Controls Embedded LED Replacement Lamps Technology Assessment

ET Project Number: ET13PGE1381

Project Manager: Jeff Beresini
Pacific Gas and Electric Company

Prepared By: Kevin Price
Evergreen Economics, Inc.
1648 Martin Luther King Jr. Way
Berkeley, CA 94709

Issued: December 30, 2014

© Copyright, 2015, Pacific Gas and Electric Company. All rights reserved.
ACKNOWLEDGEMENTS

Pacific Gas and Electric Company’s Emerging Technologies Program is responsible for this project. It was developed as part of Pacific Gas and Electric Company’s Emerging Technology – Technology Demonstration program under internal project number ET13PGE1381. Evergreen Economics, Inc., conducted this technology evaluation for Pacific Gas and Electric Company with overall guidance and management from Jeff Beresini. For more information on this project, contact JLBd@pge.com.

LEGAL NOTICE

This report was prepared for Pacific Gas and Electric Company for use by its employees and agents. Neither Pacific Gas and Electric Company nor any of its employees and agents:

(1) makes any written or oral warranty, expressed or implied, including, but not limited to those concerning merchantability or fitness for a particular purpose;

(2) assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, process, method, or policy contained herein; or

(3) represents that its use would not infringe any privately owned rights, including, but not limited to, patents, trademarks, or copyrights.
# Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETP</td>
<td>Emerging Technology Program</td>
</tr>
<tr>
<td>CFL</td>
<td>Compact Fluorescent Lamp</td>
</tr>
<tr>
<td>CIE</td>
<td>International Commission on Illumination</td>
</tr>
<tr>
<td>HOU</td>
<td>Hours of Use</td>
</tr>
<tr>
<td>iOS</td>
<td>Apple, Inc.’s mobile device operating system</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>PG&amp;E</td>
<td>Pacific Gas and Electric Company</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1: Executive Summary – All Sites – Test Lamps – Load Shapes and Dimming........................................ 2
Figure 2: Executive Summary – All Sites – Test Lamps – Color Usage................................................................. 3
Figure 3: Controls Enabled LED Savings ............................................ 1
Figure 4: CIE 1931 Color Space Diagram........................................... 6
Figure 5: Hue Data Collection and Cleaning Flowchart .................... 11
Figure 6: Hue Data Collection and Cleaning Flowchart .................... 13
Figure 7: Hue Application and “Other (white)” Color Bin ................. 16
Figure 8: All Sites – All Lamps – Lamp Use and Dimming Profile ...... 18
Figure 9: All Sites – Test Lamps – Lamp Use and Dimming Profile.... 19
Figure 10: All Sites – Comparison Lamps – Lamp Use and Dimming Profile............................................................ 19
Figure 11: All Sites – Test Lamps – Color Usage............................... 21
Figure 12: Living Rooms – Lamp Use and Dimming Profile .............. 23
Figure 13: Living Rooms – Test Lamps – Color Usage...................... 24
Figure 14: Bedrooms – Lamp Use and Dimming Profile..................... 25
Figure 15: Bedrooms – Test Lamps – Color Usage............................. 26
Figure 16: Dining Rooms – Lamp Use and Dimming Profile ............ 27
Figure 17: Dining Rooms – Test Lamps – Color Usage...................... 28
Figure 18: Bathroom – Lamp Use and Dimming Profile...................... 29
Figure 19: Bathroom – Test Lamps – Color Usage............................... 30
Figure 20: Office – Lamp Use and Dimming Profile.......................... 31
Figure 21: Kitchen – Load Shapes and Dimming................................. 32
Figure 22: Site 1 – Test Lamps – Lamp Use and Dimming Profile..... 34
Figure 23: Site 1 – Test Lamps – Color Usage........................................ 35
Figure 24: Site 2 – Test Lamps – Lamp Use and Dimming Profile..... 36
Figure 25: Site 2 – Test Lamps – Color Usage........................................ 37
Figure 26: Site 3 – Test Lamps – Lamp Use and Dimming Profile..... 38
Figure 27: Site 3 – Test Lamps – Color Usage........................................ 39
Figure 28: Site 4 – Test Lamps – Lamp Use and Dimming Profile..... 40
Figure 29: Site 4 – Test Lamps – Color Usage........................................ 41
Figure 30: Site 5 – Test Lamps – Lamp Use and Dimming Profile..... 42
Figure 31: Site 5 – Test Lamps – Color Usage................................. 43
Figure 32: Site 6 – Test Lamps – Lamp Use and Dimming Profile..... 44
