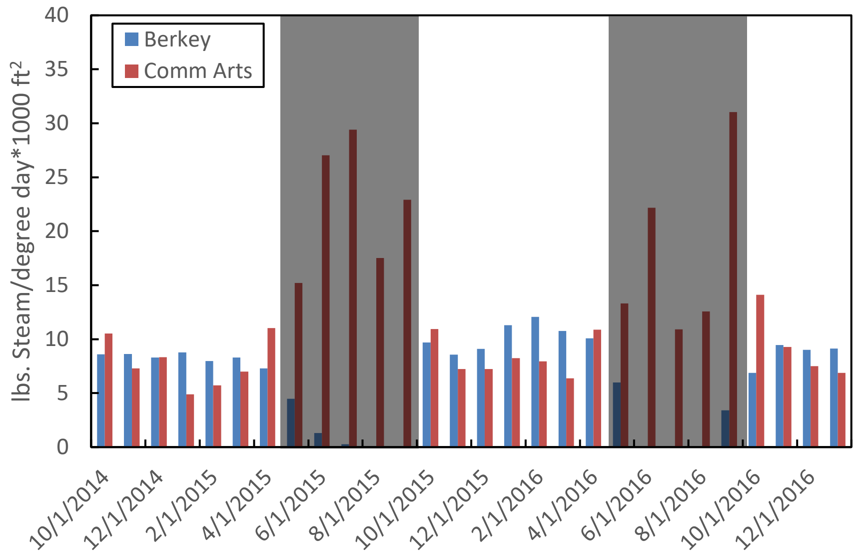


Figure 18: Comparison of HDD, CDD, and total steam consumption for Berkey Hall (WAC cooling)

To estimate the amount of steam which is required for operation of a centralized steam based cooling unit for a building currently cooled by distributed WAC, a comparison method is used between buildings of similar use type. Berkey Hall and Communication Arts are both buildings which consist of a first floor of primarily classrooms, three (Berkey) or four (Communication Arts) upper floors of primarily office space, and a single basement level. Total building area for Berkey and Communication Arts are 107,000 ft^2 and 221,000 ft^2 respectively. Due to this large discrepancy in building area, the units of $\frac{lb\ steam}{TDD*1000\ ft^2}$ are used (Figure 19) instead of the previously used $\frac{klb\ steam}{TDD}$ units (Figure 18).



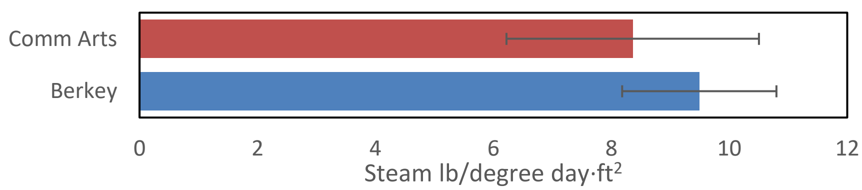


Figure 19: Comparison of Berkey Hall and Communication Arts steam use per total degree day scaled by total building area (top) and average values for heating months (bottom), indicated in the top graph by unshaded areas (Oct – Apr)

With the average scaled steam use of Berkey Hall heating months within one standard deviation of the Communication Arts average, a direct comparison was used for estimation of steam requirements for operation of a steam based cooling unit. Cooling months (May – Sept.) for Communication Arts use $24.1 \pm 8.3 \frac{lb\ steam}{TDD*1000\ ft^2}$. Therefore, the estimated amount of steam required for Berkey Hall for the cooling months is $2.6 \pm 0.9 \frac{klb\ steam}{TDD}$. Without steam cooling Berkey Hall uses 6090 ± 1520 klb steam/year. With steam cooling 9210 ± 1870 klb steam/year would be required per the 1981-2010 average monthly TDD values [23].

Discussion

Compared to steam requirements during heating months, the amount of steam required per total degree day during cooling months is significantly higher for four of the five buildings with centralized steam cooling which were analyzed: Communication Arts, Chemistry, Hannah Administration, and Wells Hall. Biomedical and Physical Sciences is the only one of the five where there is no significant difference in steam use intensity between heating and cooling months. It is expected that this is due to the much later initial construction date of the building of 2001 [24]. Of the other four buildings, the ratio of steam used in heating months to cooling months shows a downward trend with later installation dates, from an average 6.9 for Chemistry (1963) to 2.4 for Communication Arts (1981).

In most buildings with WAC cooling, units are installed in personal spaces. While this produces acceptable conditions within affected spaces, the use of these units does not extend into public spaces such as hallways and classrooms (Figure 20). This leads to a high likelihood of occupant discomfort in the WAC cooled spaces compared with those which are centrally cooled.

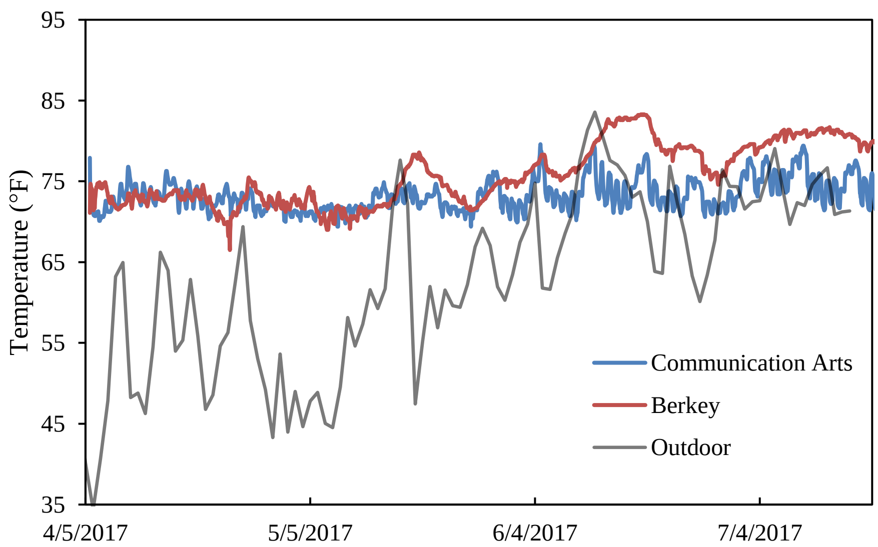


Figure 20: Comparison of Communication Arts (central cooling) and Berkey Hall (distributed/WAC cooling) temperature profiles. Outdoor temperatures are daily averages from LAN (NOAA)

A second point which must be addressed is the long-term availability of steam produced by the TB Simon power plant. The efficiency of a cogeneration plant such as TB Simon is maximized when both steam and electricity are consumed at the production rates. However, the demand on campus for electricity is generally in excess of steam requirements [25]. Construction is currently under way for solar carports over which are expected to produce approximately 15,000 MWh/year of electricity, directly offsetting production at the TB Simon power plant. Assuming a one to one relation of steam produced to electricity produced, this will result in a 5% reduction in produced steam annually.

When determining the viability of retrofitting existing spaces with centralized steam driven cooling units, several considerations must be accounted for. First, the availability of steam to power the system must be determined. With current use trends, unused excess steam could be used to power new installations providing 'free' utility costs. Therefore, any offset in electricity cost from ceasing WAC unit operation can be directly counted against the capital cost of an installation. Due to the high up-front cost of these units and required installation materials, however, a purely economic case cannot be made for any surveyed spaces. However, the increase in occupant comfort due to adequate cooling as well as the electricity use reduction and accompanied emissions reductions should be considered when determining the total impact of a proposed installation.

Energy Use Intensity of MSU Campus Spaces

Rationale

Determining the average energy use intensity of different space types on campus allows for determination of which types of devices consume the most energy. With this knowledge, recommendations for behavioral modification or equipment changes can then be provided. Equipment changes could, for example, be implemented by recommendations Spartan Marketplace stocking of various appliances that are more energy efficient. These changes will have a direct effect on end users and are not transparent like previously discussed energy saving measures.

Materials and Methods

To minimize intrusion on space occupants during in person surveys, the energy use of representative devices were applied to device counts from surveyed spaces. These energy use values were determined using a Kill A Watt meter (P3 International). Measurements were taken under different use conditions (Table 16). Devices measured were in two personal office spaces, one shared office space, and one computer lab. The generalized power use values also allowed for collection of data through an online survey which was utilized in buildings which were not targeted by in person surveying.

Table 16: Electricity draw at different states of representative devices. All units are in watts (W). Refrigerator energy consumption assumed to US Government Energy Guide value

Device	On	Off	Standby
Monitor	40	0	0.8
Refrigerator	110	--	--
Picture Frame	4	0	0
Lamp	29	0	0
Desktop Computer	29	0.8	2
Toaster	1200	0	0
Phone	1.5	0	0.8
Printer	16	0	5.7
Microwave	1100	--	1.3
Coffee Maker	3.9	--	3
Laptop	35	0	18
Speakers	15	0	5
Water heater	2000	0	0
Fan	25	0	0
Fax	16	0	5.7
Phone Charger	3.2	0	0
Cable Box (reference)	44	40	40

Device use rates were estimated for both weekdays (Mon – Fri, 8 hours/day) and weekend days (Sat – Sun). These were then extrapolated to give annual values (Table 17). Personal refrigerators were assumed to be equivalent to the US Government Energy Guide value for the refrigerator stocked by University Stores (campus distributor) as of 01/2016. Calculation method is described in the Appendix, Equation 11.

Table 17: Estimated annual energy use on a per device basis

Device	On (hrs)	Off (hrs)	Standby (hrs)	Wh/day (M-F)	Wh/day (Sa/Su)	kWh/yr
Monitor	8.0	0.0	16.0	332.8	19.2	88.5
Refrigerator	24.0	0.0	0.0	--	--	315.0
Picture Frame	24.0	0.0	0.0	96.0	96.0	25.0
Lamp	8.0	16.0	0.0	232.0	0.0	60.3
Desktop Computer	8.0	0.0	16.0	264.0	48.0	73.6
Toaster	0.1	23.9	0.0	100.0	0.0	26.0
Phone	0.3	0.0	8.0	6.9	19.2	3.8
Printer	0.0	16.0	8.0	46.1	0.0	12.0
Microwave	0.1	0.0	23.9	122.8	31.2	35.2
Coffee Maker	0.2	0.0	23.8	72.2	72.0	26.2
Laptop	1.0	0.0	5.0	125.0	0.0	32.5
Speakers	4.0	0.0	4.0	80.0	0.0	20.8
Water heater	0.1	23.9		166.7	0.0	43.3
Fan	8.0	16.0	0.0	200.0	0.0	17.0
Fax	0.0	16.0	8.0	46.1	0.0	12.0
Phone Charger	1.0	22.0	1.0	3.2	0.0	0.8

In-person surveys were performed for office spaces on acquiring permission of occupants. If a room was unoccupied or occupants did not consent to a survey no results were taken for the space. Space types surveyed included offices (single & multiple occupant), classrooms, and common spaces (eg break room). Number of devices in each space were recorded manually.

Online surveys consisted of a list of devices with radio buttons for quantity of devices in a space. Occupants were asked for their space type (personal or shared office) and building. SurveyMonkey was used for creating the survey and distribution of the survey was performed with department level emails.

There were significant variations in shared office occupant counts, with 8.2 ± 5.6 per shared office in areas surveyed on foot. Size of classrooms and lecture halls varied between 20 and 200+ allowed occupants and were therefore discounted for determining an average energy use intensity. While personal office spaces did have some variation indicated in surveys by ceiling light fixture counts, personal office spaces were of roughly comparable size across different buildings on campus (75% had 1 or 2 ceiling fixtures).

Average energy use intensity was determined only for personal office spaces due to high variation in shared office, common spaces, and classroom/lecture hall size. Each device type quantity was summed across all surveyed spaces and expected annual energy use was applied (Table 18). The total number of surveyed spaces was then divided into these values to determine the average annual usage per office space.

Results

In total 431 occupants were surveyed, consisting of 228 in personal office spaces and 203 in shared office spaces (Table 18). 198 occupants were surveyed on foot and 233 were surveyed online.

Table 18: Surveyed buildings

Building	Method	Responses
Business College Complex	In-Person/Online	116
Wells Hall	In-Person/Online	96
Erickson Hall	In-Person/Online	67
Engineering Building	Online	44
Communication Arts and Sciences	Online	31
Biomedical and Phsycial Sciences	In-Person	24
Farral Hall	In-Person/Online	17
Natural Resources	In-Person	11
Human Ecology	Online	10
Psychology	In-Person	8
IM Circle	Online	3
Oyer Hall	Online	2
Trout Food Sciences	In-Person9	2

Total energy consumption for a personal office space on the MSU campus is 539 kWh/year if ceiling lighting fixtures are not included (Figure 21). Laptops, desktops, and computer monitors consist of 2/3 of the total office energy consumption and refrigerators accounting for 1/4. Offices have an average of 1.5 computer monitors. Per results from online surveys (174 samples) 25% of offices had a desktop only, 24% had both a desktop and laptop, 45% used a laptop with secondary monitor(s), and 5% used a laptop only.

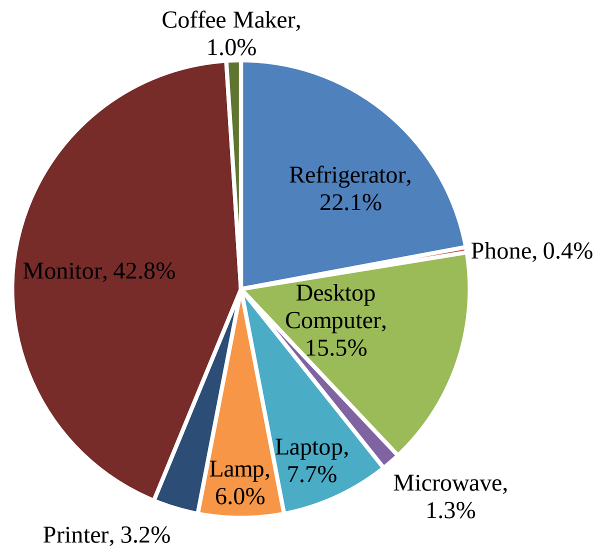


Figure 21: Energy use intensity for personal office spaces (total: 539 kWh/yr)

Ceiling fixture lighting consumes a sizable portion of electricity in most office spaces. A single fluorescent ceiling fixture consumes approximately 130 (two-lamp) to 200 (three-lamp) kWh/year. In surveyed spaces, 15% had a single fixture. Most office spaces (60%) had two ceiling fixtures, consuming between 260 and 400 kWh/year. Compared to the average energy use intensity due to other office equipment, the most significant contributor to total office energy use both in occurrence rates (all surveyed spaces contained at least one ceiling light fixture) and total energy consumption is lighting, which consumes between 33 and 43% of total office electricity (Figure 22).

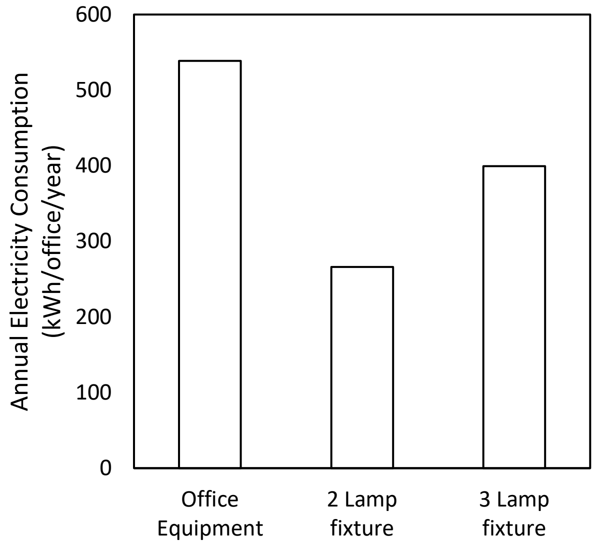


Figure 22: Comparison of total office device (not including ceiling fixtures) electricity use to two fluorescent fixtures of different configurations

Discussion

The three largest areas of office energy use determined in this study were in lighting, computing, and refrigeration. Lighting was previously discussed in Chapter 1 regarding retrofitting of hallway ceiling fixtures and further validates those studies as key target areas for energy reduction. However, the lower lighting on-rates for office spaces does not present as compelling of a business case. A simple payback period of 17.2 ± 2.2 years for 2 lamp retrofits and 14.8 ± 1.9 years for 3 lamp retrofits is expected in most office spaces (see Chapter 1 – *Hallway LED Retrofits* for more detailed description of retrofit systems and cost assumptions). Applying the results from the daylight harvesting light management system installation (Chapter 1), similar paybacks are expected to the installation of LED retrofits. In an office with 2 ceiling light fixtures, a payback of 24.9 ± 3.2 years for 2 lamp fixtures and 16.6 ± 2.1 years for 3 lamp fixtures is expected. Occupancy sensors for personal office spaces are not recommended unless they have easy overrides due to the degree of control that occupants have over lighting compared to common spaces and hallways. Light switches within offices are easily accessible and generally used to turn off lighting when the occupant is leaving the space for an extended period, such as at the end of their work day.

It is difficult (with current pricing) to make an economic case for lighting in office spaces despite the large energy impact, but savings are available in computing refrigeration. Due to the relatively short 3-5 year life span of computing systems per Michigan State University policy, replacement schedules can be utilized to replace high energy consumption equipment with lower intensity options. 25% of offices had a desktop only, while 24% had both a desktop and laptop. The remaining 51% had no desktop and instead used a laptop, generally with a second monitor (45% had external monitors). Per our measurements, a laptop consumes 32.5 kWh annually (on, not charging) compared to a desktop under normal conditions which consumes 73.6 kWh. A single computer monitor consumed 40W under normal conditions, so a desktop with at least two monitors (21% of total surveyed spaces) consumes 251 kWh annually under normal conditions. A laptop with a single monitor attached will consume 121 kWh annually, 48% of the consumption of a desktop system with a similar total screen area. This 130kWh reduction in annual electricity use corresponds to a 24% decrease in current average office energy use each year.

After lighting and computer equipment, the next largest consumer of electricity within personal office spaces is the refrigerator. While the refrigerators within personal office spaces have a smaller total volume, electricity use is often on par with much higher volume 'standard' refrigerators. For example, a 4.5 ft^3 unit is listed at 315 kWh/year, while an 18.1 ft^3 unit (Frigidaire) is listed at 404 kWh. With a single personal refrigerator generally consuming more than half of the electricity as a shared refrigerator, moving to centralized refrigerators in either break rooms or departmental offices can provide a significant reduction. If one 404 kWh/year shared refrigerator was substituted for every two personal refrigerators, energy reductions of 388MWh/year can be achieved. If one 18.1 ft^3 shared refrigerator is instead substituted for four personal refrigerators (18.0 ft^3 total volume), an energy reduction of 1.47GWh/year is available.

Summary

Reductions in annual electricity use of up to 631 MWhrs can be achieved by utilizing steam absorption chillers in place of distributed window air conditioning units in all surveyed buildings. In addition to consuming a significant amount of electricity annually, these systems are often outdated and do not provide adequate cooling within the building at large. Based on the analysis of Berkey Hall, it is expected that to achieve this electricity use reduction 44,200 ± 15,200 klb of steam would be required annually. Another target for energy reduction on campus lies within the almost 10,000 office spaces on campus. Lighting, computing, and personal refrigerators consume the largest share of the total office energy profile, and recommendations are provided for reducing each of these targets. The total impact of implementing the computer and refrigerator recommendations would provide a ~0.2% reduction in total electricity consumption. If LED retrofits were implemented in every office on campus, a ~0.6% would be available. While this is significant, the relatively low light on-rates limits the economic viability of these installations.

CHAPTER 3: Luminescent Solar Concentrator Outreach Activity

Introduction

With increasing greenhouse gas emissions [26], electricity costs [27], and international agreements on combatting climate change [28], the need for access to inexpensive renewable energy is increasing every year. Globally, 21.6 trillion kWh of electricity were generated in 2012 and this value is projected to increase to 36.5 trillion kWh by 2040 [29]. Increasing the fraction of this energy which comes from renewable sources is necessary for securing the energy future of the world and limiting the negative environmental impact in meeting that energy demand. The single largest source of renewable energy generation is our sun, which provides enough energy to power the planet for an entire year in less than one hour [30]. A key to effectively harnessing this energy lies in finding ways to creatively and synergistically deploy various solar technologies across a wide variety of spaces and we aim to promote this kind of creative thinking.