Figure 33: Site 7 – Test Lamps – Lamp Use and Dimming Profile..... 45
Figure 34: Site 8 – Test Lamps – Lamp Use and Dimming Profile..... 46
Figure 35: Site 8 – Test Lamps – Color Usage............................... 47
Figure 36: No Children / Detached Home (Test Lamps) – Lamp Use and Dimming Profile................................. 49
Figure 37: No Children / Attached Home (Test Lamps) – Lamp Use and Dimming Profile................................. 50
Figure 38: Elementary Age Children / Detached Home (Test Lamps) – Lamp Use and Dimming Profile......................... 51
Figure 39: Teenage Children / Detached Home (Test Lamps) – Lamp Use and Dimming Profile................................. 52
Figure 40: Site 1 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 59
Figure 41: Site 1 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 59
Figure 42: Site 2 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 60
Figure 43: Site 2 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 60
Figure 44: Site 3 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 61
Figure 45: Site 3 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 61
Figure 46: Site 4 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 62
Figure 47: Site 4 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 62
Figure 48: Site 5 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 63
Figure 49: Site 5 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 63
Figure 50: Site 7 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 64
Figure 51: Site 7 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 64
Figure 52: Site 8 – Living Room Test Lamp – Lamp Use and Dimming Profile .................................................. 65
Figure 53: Site 8 – Living Room Comparison Lamp – Lamp Use and Dimming Profile .................................................. 65
Figure 54: Site 1 – Bedroom Test Lamp – Lamp Use and Dimming Profile ............................................. 66
Figure 55: Site 1 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile ............................................. 66
Figure 56: Site 3 – Bedroom Test Lamp – Lamp Use and Dimming Profile ....................................................... 67
Figure 57: Site 3 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile ............................................. 67
Figure 58: Site 5 – Bedroom Test Lamp – Lamp Use and Dimming Profile ....................................................... 68
Figure 59: Site 5 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile ............................................. 68
Figure 60: Site 7 – Bedroom Test Lamp – Lamp Use and Dimming Profile ....................................................... 69
Figure 61: Site 7 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile ............................................. 69
Figure 62: Site 8 – Bedroom (1) Test Lamp – Lamp Use and Dimming Profile ..................................................... 70
Figure 63: Site 8 – Bedroom (1) Comparison Lamp – Lamp Use and Dimming Profile ........................................ 70
Figure 64: Site 8 – Bedroom (2) Test Lamp – Lamp Use and Dimming Profile ..................................................... 71
Figure 65: Site 8 – Bedroom (2) Comparison Lamp – Lamp Use and Dimming Profile ........................................ 71
Figure 66: Site 3 – Dining Room Test Lamp – Lamp Use and Dimming Profile ...................................................... 72
Figure 67: Site 3 – Dining Room Comparison – Lamp Use and Dimming Profile .................................................... 72
Figure 68: Site 5 – Bathroom Test Lamp – Lamp Use and Dimming Profile .......................................................... 73
Figure 69: Site 5 – Bathroom Comparison Lamp – Lamp Use and Dimming Profile .............................................. 73
Figure 70: Site 7 – Office Test Lamp – Lamp Use and Dimming Profile .............................................................. 74
Figure 71: Site 7 – Office Comparison Lamp – Lamp Use and Dimming Profile ..................................................... 74

TABLES

Table 1: Site Descriptions ........................................................................ 9
Table 2: Color Bins

Table 3: White Color Temperature Bins

Table 4: Average Hours of Use per Day – Test vs Secondary Lamps

Table 5: Use of Dimming – All Test Lamp (Phase 2)

Table 6: Room Types and characteristics

Table 7: Use of Dimming – Test Lamps, By Room Type (Phase 2)