While solar panels are becoming a more ubiquitous and publicly recognizable form of solar harvesting, current photovoltaic (PV) technologies are often prohibitively expensive in relation to savings available [31] and can be constrained in application areas due to bulkiness, flexibility, or aesthetics. Thin film silicon (Si) cells [32], transparent organic PV [33], and luminescent solar concentrators (LSC) [34, 35] are all technologies which seek to address one or more of these issues. For this demonstration, we have developed a solar module design kit for making artistic and colorful LSC paintings that are both art and solar energy generators as a route to engage students in the understanding of optics, waveguides, energy transport, solar energy, and the necessity of renewable energy generating devices.

Concepts of Materials

The fundamental goal of an LSC device is to concentrate light gathered over a large area concentrator (waveguide) onto a small area of expensive, edge-mounted solar cells to reduce the overall solar cell system cost (Figure 23). Concentrators are doped with molecules which absorb certain fractions of the solar flux and re-emit this energy as luminescence at a longer wavelength (lower energy). This photoluminescence is then waveguided by total internal reflection to edge mounted solar cells for energy generation [34] or lost from the front/back of the waveguide if emitted photons contact the waveguide surface at angles inside the escape cone. This principle is similar to that experienced at amusement parks in fiber-connected flashlights. The efficiency of waveguiding (Equation 6) is dictated by the contrast in the index of refraction of the waveguide and the surrounding media (air):

$$\eta_{WG} = \sqrt{\left(1 - \frac{1}{n^2}\right)}^{11} \qquad (6)$$

For typical waveguides such as PMMA with an index of n = 1.5, this translates to a waveguiding efficiency of 75%. This means that up to 75% of the light which is captured within the waveguide can be directed to and emerge from the edges. Increasing total LSC efficiency (η_{LSC}) is a primary goal of current research in the field and is defined by:

$$\eta_{LSC} = (1 - R) * \eta_{Abs} * \eta_{PL} * \eta_{RA} * \eta_{PV} * \eta_{WG} \qquad (7)$$

This equation includes the front face reflection (R), absorptive efficiency of the luminophore (η_{Abs}), photoluminescent efficiency (η_{PL}), reabsorption suppression efficiency (η_{RA}), and photovoltaic efficiency (η_{PV}) [36]. Current LSC research goals focus on increasing the efficiencies above [37, 38] as well as scale of devices [39, 40], flexibility [40], and increasing concentrator transparency [41, 42, 43]. Ultimately there are two goals of developing LSC technologies: 1) reduction in total PV surface area required for collecting light to reduce module costs and 2) the ability to deploy solar harvesting devices in new areas.

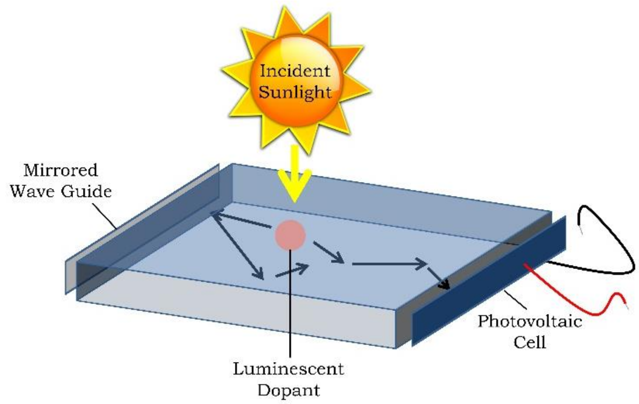


Figure 23: Luminescent solar concentrator schematic

LSC devices were originally developed as a simpler solution to mirror based concentrators[10] which harvest direct-incidence sunlight. LSCs can collect light across a wide range of incidence angles (including diffuse light), so complicated tracking equipment is not required for efficient collection of sunlight. Early concentrator designs generally absorbed and emitted light in the visible range, making them unsuitable for windows and other areas where the accurate transmission of natural light is desired [44]. However, these visibly absorbing and/or emitting concentrators often boast much higher efficiencies [45, 46] than transparent LSC devices [41, 42, 43] which allow for increased levels of visible light transmission. Application of both types of LSC devices into architectural spaces has become a focus of research [45, 47]. The light transmission characteristics of different devices provides architectural designers flexibility in implementation of solar harvesting technologies, from standard office windows to colorful designs such as at the Palais de Congrés in Montreal, Québec. The creation of visually appealing designs which can harvest energy and demonstrate the working principles of LSC technology are the focus of the demonstration described in this work.

Goals of the Demonstration

This This work examines an approach to LSC technology implementation which is different than uniform LSC applications seen in previous studies. By incorporating absorptive and luminescent dopants into clear paint formulations, they can be painted onto an optically clear sheet which constitutes the waveguide of the LSC. We are focused on developing an activity generally associated with creativity (painting) with solving an engineering problem (solar energy generation). Increasing student creativity in the approach of engineering problems helps to drive innovation which is essential for advances in science to occur [48]. The demonstration has four primary educational objectives:

1) To engage students in discussion of renewable energy

2) To highlight the energy potential from the sun

3) To develop fun and instructive solar cell activities

4) To associate creativity of design with STEM principles (e.g. linking art and energy)

Design of Materials and Demonstration

The key ingredients for building an LSC include a waveguide, PV cell(s), and luminescent materials. A 6”x6”x1/4” PMMA sheet was used as the waveguide for its suitable trapping (waveguide) efficiency as well the near complete transmission of light through the material before painting. The sheet dimensions allow for straightforward design and attachment of solar modules. While power can be generated with either flashlights or sunlight (indeed, both are encouraged), local illumination with the use of flashlights to control light penetration area and angle helps to visualize the principles of wave-guiding and can make the glowing light more apparent. Different penetration angles can also be used to promote discussion on possible efficiency loss pathways.

Five different colored paints (red, orange, yellow, green, and blue) were designed. Paint color is determined by the absorptive, luminescent, and reflective properties of constituent dyes. Absorptive filtering allows for the transmission of certain wavelengths of light which results in visible paint coloring (the dominant mechanism in this exercise). Under normal lighting conditions, the paints produce luminescence from absorbed light which also contributes to the overall perceived color by producing a noticeable glow (the second dominant mechanism of coloring in this exercise). On application, a small amount of reflection from the surface of the waveguide [44] also produces some coloring but is less important here.

The light absorbed by luminophore (dye) molecules is emitted at a longer wavelength (lower energy) than the absorptive color of the paint. This is caused by vibrational losses of the energy of electrons in the excited state before they return to the ground state. For example, a dye which has a yellow absorptive tint when in solution emits green light under excitation by flashlight; a dye which has a red absorptive tint (absorbing green light) emits red light which reinforces the color. For this demonstration, matching paint absorption color with emission color was desired to amplify particular coloring. This was achieved by mixing commercially available luminescent dyes so the imparted color from absorption and luminescence were similarly matched. The complementary blending of both the emission and absorption spectra of different dyes was performed to produce the five-color spectrum used in the demonstration (Figure 24). This mixing is described in greater detail in the *Discussion* section. The dyes are dissolved into an acetone solution and then combined with a poly(butyl methacrylate-co-methyl methacrylate) resin based polymer matrix solution (n = 1.51) to create the final paint which can adhere to the PMMA waveguide and dry within 15 minutes of application.

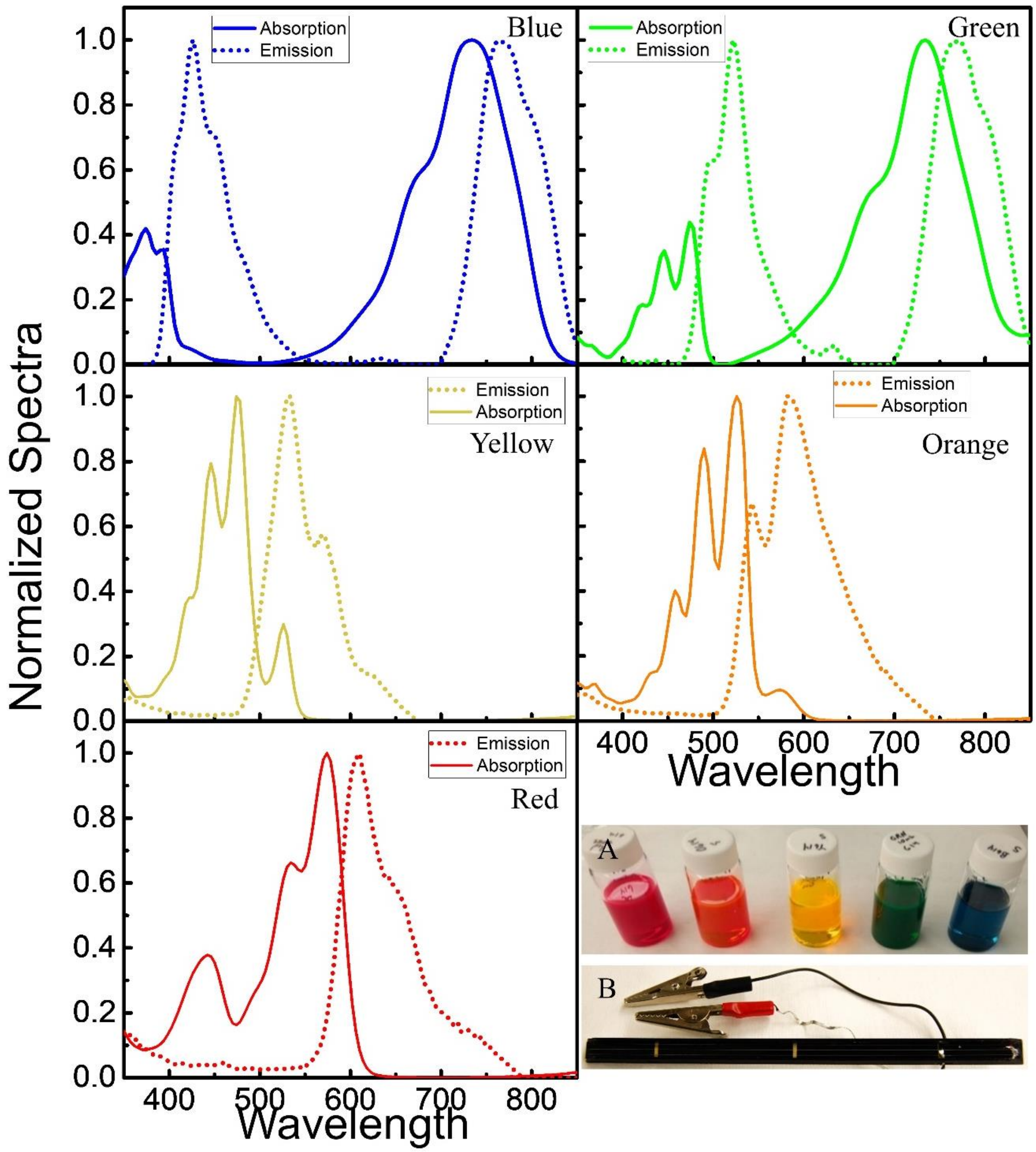


Figure 24: Normalized absorption (solid) and emission (dots) spectra of paints used in the demonstration (A). Solar cell module (D). Note that the multiple absorption and emission peaks for blue and green paints stem from two distinct dyes with one dye emitting in the visible and one emitting in the infrared to reinforce absorptive coloring and provide greater power.

Disposable pipettes were used in place of traditional paintbrushes to increase the thickness (and associated color density) of applied paints. The technique used is similar to drop casting, a common method[18] used in prototyping new dye formulations. Paint brushes can also be utilized but often require multiple coats due to the limited dye solubility of the paints. We note that even if higher solubilities were possible, concentrations above those utilized in this work often lead to “concentration quenching” of the luminophore resulting in a reduction in luminescence efficiency [49] and less glowing. Pipettes are initially less intuitive for participants to use but provide more control than brushes. It is helpful to have participants practice controlling them with scrap pieces of acrylic before attempting more complicated patterns and paintings.

Clips were designed and 3D printed to allow easy mounting and dismounting of fragile PV cell around the edge of the waveguide. A laser-cut 6” x 1/4” silicon solar cell was inserted into the printed clip with holes for soldered electrical leads (Figure 24D). The cell was then encapsulated in a clear epoxy for durability. Producing solar modules which were durable and easy to attach was a necessity for hands-on demonstration, especially for younger participants.

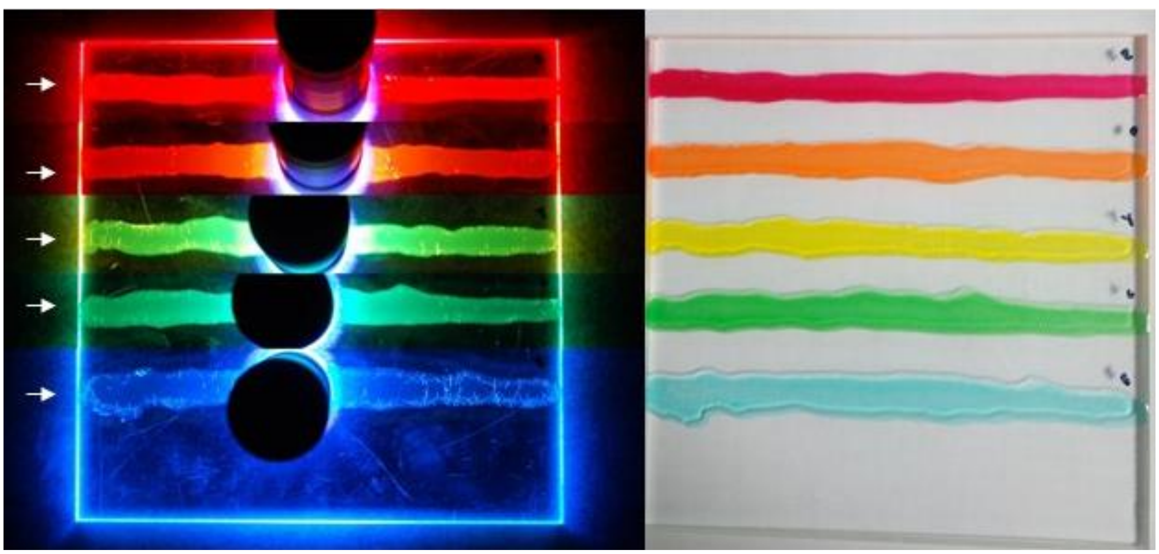


Figure 25: Sample painted device under direct illumination (left) and ambient conditions (right). Note luminescence along waveguide edge where solar modules are attached during demonstration

The demonstration is comprised of four segments: 1) initial introduction to solar energy and LSCs, 2) painting of devices, 3) paint drying time, and 4) device testing. The painting is preceded by an introduction which briefly describes the principles of LSC technology and a demonstration with a previously painted LSC device (Figure 25). Students were then allowed 5-10 minutes to paint their own LSC devices. During the following drying time (~15 minutes), a variety of topics were covered dependent on age/educational level of participating students. A discussion on the difficulties facing the implementation of solar harvesting technologies, including cost, application areas, and integration into the electrical grid were presented to students at all educational levels. For more advanced students, additional topics can include: factors which impact LSC efficiency, efficiency records, use of blocking diodes to prevent battery discharge, maximum power point tracking, and battery recharging time from instantaneous or average solar flux [50].

Upon completion of drying, solar modules were attached to one edge of each student's device and returned to students. Fans were then connected to the LSC to first get a qualitative idea of power generation by the devices before moving on to multimeters where current and voltage could be measured. Students were encouraged to collaborate and experiment with linking devices together in parallel and/or series to determine changes to device output in current, voltage, and fan speed.

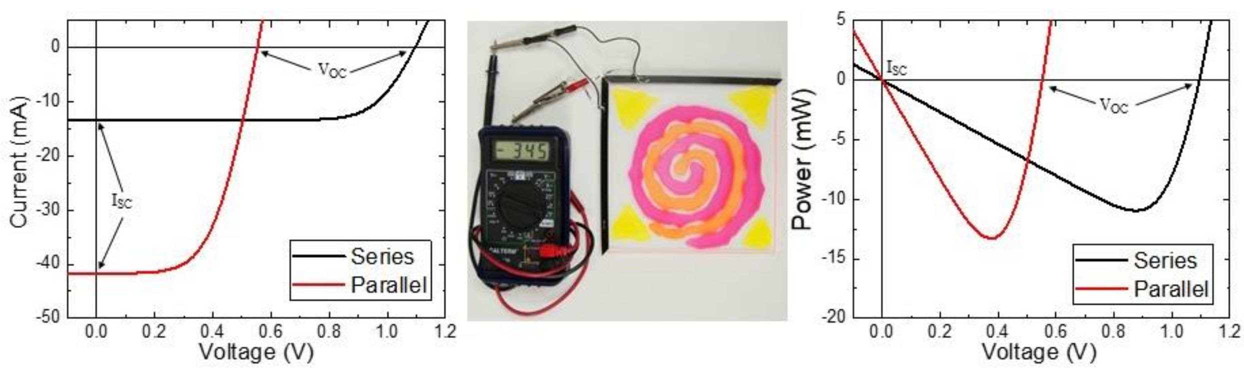


Figure 26: Current-Voltage (IV, left) and Power-Voltage (right) of device (center) with two edge mounted solar modules connected in series and parallel. Multimeter is connected in parallel, reading mV (center)

An *IV* curve (Figure 26) from two solar cell modules attached to a painted LSC in either parallel or series displays possible voltage and current combinations. The short circuit current, I_{SC} (current at zero voltage), and the open circuit voltage, V_{OC} (voltage at zero current), are used to characterize solar harvesting devices, but operation at either of these points will not provide usable power since $P = I * V$.

Power output is maximized at the *MPP* (maximum power point), which for the painting in Figure 4 was 11.0 mW (0.87V, 12.6mA) or 13.3 mW (0.38V, 35.0 mA) for series and parallel respectively.

Hazards

The solvent used in this demonstration is acetone (the active ingredient in nail polish remover), which has a high vapor pressure and produces a noticeable smell. The demonstration should be performed in a well-ventilated space. If participants handle paints the use of gloves and smocks are recommended to prevent staining of skin or clothing.

Discussion

Two questions were most frequently brought up by participants in the demonstration: 1) which color is the best and 2) how can a device which powers a fan or other device be produced? These questions provide an opportunity to discuss the mechanics behind electricity generation using LSC devices in more detail and are outlined below.

What Is the Best Color?

The question first raised by most students is which paint will produce the most power. While the most efficient device is not the goal of this activity, in real world applications the highest device efficiency is desired. Photon energy (E, eV) is inversely proportional to the wavelength (λ, μm) by Equation 8:

$$E = \frac{1.240\ eV * \mu m}{\lambda} \qquad (8)$$

As a result of this equation, many student’s initial (and intuitive) conclusion is that lower wavelength (higher energy) fluorescence/solar-absorption would yield higher current generation. However, the energy of the photon does not directly impact the efficiency of current generation because the excess energy of all the absorbed photons is thermalized to the bandgap and each absorbed solar photon produces, at most, one luminescence photon. This re-emitted photon can be reabsorbed, lost through the escape cone, or produce a maximum of one electron in the solar cell (in the absence of multiexciton generation). That is, the energy of the photon is not informative about the power generation in single junction LSCs. Again, the amount of power generated depends on the overall amount of absorption within a particular wavelength range, the amount of photons in the light source at those wavelengths, the luminescence efficiency, reabsorption losses from the dyes, and the efficiency of converting particular wavelength photons into electrons in the solar cell (Equation 7). The photoluminescent efficiencies for the constituent luminescent dyes described above are all similarly high (typically >85%); the wavelength efficiency (or quantum efficiency) for Si PVs is relatively flat across the spectrum (500-1000nm) except at UV and blue wavelengths where the efficiency drops off by about half; the solar photon spectrum is also relatively flat in the range of 500nm-1000nm (visible and infrared, Figure 27). The "best" color can then be attributed to the tuning of absorption widths (total light source absorption) combined with a particular pairing of light source. For example, the red paint has an absorption peak of ~570nm, a wavelength which is emitted at a much higher intensity by flashlights used in the demonstration. This leads to a high current generation potential. For the blue and green paints, a luminophore which emits in the near-infrared is used with a visibly luminescent dye to reinforce the blue or green color by absorbing the red part of the spectrum. This causes blue and green paints to absorb light at ~650-800nm (infrared) and 300-400nm (ultraviolet). Most commercial fluorescent and LED lamps do not emit at all in the ultraviolet or infrared, and the combination of these factors results in a low total current generation potential by these paints under artificial illumination. The blue and green paints have a higher current generation potential under sunlight, where their light production in both the ultraviolet and infrared portions of the spectrum. Reabsorption of the luminescence in the same or other dyes also plays a role in the overall current generation potential of a given paint.