Table 8: Average Hours of Use By Study Site

Table 9: Use of Dimming – Test Lamps, By Site (Phase 2)

Table 10: Site Demographic Groupings

Table 11: Use of Dimming – Test Lamps, By Demographic Groupings (Phase 2)

Table 12: Comparable Connected LED Products

Table 13: Manufacturer Respondent Dispositions

EQUATIONS

Equation 1: Controls Enabled LED Energy Savings
CONTENTS

EXECUTIVE SUMMARY .................................................................................................................. 1
INTRODUCTION ............................................................................................................................... 1
BACKGROUND .................................................................................................................................. 2
EMERGING TECHNOLOGY/PRODUCT ............................................................................................. 2
ASSESSMENT OBJECTIVES ............................................................................................................ 3
TECHNOLOGY/PRODUCT EVALUATION ......................................................................................... 3
  Field Placement .......................................................................................................................... 3
  Market Study .............................................................................................................................. 3
TECHNICAL APPROACH/TEST METHODOLOGY ........................................................................ 4
  Field Testing of Technology ......................................................................................................... 4
  Test Plan ..................................................................................................................................... 4
  Study Period ............................................................................................................................... 4
  Key Variables ........................................................................................................................... 5
  Instrumentation Plan .................................................................................................................. 6
  Metering Protocols and Testing ................................................................................................. 7
  Site Recruitment and Prescreening ............................................................................................. 7
  Two-Phase Placement ................................................................................................................. 7

RESULTS .......................................................................................................................................... 8
  Field Placement .......................................................................................................................... 8
  Data Analysis ............................................................................................................................. 8
  Findings .................................................................................................................................... 16
  Market Study ............................................................................................................................. 52
  Literature Review ....................................................................................................................... 52
  Manufacturer In-depth Interviews ............................................................................................. 54

EVALUATIONS .................................................................................................................................. 56
  Financial Analysis ....................................................................................................................... 57

RECOMMENDATIONS .................................................................................................................... 58

APPENDICES ................................................................................................................................... 59
  TEST AND SECONDARY LAMP COMPARISON ........................................................................ 59
    Living Rooms .......................................................................................................................... 59
    Bedrooms ................................................................................................................................. 66
    Dining Room .......................................................................................................................... 72
    Bathroom ................................................................................................................................. 73
    Office ....................................................................................................................................... 74
EXECUTIVE SUMMARY

PROJECT GOAL

The goal of the study is to perform an initial assessment of Wi-Fi-enabled controls embedded LED lamps. There are two objectives of this technology assessment study:

- Assess the market feasibility of controls enabled LEDs in residential applications by conducting market research with manufacturers to determine their future plans related to LEDs with embedded controls; and,
- Assess the technical feasibility of deriving energy savings from controls enabled LEDs in residential applications by providing preliminary data on a small sample of sites. These data may be used to understand the potential for behavior-related savings as a result of measure installation.

This study is an initial assessment of the potential for energy savings from LEDs with embedded controls. This study focuses on changes in usage patterns that may impact overall lighting energy usage.

PROJECT DESCRIPTION

This technology assessment consists of two components, each described below.

The technical savings assessment portion of the study is intended to provide preliminary data on a small sample of sites and lamps that may be used to understand the potential for savings and changes in usage patterns as a result of measure installation. PG&E work paper energy savings due to straightforward LED lamp retrofits are already established and based on agreed upon wattage reduction ratios. The focus, therefore, is understanding whether behavioral changes associated with embedded controls are a potential source of additional energy savings (beyond the wattage reduction) in residential fixtures that currently lack controllability (beyond standard on/off control).

The purpose of the market study component of this study is to assess the long-term plans of manufacturers with respect to controls enabled LEDs in residential applications. The research encompassed a search for related EM&V studies, summary of findings from related EMV&V studies, Internet research for comparable products and specifications/pricing for comparable products, and in-depth interviews with controls enabled LED manufacturers.

PROJECT FINDINGS/RESULTS

Figure 1, below, presents the lamp use profile for connected LEDs included in this study. Users were not permitted to use the functionality of the connected LEDs during Phase 1, but were permitted to use the functionality during Phase 2.