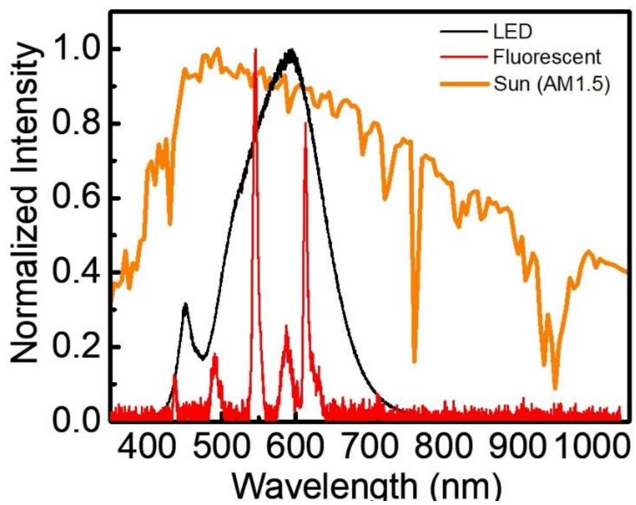


Figure 27: Spectrum of sunlgiht, LED lamp, and fluorescent lamp

How to Produce a Usable Device?

Generation of the most power possible from a device is important but is often secondary to producing the correct voltage and current for a particular application. Fortunately, this can be achieved primarily through different PV cell arrangement. Connection of multiple devices into an array as seen in large scale solar installations is carefully considered to satisfy voltage/current requirements. Similarly, connection of PV cells used in the demonstration in series and/or parallel circuits allows for tuning of voltage or current respectively to meet application requirements. An application requiring higher current levels than provided by a single device could utilize several devices with solar cell modules connected in parallel to increase output current; an application requiring higher voltage than produced by a single PV module (~0.4V for Si based LSCs) could be configured with several modules wired together in series to build voltage like batteries in series.

In this demonstration, the DC fan required 0.3V to begin operation. Because the operating point in both series and parallel exceeds the 0.3V threshold, the fan speed is limited only by the current provided. The combination which produces the most current will then yield the fastest fan speed. Wiring the edge mounted solar cells in parallel will produce the best device in this case. However, many applications (e.g. recharging batteries) require at least 1.8V, significantly more than can be generated by two cells connected in series. Connection of several devices (e.g. four cells from the four edges) in series is then required to produce a device suitable for these applications if they are to be powered directly.

Outreach Events

This demonstration was initially performed during Grandparent's University, an annual MSU program for school alumni to bring their grandchildren (8 – 12 years of age) to campus to participate in educational activities. During the two LSC painting outreach activities, students created their own LSC designs and tested them under illumination by the sun as well as with the use of flashlights as previously described (Figure 28).

Figure 28: MSU Grandparent's University outreach activity

A second outreach event participated in was the MSU Science Festival. Posters were designed covering the energy use intensity surveys (Chapter 2) and other topics investigated by SPARTA and how they could be applied at participants homes. Colored panels were included (Figure 29) to provide an explanation of the mechanisms of LSC devices, and small solar toys were provided for further participant engagement.

Figure 29: MSU Science Festival student participation

Conclusions

The goals of these described outreach activities are to engage students in discussion of renewable energy, highlight the potential from the sun, develop a fun and instructive activity, and associate creativity of design with STEM principles. Throughout the activity students are engaged in the discussion of renewable energy, from initial concepts of total available potential through to devices used in harvesting solar energy. With the use of different measuring devices, the energy potential available from the sun can be demonstrated both quantitatively and qualitatively. Parallels can be drawn between the activity provided and current research in the energy generation field. Materials (dyes used in paints) and techniques (drop-casting) used in the activity are the same as those used in current LSC research. While the competitive nature of students will often drive them to want to find the 'best' design, discussion of the efficiency factors follows the painting activity and therefore will not influence the painting of student devices. This allows students the freedom to produce devices which generate energy while expressing themselves through artistic paintings.

SUMMARY AND FUTURE WORK

The ultimate goal of the Michigan State University Energy Transition Plan is to source 100% of the required energy for campus from renewable sources [25]. To make this goal more reachable, there are essentially three pathways which can be taken: increasing the amount of energy produced by renewable energy sources, carbon capture and sequestration, and reduction of overall energy use so that less energy must be generated from non-renewable sources. In this thesis, several opportunities for reducing total energy use are investigated and potential savings are quantified. Engaging students in community outreach activities is important for driving interest and creativity in renewable energy generation. Because of the long-term investment which is inherent in the MSU Energy Transition Plan as well as any other approach to decreasing reliance on non-renewable energy sources, engaging students in these discussions benefits not only the student but can pay dividends in the future by helping steer them towards careers in the STEM, renewable energy, or sustainability fields.

In the first chapter, energy savings available from lighting retrofits for LED conversion and with various control methods are investigated. Retrofitting LED bulbs and drivers in ceiling fixtures is very economical in many spaces on the MSU campus, dependent on pricing scheme used for electricity purchase and the targeted areas for deployment (e.g. high on-rate). Because much of the electricity used on campus is purchased internally from the TB Simon power plant, choosing the right price level when determining economic indicators is very important. Due to the varying widths and light fixture concentrations, determining a single generalized value required to trigger a 5-year payback for occupancy sensor installations is not possible. However, most installations require around a $4 - $6 per linear foot of hallway to reach economic viability. Daylight harvesting systems are not economical as retrofits due to the exceedingly high equipment costs.

The second chapter focuses on energy use analyses of buildings and their occupants on the MSU campus. Cooling is a significant portion of HVAC operating load in the summer, and an estimation of electricity savings and steam utility requirements to switch from distributed window air conditioning units to steam absorption driven central cooling is performed. Increasing levels of steam use over the summer as facilitated by new installations of steam-based cooling units for buildings currently serviced by electrically powered window air conditioning units would cause a favorable increase in overall power plant efficiency. The average energy use intensity is determined for personal office spaces, with computing and lighting consuming the majority of total power use. A shift from desktop use to laptop use can see significant energy use reductions of 130kWh/yr in each instance with minimal reduction of total screen space, and switching from personal to communal refrigerators can realize energy use reductions of up to 1.47GWh/year.

The final chapter outlines an outreach activity used to engage students in a discussion of renewable energy generation, the second pathway for reaching the Energy Transition Plans goals. Luminescent solar concentrators are an alternative method for harvesting solar energy which can provide a tangible reminder for students of the power available from the sun, the largest source of renewable energy.

Moving forward, an aggressive approach to energy reductions on campus can be maintained. The implementation of LED lighting is an inexpensive way to greatly reduce total campus energy consumption. While four buildings are currently scheduled for retrofits, these reductions are estimated to reduce total campus energy consumption by 399 MWh annually (0.14%). If retrofits are implemented in all surveyed spaces, a reduction of 939 MWh annually (0.37%) is readily available. A complete economic evaluation of steam-cooling implementation is recommended at larger buildings such as Natural Sciences, Giltner, and Berkey Hall. To continue pursuing the goals of the MSU Energy Transition Plan, novel methods of energy reduction must continue to be analyzed and implemented alongside renewable energy generation to eventually reach 100% renewable campus.

APPENDIX

The determination of installed LED retrofit lifetimes (Equation 9) takes into account the manufacturer specified lifetime (L) (50,000 hours for CREE UR2-48-4500L, three-lamp retrofit; 60,000 hours for Precision Paragon TKG24-40VW-EU, two-lamp retrofit) and the expected light on rate after installation. The light on-rate after installation is assumed to be equal to the measured light on rate. Assuming 365 days per year, each year has 8,760 hours.

$$Installation\ Lifetime\ (years) = \frac{L\ (hrs)}{On\ Rate * 8760\,\frac{hrs}{year}} \tag{9}$$

Comparing this to the payback period at the lowest electricity pricing rate ($0.05755/kWh), the Packaging building will see the lowest difference between payback period and expected lifetime, with the retrofit expected to provide enough savings from electricity reductions 1.76 years before the end of the installation lifetime (Table 19)

Table 19: Comparison of payback period at $0.05755/kWh electricity purchse rate with installed system lifetime

Building	Expected Lifetime (yrs)	Payback Period (yrs)	Lifetime - Payback (yrs)
Agriculture Hall	8.82	6.25	2.56
Computer Center	12.65	9.50	3.14
Giltner Hall	6.85	4.58	2.27
Berkey	9.05	6.09	2.96
Trout Food Science	8.83	6.09	2.74
Packaging	6.85	5.09	**1.76**
Natural Resources	10.24	6.84	3.40
Wells - B+C Wing	10.16	6.84	3.33
Engineering	5.71	3.92	1.79
Bessey	10.54	7.26	3.28
Wells - A+D Wing	8.15	5.34	2.81
Chemistry	6.68	4.58	2.10
Biochemistry	6.94	4.67	2.27
North Kedzie	8.15	5.50	2.64
BPS	9.80	6.42	3.38
Plant and Soil Sciences	6.98	4.58	2.39
Baker	9.08	6.09	3.00
Music Practice	7.88	5.34	2.54
Comm. Arts	6.85	4.58	2.27
Wells Combined	8.68	5.67	3.01
Student Services Building	6.85	4.84	2.01