There is an increase in usage among the test lamps from Phase 1 to Phase 2. However, there is also substantial use of dimming across test lamps that may offset the energy consumption of greater hours of operation (lamps were dimmed approximately 18.5% of the time they were “on” during Phase 2).
Overall color usage among test lamps during the second phase of the study period is shown below in Figure 2, for both morning and evening timeframes. As shown, the default white color is used the majority of the time across all lamps (69.3% in mornings and 66.7% in evenings). Other white temperatures are used to varying degrees. Color is infrequently used in the mornings (3.7% on average across all test lamps), but accounts for 6.7 percent of on-time in evenings, across all lamps.

In both morning and evening periods, reddish colors accounted for the majority of color usage. In the mornings, yellowish colors were used nearly as frequently as red. In both morning and evening timeframes, blue and fuchsia colors were used very infrequently.
A summary of the findings from this technology assessment is presented below:

1. Hours of use increased more for the test lamps than the comparison lamps between Phase 1 and Phase 2, possibly indicating that installation of connected LEDs would lead to greater operating hours and possibly energy consumption (relative to standard LEDs). This analysis accounted for changes in hours of use due to seasonality.

2. The possibility of increased energy consumption based on hours of use among test lamps may be offset by frequent use of the dimming features. The results indicate...
that dimming was frequently used among test lamps installed in bedrooms and living rooms (approximately 38% and 20% of “on” time, respectively).

3. There appear to be situations where increased usage occurred in the test lamp, and decreased usage in the comparison lamp (which was only controlled via the standard wall switch) – this suggests usage of connected LEDs may impact the use of other lamps within a room. In these cases, some portion of the usage is moving from one lamp to the other, and does not necessarily reflect net increase in usage overall.

4. Color functionality was used heavily by some households, and not at all by others. Color usage was most prevalent in sites with young adults and no children, and the site with teenage children.

5. Color was more frequently used in the evenings in living rooms and bedrooms, and more frequently in the morning in dining rooms (on average, across test lamps). Color was almost never used in bathrooms (it was never used in the office or kitchen where test lamps were installed, but this was more to do with the household not using the color functionality across any of their lamps).

6. White light color temperature tuning is another benefit of this technology, and was used extensively by Site 2, Site 3, and Site 4. Color temperature has been a barrier to efficient lighting adoption (both for fluorescent and LED technologies), and the ability to tune the temperature to satisfy your particular temperature needs is a benefit of this technology (this was mentioned by four of five manufacturers interviewed for the market study component of this assessment).

7. Brightness controllability was used significantly at Site 2, Site 3, Site 4, and Site 5 (for other sites it was rarely used). This could be a driver of sales based on the wants and needs of the end-user.

8. Some end-users were frustrated with the way the lamps were controlled by their cell phones. Both the new method of using a phone to turn on/off or adjust lighting and issues with the user interface were barriers to using the control features of the system. These may be barriers to the adoption and use of connected LEDs, and affected the amount that study participants used the feature set of the Hue. These issues may manifest themselves in the residential mass consumer market, and thus savings from the connected aspect of smart-phone controlled LEDs may not exist for all purchasers.

9. Lamp connectivity issues impact the usability of the lamps themselves. This is a potential barrier, although there are a number of manufacturers using a variety of different wireless connectivity protocols (e.g., WiFi, zigbee, Bluetooth), so improvements in this area are likely achievable by manufacturers.

10. Lamps must be installed in fixtures controlled only by on/off switches (not dimmers). Furthermore, lamps must be powered “on” at the switch in order to control them via the application (lamps may be turned “off” via the application). If a fixture is turned “off” by the switch, the lamp receives no power and thus cannot be controlled remotely.

11. Product cost is generally high for products in this category, but cost is expected to decline significantly in the near-term.

12. Connected LEDs offer a way to overcome drawbacks of currently available lighting hours of use meters. Traditional lighting monitoring equipment typically relies on photocell readings to determine the on/off status of a lamp, where ambient light can create false “on” readings due to installer error. Connected lamps allow for a higher
degree of certainty regarding the on/off status and other characteristics of the lamp, such as light color or brightness, because the status data is continuously communicated to a centralized hub. However, connectivity issues – mentioned above in the ninth finding – may disrupt data collection and/or require implementing data cleaning procedures.

**PROJECT RECOMMENDATIONS**

The findings from this assessment suggest that further study in the area of connected LEDs is warranted at this time. There exist a range of available products at different price points and with different feature sets, and manufacturers are supporting the products as serious lighting solutions. Furthermore, the results of the market study suggest that the user experience with connected LEDs may change in the near-term, with more manufacturers producing connected LEDs that adjust to the user and do not require as much user input (e.g., via a smartphone). Manufacturers believe that connected LEDs are the future of residential – and perhaps commercial – lighting, and not just a novelty item.

Additionally, this assessment shows that usage changes with the introduction of application-controlled connected LEDs. A more robust study, in terms of the number of homes and total number of lamps, may be able to address whether energy savings from the use of dimming (or color) offsets any potential increase in energy consumption due to increases in hours of use.

It is also recommended that PG&E consider opportunities for additional human-centric studies related to the color tuning aspect of connected LEDs. This feature alone would help to alleviate an efficient lighting market barrier that precedes the introduction of LEDs into the residential mass market (consumer dissatisfaction with fluorescent and LED light quality).

Until further study of this technology group, it is not recommended that PG&E adopts a new measure category for this technology into the energy efficiency program. However, since connected lamps may be a good entry point into the efficiency market for consumers, and since they allow for tuning of color temperature to suit the needs of consumers, it is recommended that these lamps be considered for residential\(^1\) and targeted commercial energy efficiency programs as part of the existing LED measures.

---

\(^1\) Though this may not be feasible as many (if not all) of the available LEDs with embedded controls do not meet the California Energy Commission (CEC) Voluntary California Quality LED Lamp Specification (which serves as the minimum quality standard for LED replacement lamp products that are incented in IOU Upstream Residential Lighting Programs).
INTRODUCTION

PG&E contracted with Evergreen to conduct technical and market research to assess the energy savings and market potential for residential screw-based controls embedded LED replacement lamps. With embedded controls, the technology offers savings beyond the replacement lamp wattage differential.

While the specific technology enlisted for this study, a Wi-Fi enabled lighting system from Philips called the “Philips Hue”, offers promise, it may or may not be indicative of lighting suppliers’ commitments to investing in similar products. Therefore, one goal of the study is to identify market trends that could inform PG&E in determining where to focus Energy Efficiency Program resources.

The technical savings assessment portion of the study is intended to provide preliminary data on a small sample of sites and lamps that may be used to understand the potential for savings and changes in behavior as a result of measure installation. The sample was developed based on the need for both information-rich cases and ease of implementation, and may not reflect how the general population might use this technology.

PG&E work paper energy savings due to straightforward LED lamp retrofits are already established and based on agreed upon wattage reduction ratios. The equation for calculating total energy savings for controls enabled LEDs, shown below in Equation 1, incorporates a change in hours of use (HOU) based upon a controls factor that impacts the usage patterns or behavior of end-users. Further, the energy consumption of the lamp may be changed depending on the use of dimming or color rendering capacities of the LEDs. Controls enabled LED energy savings (not including interactive effects) are further demonstrated by Figure 3, shown below the equation.

**Equation 1: Controls Enabled LED Energy Savings**

\[
\text{Controls Enabled LED Energy Savings} = \left[ (HOU_{\text{pre}} \times (LampW_{\text{pre}})) - (HOU_{\text{pre}} \pm \text{ControlsFactor}_{\text{post}}) \times (LampW_{\text{post}} \times \text{DimmingFactor} \times \text{ColorFactor}) \right]
\]

**Figure 3: Controls Enabled LED Savings**

![Diagram showing energy savings comparisons between controls enabled LED, LED lamp, and existing CFL/Incandescent baseline.]
BACKGROUND

Residential LEDs offer significant energy savings potential over incumbent technologies (incandescents, CFLs, halogens, etc.). The power consumption differential between incumbent technologies and LEDs is assumed to be a known constant for this study. The focus, therefore, is understanding whether behavioral changes associated with embedded controls are a potential source of additional energy savings (beyond the wattage reduction) in residential fixtures that currently lack controllability (beyond standard on/off control).