The following Tables (19-39) outline the results of light on-rate measurements which were performed under the methodology described in Chapter 1 – Hallway LED retrofits. The row labeled *Low* indicates the lower bound on rate (estimate) and *High* indicates the upper bound on rate (estimate). The row labeled *Act* indicates the actual measured on rate. The row labeled 'Fixtures' indicates the number lighting fixtures present in the surveyed hallways. The total on rate is weighted by the number of fixtures affected by the on rates by Equation 10, where *i* is the floor number.

$$On\ Rate = \frac{\sum_{i=1}^{n} On\ Rate_i * Fixtures_i}{\sum_{i=1}^{n} Fixtures_i} \qquad (10)$$

Table 20: Agriculture Hall light on-rate

Floor	B	1	2	3	4	**Total**
Fixtures	13	11	14	13	13	**64**
Low	100%	50%	63%	52%	87%	**71%**
Act	100%	50%	68%	70%	97%	**78%**
High	100%	50%	74%	85%	100%	**83%**

Table 21: Computer Center light on-rate

Floor	1	2	3	4	5	**Total**
Fixtures	11	11	11	11	11	**55**
Low	52%	52%	*46%*	*46%*	33%	**46%**
Act	60%	59%	*54%*	*54%*	44%	**54%**
High	71%	70%	*64%*	*64%*	51%	**64%**

Table 22: Giltner Hall light on-rate

Floor	1	2	3	4	**Total**
Fixtures	58	51	45	27	**181**
Low	100%	100%	100%	100%	**100%**
Act	100%	100%	100%	100%	**100%**
High	100%	100%	100%	100%	**100%**

Table 23: Berkey Hall light on-rate

Floor	B	1	2	3	4	**Total**
Fixtures	30	33	35	33	25	**156**
Low	75%	68%	64%	50%	86%	**67%**
Act	82%	79%	75%	57%	90%	**76%**
High	89%	99%	84%	72%	95%	**87%**

Table 24: Trout Food Science light on-rate

Floor	B	1	2	3	**Total**
Fixtures	22	22	28	26	**98**
Low	50%	100%	50%	100%	**74%**
Act	60%	100%	53%	100%	**78%**
High	71%	100%	61%	100%	**82%**

Table 25: Packaging Building light on-rate

Floor	1	**Total**
Fixtures	37	**37**
Low	100%	**100%**
Act	100%	**100%**
High	100%	**100%**

Table 26: Natural Resources light on-rate

Floor	B	1	2	3	**Total**
Fixtures	56	61	34	34	**185**
Low	50%	36%	100%	51%	**55%**
Act	69%	42%	100%	75%	**67%**
High	75%	46%	100%	90%	**73%**

Table 27: Wells Hall (B/C Wings) light on-rate

Floor	1	2	3	**Total**
Fixtures	75	30	40	**145**
Low	50%	100%	70%	**66%**
Act	50%	100%	76%	**67%**
High	50%	100%	82%	**69%**

Table 28: Engineering Building light on-rate

Floor	1	2	3	4	**Total**
Fixtures					**284**
Low	100%	100%	100%	100%	**100%**
Act	100%	100%	100%	100%	**100%**
High	100%	100%	100%	100%	**100%**

Table 29: Bessey Hall light on-rate

Floor	1	2	**Total**
Fixtures			**158**
Low	50%	51%	**51%**
Act	51%	57%	**54%**
High	57%	64%	**60%**

Table 30: Wells Hall (A/D Wings) light on-rate

Floor	1	2	3	4	5	6	7	**Total**
Fixtures	36	62	62	40	40	40	40	**320**
Low	*79%*	100%	100%	100%	50%	76%	50%	**83%**
Act	*81%*	100%	100%	100%	50%	87%	50%	**84%**
High	*83%*	100%	100%	100%	50%	100%	50%	**86%**

Table 31: Chemistry Building light on-rate

Floor	SB	B	1	2	3	4	5	**Total**
Fixtures	52	30	30	30	31	31	32	**184**
Low	50%	75%	17%	50%	100%	71%	69%	**64%**
Act	53%	88%	48%	74%	100%	89%	75%	**85%**
High	60%	95%	72%	86%	100%	100%	84%	**91%**

Table 32: Biochemistry light on-rate

Floor	B	1	2	3	4	5	**Total**
Fixtures	21	21	23	22	22	22	**131**
Low	*94%*	100%	76%	100%	100%	*94%*	**94%**
Act	*99%*	100%	95%	100%	100%	*99%*	**99%**
High	*100%*	100%	100%	100%	100%	*100%*	**100%**

Table 33: North Kedzie Hall light on-rate

Floor	1	2	3	**Total**
Fixtures	36	45	48	**129**
Low	79%	64%	56%	**65%**
Act	93%	84%	78%	**84%**
High	100%	100%	90%	**96%**

Table 34: Biomedical & Physical Sciences light on-rate

Floor	B	1	2	3	4	5	6	**Total**
Fixtures		58	47	58	58	26	24	**271**
Low	28%	76%	100%	58%	57%	47%	44%	**66%**
Act	37%	81%	100%	61%	61%	50%	47%	**70%**
High	44%	84%	100%	65%	66%	53%	50%	**73%**

Table 35: Plant and Soil Sciences light on-rate

Floor	B	1	2	3	4	5	**Total**
Fixtures	34	46	44	44	44	44	**256**
Low	97%	100%	100%	90%	100%	97%	**97%**
Act	98%	100%	100%	93%	100%	98%	**98%**
High	99%	100%	100%	97%	100%	99%	**99%**

Table 36: Baker Hall light on-rate

Floor	1	2	3	4	5	**Total**
Fixtures	33	33	33	33	33	**165**
Low	71%	75%	55%	57%	59%	**64%**
Act	89%	87%	60%	73%	68%	**75%**
High	100%	93%	67%	93%	74%	**85%**

Table 37: Kresge Hall light on-rate

Floor	B	1	2	3	**Total**
Fixtures	58	50	50	50	**150**
Low	50%	75%	50%	50%	**56%**
Act	50%	77%	73%	56%	**64%**
High	50%	81%	86%	72%	**71%**

Table 38: Communication Arts & Sciences light on-rate

Floor	2	3	4	5	**Total**
Fixtures	65	27	27	27	**146**
Low	100%	100%	100%	100%	**100%**
Act	100%	100%	100%	100%	**100%**
High	100%	100%	100%	100%	**100%**

Table 39: Music Practice Building light on-rate

Floor	B	1	2	3	4	5	Stairs	**Total**
Fixtures	13	6	13	13	13	13	60	**118**
Low	95%	*82%*	75%	89%	*82%*	*82%*	*82%*	**83%**
Act	95%	*86%*	80%	91%	*86%*	*86%*	*86%*	**87%**
High	96%	*89%*	84%	94%	*89%*	*89%*	*89%*	**89%**

Table 40: Student Services Building light on-rate

Floor	B	1	2	3	Total
Fixtures	26		8	26	60
Low	100%	100%	*100%*	100%	100%
Act	100%	100%	*100%*	100%	100%
High	100%	100%	*100%*	100%	100%

The following Tables (41, 42, 43) provide the results from Chapter 1 – Hallway LED retrofits. The upper and lower bounds of each metric are determined by applying the *low* and *high* light on-rates in Tables 20 – 40, while the baseline value is determined at the *act* measured on rate. The payback period is determined by Equation 2, net present value by Equation 3, and return on investment by Equation 4. Annual savings refer to the amount in dollars saved due to the energy reduction (Equation 1) from installing lower wattage LED retrofits in place of fluorescent fixtures.

Table 41: Economic metrics at fuel cost of electricity($0.05755/kWh)

Building Name	Low Payback Period (years)	Payback Period (years)	High Payback Period (years)	Low Net Present Value	Net Present Value	High Net Present Value	Low Return on Investment	Return on Investment	High Return on Investment	Low Annual Savings	Annual Savings	High Annual Savings
Agriculture Hall	5.8	6.3	6.9	$6,815	$7,235	$7,614	111%	118%	125%	$900	$955	$1,005
Computer Center	7.9	9.5	11.5	$5,035	$5,622	$6,135	96%	107%	117%	$512	$572	$624
Giltner Hall	4.6	4.6	4.6	$21,725	$22,388	$23,086	126%	129%	134%	$3,374	$3,477	$3,585
Berkey	5.3	6.1	6.8	$17,600	$18,662	$19,524	118%	125%	131%	$2,138	$2,267	$2,372
Trout Food Science	5.8	6.1	6.3	$10,983	$11,447	$11,969	117%	122%	128%	$1,401	$1,460	$1,526
Packaging	5.1	5.1	5.1	$3,979	$4,099	$4,226	113%	116%	120%	$690	$711	$733
Natural Resources	6.3	6.8	8.3	$20,307	$21,925	$23,059	115%	124%	130%	$2,202	$2,377	$2,500
Wells - B+C Wing	6.7	6.8	7.0	$16,204	$17,001	$17,820	117%	123%	129%	$1,789	$1,877	$1,967
Engineering	3.9	3.9	3.9	$40,313	$41,325	$42,383	123%	126%	130%	$7,263	$7,445	$7,636
Bessey	6.5	7.3	7.8	$20,469	$21,660	$22,890	113%	119%	126%	$2,121	$2,244	$2,371
Wells - A+D Wing	5.3	5.3	5.4	$37,997	$39,366	$40,875	124%	129%	134%	$4,989	$5,168	$5,366
Chemistry	4.3	4.6	6.2	$24,916	$26,473	$27,098	118%	125%	128%	$3,876	$4,119	$4,216
Biochemistry	4.6	4.7	4.9	$15,375	$16,008	$16,538	123%	128%	132%	$2,385	$2,483	$2,565
North Kedzie	4.8	5.5	7.1	$14,405	$15,453	$16,218	117%	125%	132%	$1,942	$2,083	$2,187
BPS	6.2	6.4	6.8	$31,133	$32,707	$34,402	120%	126%	133%	$3,461	$3,636	$3,825
Plant and Soil Sciences	4.6	4.6	4.7	$30,844	$31,697	$32,643	126%	130%	133%	$4,697	$4,827	$4,971
Baker	5.3	6.1	7.2	$18,544	$19,715	$20,821	118%	125%	132%	$2,248	$2,389	$2,524
Music Practice	5.2	5.3	5.6	$13,559	$14,140	$14,610	120%	125%	130%	$1,888	$1,969	$2,034
Comm. Arts	4.6	4.6	4.6	$17,412	$17,943	$18,502	125%	129%	133%	$2,721	$2,804	$2,892
Wells Combined	5.5	5.7	5.8	$55,190	$57,507	$59,498	124%	129%	134%	$6,761	$7,045	$7,289
Student Services Building	4.8	4.8	4.8	$6,814	$7,021	$7,239	119%	122%	126%	$1,118	$1,152	$1,188