Recent technological advances in home automation offer the capacity for embedding controls into screw-in lamps and controlling the lamps via wireless communication strategies (e.g., Wi-Fi, zigbee). LEDs are particularly suited to couple with embedded controls because LED hardware already requires engineering of heat sinks (wireless communication hardware share the need for moderate temperatures in order to operate). In addition, LEDs are capable of dimming and, with additional engineering considerations, producing a varied color output.

EMERGING TECHNOLOGY/PRODUCT

This technology assessment focuses on controls enabled LEDs in residential applications. The study is narrowly focused on one particular controls enabled LED system produced by Philips: the Hue.

The Philips Hue system consists of a set of lamps that communicate via Wi-Fi with an included “bridge.” The bridge is connected to the home’s Internet router, connecting the entire system to the Internet. The lamps are controlled by either the normal fixture on/off switch, an iOS or Android application, or via a password protected web portal.

Embedded within the Philips Hue are the following key control strategies (each of which can be implemented remotely:

- On/off
- Dimming
- Color rendering (over 16 million color variations)
- Scheduling

In addition, the user can develop additional software packages to control the Hue system based on any number of defined occurrences (e.g., flashing red LEDs to indicate a local severe weather alert, based on data from an Internet website such as the National Oceanic and Atmospheric Administration).

Potential advantages of controls enabled LEDs include optimization of light color/brightness, integration of timers, and occupant security due to timers or remote controllability. Energy savings potential may exist, but changes in lighting HOU or color rendering may increase the overall energy consumption of the lamps compared to standard on/off lamps.

Market barriers to the adoption of this technology include upfront cost and ease of use (the use of an application constitutes a significant change in the way end-users interact with their home’s lighting).
ASSESSMENT OBJECTIVES

The goal of the study is to perform an initial assessment of Wi-Fi-enabled controls embedded LED lamps. There are two objectives of this technology assessment study:

- Assess the market feasibility of controls enabled LEDs in residential applications by conducting market research with manufacturers to determine their future plans related to LEDs with embedded controls; and,
- Assess the technical feasibility of deriving energy savings from controls enabled LEDs in residential applications by providing preliminary data on a small sample of sites. These data may be used to understand the potential for behavior-related savings as a result of measure installation.

This study is an initial assessment of the potential for energy savings from LEDs with embedded controls. This study focuses on changes in usage patterns that may impact overall lighting energy usage.

TECHNOLOGY/PRODUCT EVALUATION

This technology assessment consists of two components, each described below.

FIELD PLACEMENT

The field placement component of the study aims to assess the potential for PG&E to realize energy savings beyond traditionally controlled LEDs through incorporation of control enabled LEDs into PG&E’s Lighting Program. The field placement took place in the homes of Evergreen Economics and PG&E staff.

The field placement was conducted by Kevin Price and Chad Fulton of Evergreen Economics. Mr. Price managed the effort, and has managed similar lighting metering studies for impact evaluations in California. Mr. Fulton developed, tested, and deployed all software for the field placement. Data analysis was led by John Cornwell of Evergreen Economics with assistance from Mr. Price and Mr. Fulton.

MARKET STUDY

The purpose of the market study component of this study is to assess the long-term plans of manufacturers with respect to controls enabled LEDs in residential applications.

The market study was conducted by Kevin Price of Evergreen Economics, who has extensive experience conducting residential and commercial lighting market research for LEDs and other lighting technologies. The research encompassed a search for related EM&V studies, summary of findings from related EMV&V studies, Internet research for comparable products and specifications/pricing for comparable products, and in-depth interviews with controls enabled LED manufacturers.
FIELD TESTING OF TECHNOLOGY

The Philips Hue Starter Pack (MSRP $199.95) consists of a set of three screw-in LED lamps that communicate wirelessly with an included “bridge.” The bridge is connected to the home’s Internet router, connecting the entire system to the Internet. The lamps are controlled by either the normal fixture switch, an iOS or Android application, or via a password protected web portal.