Table 42: Economic metrics at produced cost of electricity ($0.07492/kWh)

Building Name	Low Payback Period (years)	Payback Period (years)	High Payback Period (years)	Low Net Present Value	Net Present Value	High Net Present Value	Low Return on Investment	Return on Investment	High Return on Investment	Low Annual Savings	Annual Savings	High Annual Savings
Agriculture Hall	4.4	4.8	5.3	$8,929	$9,463	$9,952	146%	155%	163%	$1,173	$1,243	$1,308
Computer Center	6.0	7.1	8.5	$6,728	$7,472	$8,112	128%	142%	154%	$671	$745	$809
Giltner Hall	3.5	3.5	3.5	$27,959	$28,825	$29,739	162%	167%	172%	$4,390	$4,526	$4,669
Berkey	4.0	4.7	5.3	$22,725	$24,090	$25,190	152%	162%	169%	$2,784	$2,951	$3,086
Trout Food Science	4.3	4.6	4.8	$14,250	$14,853	$15,529	152%	159%	166%	$1,823	$1,900	$1,987
Packaging	3.8	3.8	3.8	$5,253	$5,415	$5,586	149%	153%	158%	$898	$925	$954
Natural Resources	4.8	5.3	6.4	$26,210	$28,284	$29,754	148%	160%	168%	$2,868	$3,095	$3,256
Wells - B+C Wing	5.1	5.3	5.3	$20,942	$21,985	$23,057	151%	159%	166%	$2,327	$2,443	$2,562
Engineering	3.0	3.0	3.0	$51,526	$52,843	$54,223	158%	162%	166%	$9,451	$9,692	$9,945
Bessey	5.0	5.6	6.0	$26,296	$27,842	$29,432	145%	153%	162%	$2,759	$2,921	$3,088
Wells - A+D Wing	4.0	4.1	4.2	$48,785	$50,572	$52,536	160%	165%	172%	$6,490	$6,728	$6,989
Chemistry	3.3	3.6	4.8	$31,940	$33,922	$34,727	151%	160%	164%	$5,049	$5,362	$5,489
Biochemistry	3.5	3.6	3.8	$19,835	$20,659	$21,353	158%	165%	171%	$3,104	$3,233	$3,341
North Kedzie	3.7	4.3	5.4	$18,644	$19,970	$20,949	151%	162%	170%	$2,532	$2,712	$2,845
BPS	4.8	5.0	5.3	$40,025	$42,073	$44,282	155%	163%	171%	$4,504	$4,734	$4,983
Plant and Soil Sciences	3.5	3.6	3.6	$39,622	$40,737	$41,972	162%	167%	172%	$6,112	$6,284	$6,475
Baker	4.1	4.7	5.5	$23,939	$25,435	$26,860	152%	161%	170%	$2,928	$3,111	$3,285
Music Practice	4.0	4.1	4.3	$17,529	$18,286	$18,898	155%	162%	168%	$2,457	$2,563	$2,649
Comm. Arts	3.5	3.5	3.5	$22,440	$23,135	$23,869	161%	166%	171%	$3,541	$3,651	$3,766
Wells Combined	4.3	4.3	4.5	$70,783	$73,799	$76,391	159%	166%	172%	$8,797	$9,171	$9,494
Student Services Building	3.7	3.7	3.7	$8,880	$9,154	$9,444	155%	160%	165%	$1,455	$1,500	$1,548

Table 43: Economic metrics at delivered cost of electricity ($0.09206/kWh)

Building Name	Low Payback Period (years)	Payback Period (years)	High Payback Period (years)	Low Net Present Value	Net Present Value	High Net Present Value	Low Return on Investment	Return on Investment	High Return on Investment	Low Annual Savings	Annual Savings	High Annual Savings
Agriculture Hall	5.8	6.3	6.9	$6,815	$7,235	$7,614	111%	118%	125%	$900	$955	$1,005
Computer Center	7.9	9.5	11.5	$5,035	$5,622	$6,135	96%	107%	117%	$512	$572	$624
Giltner Hall	4.6	4.6	4.6	$21,725	$22,388	$23,086	126%	129%	134%	$3,374	$3,477	$3,585
Berkey	5.3	6.1	6.8	$17,600	$18,662	$19,524	118%	125%	131%	$2,138	$2,267	$2,372
Trout Food Science	5.8	6.1	6.3	$10,983	$11,447	$11,969	117%	122%	128%	$1,401	$1,460	$1,526
Packaging	5.1	5.1	5.1	$3,979	$4,099	$4,226	113%	116%	120%	$690	$711	$733
Natural Resources	6.3	6.8	8.3	$20,307	$21,925	$23,059	115%	124%	130%	$2,202	$2,377	$2,500
Wells - B+C Wing	6.7	6.8	7.0	$16,204	$17,001	$17,820	117%	123%	129%	$1,789	$1,877	$1,967
Engineering	3.9	3.9	3.9	$40,313	$41,325	$42,383	123%	126%	130%	$7,263	$7,445	$7,636
Bessey	6.5	7.3	7.8	$20,469	$21,660	$22,890	113%	119%	126%	$2,121	$2,244	$2,371
Wells - A+D Wing	5.3	5.3	5.4	$37,997	$39,366	$40,875	124%	129%	134%	$4,989	$5,168	$5,366
Chemistry	4.3	4.6	6.2	$24,916	$26,473	$27,098	118%	125%	128%	$3,876	$4,119	$4,216
Biochemistry	4.6	4.7	4.9	$15,375	$16,008	$16,538	123%	128%	132%	$2,385	$2,483	$2,565
North Kedzie	4.8	5.5	7.1	$14,405	$15,453	$16,218	117%	125%	132%	$1,942	$2,083	$2,187
BPS	6.2	6.4	6.8	$31,133	$32,707	$34,402	120%	126%	133%	$3,461	$3,636	$3,825
Plant and Soil Sciences	4.6	4.6	4.7	$30,844	$31,697	$32,643	126%	130%	133%	$4,697	$4,827	$4,971
Baker	5.3	6.1	7.2	$18,544	$19,715	$20,821	118%	125%	132%	$2,248	$2,389	$2,524
Music Practice	5.2	5.3	5.6	$13,559	$14,140	$14,610	120%	125%	130%	$1,888	$1,969	$2,034
Comm. Arts	4.6	4.6	4.6	$17,412	$17,943	$18,502	125%	129%	133%	$2,721	$2,804	$2,892
Wells Combined	5.5	5.7	5.8	$55,190	$57,507	$59,498	124%	129%	134%	$6,761	$7,045	$7,289
Student Services Building	4.8	4.8	4.8	$6,814	$7,021	$7,239	119%	122%	126%	$1,118	$1,152	$1,188

To determine the electricity reduction available from combining occupancy sensing control systems alongside LED retrofits, the case the Engineering Building is examined. Three lamp F32T8 fixture (96 W) light on-rates are 100%, and with 284 fixtures the total annual electrical draw is currently 238.8 MWh/year. Retrofitting fixtures with CREE UR2-48-4500L LED systems (44 W) will reduce the annual electricity consumption rate to 109.4 MWh/year (54.2% reduction). Applying the average expected light on-rate reduction due to occupancy sensing system installation (43%) to the 109.4MWh/year rate of consumption with installed LED retrofits results in an annual electricity consumption rate of 62.4 MWh/year, a reduction of 73.8% over fluorescent fixtures with no occupancy sensing systems installed.

*

To calculate the estimated annual energy use for devices in Table 17 (Chapter 2 – Energy Use Intensity of MSU Campus Spaces), average daily energy use was determined for both weekdays and weekends. For weekdays, it is assumed that offices are occupied 8 hours each day. For weekends, it is assumed that offices remain unoccupied. Using the wattage draw values (W_i) from Table 16 and the On/Off/Standby hours ($Time_i$) from Table 17, the following Equation is used to calculate *device draw* in watt-hours (Wh) used per day.

$$device\ draw = W_{on} * Time_{on} + W_{standby} * Time_{standby} + W_{off} * W_{off} \quad (11)$$

The values in Table 17 for hourly usage are for weekdays. Weekend operation assumes spaces are unoccupied, so on time for all devices (except for refrigerators) is assumed to be zero hours. All other devices are assumed to be left in standby mode except for laptops. It is assumed that laptops are taken home with occupants and therefore do not draw power within the office space during the weekend.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. EIA. (2017). Commercial Buidlings Energy Consumption Survey 2012 - Trends in Lighting in Commercial Buildings. Retrieved from https://www.eia.gov/consumption/commercial/reports/2012/lighting/

2. Comstock, O., & Jarzomski, K. (2014, March). LED Bulb Efficiency Expected to Continue Improving as Cost Declines. US Energy Inveromation Administration. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=15471

3. Ding, Y. (2015). *Solar Energy Related Applications, Education, and Building Retrofits*. ProQuest. Retrieved from http://search.proquest.com.proxy1.cl.msu.edu/docview/1657428372

4. Davis III, J. A., & Nutter, D. W. (2010). Occupancy diversity factors for common university building types. *Energy and Buildings*, *42*(9), 1543–1551. https://doi.org/10.1016/j.enbuild.2010.03.025

5. Guo, X., Tiller, D., Henze, G., & Waters, C. (2010). The performance of occupancy-based lighting control systems: A review. *Lighting Research & Technology*, *42*(4), 415–431. https://doi.org/10.1177/1477153510376225

6. Osterhaus, Werner K.E. (1993). Office Lighting: A Review of 80 Years of Standards and Recommendations. In *1993 IEEE Industry Applications Society Annual Meeting*.

7. Energy Trust of Oregon. (2013, July). Footcandle Light Guide. Retrieved from https://www.lightingdesignlab.com/sites/default/files/pdf/Footcandle_Lighting%20Guide_Rev.072013.pdf

8. Grossman, A. J. (2014). *Renewable energy and conservation measures for non-residential buildings* (M.S.). Michigan State University, Ann Arbor. Retrieved from https://search.proquest.com/docview/1547038417?accountid=12598

9. Bauer, W., Bollman, D., Ellerhorst, R., Latta, W., & Verhanovitz, N. (2017). Integration of Research, Teaching, and Practice in the Implementation of the Michigan State University Energy Transition Plan. In *Handbook of Theory and Practice of Sustainable Development in Higher Education* (Vol. 2, pp. 401–412).

10. Consumers Energy. (2017). Business Energy Efficiency Programs: 2017 Incentive Catalog. Retrieved from https://www.consumersenergy.com/~/media/CE/Documents/Energy%20Efficiency/Business/business-catalog.ashx

11. US Department of Energy. (n.d.). Energy Escalation Rate Calculator. Retrieved 1/6/2016

12. Hastbacka, M., Beeson, T., Cooperman, A., Dieckmann, J., & Bouza, A. (2013). Harvesting daylight. *ASHRAE Journal*, *55*(4), 60+.

13. Dubois, M.-C., & Blomsterberg, Å. (2011). Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review. *Energy and Buildings*, *43*(10), 2572–2582. https://doi.org/10.1016/j.enbuild.2011.07.001

14. Galasiu, A. D., & Veitch, J. A. (2006). Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Special Issue on Daylighting Buildings*, *38*(7), 728–742. doi:10.1016/j.enbuild.2006.03.001

15. AMO Energy Resources Center, U. D. of E. (n.d.). Daylighting Tool.

16. Lutron Electronics Co. (2010). Light Control and LEED. Retrieved from http://e2s2.ndia.org/pastmeetings/2011/tracks/Documents/12559.pdf

17. Doulos, L. T., Tsangrassoulis, A., Kontaxis, P. A., Kontadakis, A., & Topalis, F. V. (2017). Harvesting daylight with LED or T5 fluorescent lamps? The role of dimming. *Energy and Buildings*, *140*, 336–347. doi:10.1016/j.enbuild.2017.02.013

18. D&R International, Ltd. (2012). *2011 Buildings Energy Data Book*.

19. Office of Planning and Budgets – Facilities and Planning and Space Management. (2016). Room Use By Building. Retrieved 1/28/2016

20. US EPA. (2013). Room Air Conditioner Calculator. Retrieved from www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/CalculatorRoomAC.xls

21. Korn, D., & Walczyk, J. (2016). Exactly What Is a Full Load Cooling Hour and Does Size Really Matter? ACEEE Summer Study on Energy Efficiency in Buildings. Retrieved from http://aceee.org/files/proceedings/2016/data/papers/1_1168.pdf

22. EnergyCAP. (2017). *Weather Data Depot*. EnergyCAP.

23. NOAA. (2017, June 15). Summary of Monthly Normals 1981-2010. NOAA.

24. Facilities Information Tool. (2017). Michigan State University

25. Michigan State University. (2012). Energy Transition Plan. Michigan State University. Retrieved from http://ipf.msu.edu/files/pdfs/energy-transition-plan.pdf

26. "Climate Change 2014: Mitigation of Climate Change." IPCC, 2014.

27. "Short-Term Energy Outlook." US Energy Information Administration, 2016.

28. Savaresi, Annalisa. "The Paris Agreement: A New Beginning?" *Journal of Energy & Natural Resources Law* 34, no. 1 (January 2, 2016): 16–26. doi:10.1080/02646811.2016.1133983.

29. Energy Information Administration. "International Energy Outlook 2016: With Projections to 2040." (May, 2016): 19-44.

30. Lewis, Nathan S, and Daniel G Nocera. "Powering the Planet: Chemical Challenges in Solar Energy Utilization." *Proceedings of the National Academy of Sciences of the United States of America* 103, no. 43 (October 24, 2006): 15729–35. doi:10.1073/pnas.0603395103.

31. Breyer, Christian, and Alexander Gerlach. "Global Overview on Grid-Parity." *Progress in Photovoltaics: Research and Applications* 21, no. 1 (2013): 121–36. doi:10.1002/pip.1254.

32. Yang, Hung-Jen, Chien-Hsun Chen, Wei-Cheng Lai, Chien-Liang Wu, Chien-Fu Huang, Yu-Hung Chen, and Jenn-Chang Hwang. "Adjusted Colorful Amorphous Slicon Thin Film Solar Cells by a Multilayer Film Design." *Journal of The Electrochemical Society* 158, no. 9 (September 1, 2011): H851–53. doi:10.1149/1.3604949.

33. Lunt, Richard R., and Vladimir Bulovic. "Transparent, near-Infrared Organic Photovoltaic Solar Cells for Window and Energy-Scavenging Applications." *Applied Physics Letters* 98, no. 11 (2011). doi:http://dx.doi.org/10.1063/1.3567516.

34. Batchelder, J. S., A. H. Zewai, and T. Cole. "Luminescent Solar Concentrators. 1: Theory of Operation and Techniques for Performance Evaluation." *Applied Optics* 18, no. 18 (September 15, 1979): 3090–3110. doi:10.1364/AO.18.003090.

35. Weber, W. H., and John Lambe. "Luminescent Greenhouse Collector for Solar Radiation." *Applied Optics* 15, no. 10 (October 1, 1976): 2299–2300. doi:10.1364/AO.15.002299.

36. Yang, Chenchen, and Richard R. Lunt. "Limits of Visibly Transparent Luminescent Solar Concentrators." *Advanced Optical Materials* 5, no. 8 (2017). doi:10.1002/adom.201600851.

37. Bradshaw, Liam R., Kathryn E. Knowles, Stephen McDowall, and Daniel R. Gamelin. "Nanocrystals for Luminescent Solar Concentrators." *Nano Letters* 15, no. 2 (February 11, 2015): 1315–23. doi:10.1021/nl504510t.

38. Coropceanu, Igor, and Moungi G. Bawendi. "Core/Shell Quantum Dot Based Luminescent Solar Concentrators with Reduced Reabsorption and Enhanced Efficiency." *Nano Letters* 14, no. 7 (July 9, 2014): 4097–4101. doi:10.1021/nl501627e.

39. Kanellis, Michalis, Minne M. de Jong, Lenneke Slooff, and Michael G. Debije. "The Solar Noise Barrier Project: 1. Effect of Incident Light Orientation on the Performance of a Large-Scale Luminescent Solar Concentrator Noise Barrier." *Renewable Energy* 103 (April 2017): 647–52. doi:10.1016/j.renene.2016.10.078.

40. Correia, Sandra F. H., Patrícia P. Lima, Edison Pecoraro, Sidney J. L. Ribeiro, Paulo S. André, Rute A. S. Ferreira, and Luís D. Carlos. "Scale up the Collection Area of Luminescent Solar Concentrators towards Metre-Length Flexible Waveguiding Photovoltaics." *Progress in Photovoltaics: Research and Applications* 24, no. 9 (September 1, 2016): 1178–93. doi:10.1002/pip.2772.

41. Zhao, Yimu, and Richard R. Lunt. "Transparent Luminescent Solar Concentrators for Large-Area Solar Windows Enabled by Massive Stokes-Shift Nanocluster Phosphors." *Advanced Energy Materials* 3, no. 9 (September 1, 2013): 1143–48. doi:10.1002/aenm.201300173.

42. Meinardi, Francesco, Hunter McDaniel, Francesco Carulli, Annalisa Colombo, Kirill A. Velizhanin, Nikolay S. Makarov, Roberto Simonutti, Victor I. Klimov, and Sergio Brovelli. "Highly Efficient Large-Area Colourless Luminescent Solar Concentrators Using Heavy-Metal-Free Colloidal Quantum Dots." *Nat Nano* 10, no. 10 (October 2015): 878–85.

43. Zhao, Y., Meek, G., Levine, B., Lunt, R. "Near-Infrared Harvesting Transparent Luminescent Solar Concentrators." *Advanced Optical Materials* 2, no. 7 (2014): 606-611. doi: 10.1002/adom.201400103

44. Vossen, Finn M., Mariëlle P.J. Aarts, and Michael G. Debije. "Visual Performance of Red Luminescent Solar Concentrating Windows in an Office Environment." *Energy and Buildings* 113 (February 1, 2016): 123–32. doi:10.1016/j.enbuild.2015.12.022.

45. Debije, MG Michael, and PPC Paul Verbunt. "Thirty Years of Luminescent Solar Concentrator Research : Solar Energy for the Built Environment." *Advanced Energy Materials* 2, no. 1 (2012): 12.

46. Slooff, L. H., E. E. Bende, A. R. Burgers, T. Budel, M. Pravettoni, R. P. Kenny, E. D. Dunlop, and A. Büchtemann. "A Luminescent Solar Concentrator with 7.1% Power Conversion Efficiency." *Physica Status Solidi (RRL) – Rapid Research Letters* 2, no. 6 (December 1, 2008): 257–59. doi:10.1002/pssr.200802186.

47. Chemisana, Daniel. "Building Integrated Concentrating Photovoltaics: A Review." *Renewable and Sustainable Energy Reviews* 15, no. 1 (January 2011): 603–11. doi:10.1016/j.rser.2010.07.017.

48. Thompson, G, and M Lordan. "A Review of Creativity Principles Applied to Engineering Design." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 213, no. 1 (February 1, 1999): 17–31.

49. Lakowicz, J. R. (1983). Quenching of Fluorescence. In J. R. Lakowicz (Ed.), *Principles of Fluorescence Spectroscopy* (pp. 257–301). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-7658-7_9

50. Lunt, R. "Solar Charging Calculator." http://www.egr.msu.edu/~rlunt/Solar_Charging_Worksheet_Calculator.xlsx