The Hue Starter Pack used for this study includes A19-shaped LEDs (additional LEDs can be purchased and up to 50 total can be connected to a single bridge). These LEDs are rated at 9W, and produce a variable maximum lumen output depending on the color temperature (360 lumens at 2000K, 510 lumens at 3000K, 550 lumens at 6500K, 600 lumens at 4000K). They are incompatible with existing dimmer switches, but can be dimmed via the application. They are capable of producing approximately 16 million color variations and many shades of white light.  

Setup of the Hue Starter Pack and additional lamps is fairly straightforward. The lamps included with the Starter Pack are already synced with the bridge, and thus they are immediately recognized by the application. Additional lamps (MSRP $59.95 each) are “found” by turning them on at the switch and following a short series of in-app prompts. Connectivity of the lamps to the bridge is problematic over longer distances and through walls (depending on the quantity and material composition of the walls). This problem is exacerbated by the need to physically connect the bridge to the home router via an Ethernet cable, which limits the flexibility to locate the bridge in a central, ideal location (technically a home could use a longer Ethernet cable to locate the bridge anywhere in the home, but this is impractical and potentially aesthetically problematic).

The field placement involved two phases: the first phase mimicked baseline conditions while the second phase tested for changes in lighting usage behavior based on the capabilities of the control enabled LEDs. The field placement included eight homes and lasted a total of 15 weeks. The source of the test sites included Evergreen and PG&E staff homes. Evergreen and PG&E staff provided four homes each.

TEST PLAN

The study period and key variables are provided below.

STUDY PERIOD


---

² For additional specifications, including specifications of other lamps in the Hue product line, please visit: http://www2.meethue.com/en-us/the-range/hue/
**Key Variables**

Below is the list of variables collected from the Philips Hue system, along with a description of each variable. Each of these variables were tracked for each lamp in the study.

- **“On”**: true/false, whether the lamp is on;
- **“Reachable”**: true/false, whether the lamp is currently connected to the bridge (importantly, when this is “false” it is indicative of either a connectivity issue between the lamp and the bridge, or the end-user turning the fixture off via an on/off switch);
- **“Name”**: the name of the lamp, determined by the user (this was established for each lamp during installation);
- **“Bri”**: level of brightness, from 0-254 (with 0 being as dim as possible, and 254 full brightness);
- **“ColorMode”**: three potential values (HS, XY, or CT) that define the color mode of the lamp;
- **“Hue”**: the hue value of the lamp’s current light output (part of the HS color mode);
- **“Sat”**: the saturation value of the lamp’s current light output (part of the HS color mode);
- **“CT”**: color temperature of the lamp’s current light output, in mireks (the scale used to define color temperatures of white light);
- **“X”**: CIE 1931 x-axis value of the lamp’s current light output (part of the XY color mode); and,
- **“Y”**: CIE 1931 y-axis value of the lamp’s current light output (part of the XY color mode).

---

3 For detailed descriptions of the Hue’s data types and other core concepts, please visit: http://www.developers.meethue.com/documentation/core-concepts
The metering strategy employed for this effort involves a software application that communicates with the bridge to download the current setting of each variable list above for all connected Hue lamps. These data were collected at 15 second intervals for the duration of the study.

**INSTRUMENTATION PLAN**

Automated data collection is accomplished via two interface modules: one that understands the bridge and one that understands the database. Code was developed to connect the bridge’s data and the database. Data were extracted and appended to the database.

One key element to the development of the database format was understanding the Philips Hue’s application programming interface (API), which describes the extent and organization of the data provided by the bridge. The database tables were organized in a relational fashion, rather than as single “flat” table, so that the database can be easily queried at any level, including by study home, date, or specific lamp.

---

4 Source: http://www.developers.meethue.com/documentation/core-concepts
**Metering Protocols and Testing**

To test the metering protocols and software, a Philips Hue system was purchased for installation in a test home (which was converted to a study home during the site recruitment and prescreening phase of the project). To maintain complete control of the metering protocols testing, the test site was an Evergreen staff member's home. Quality control tests were developed to ensure that data collection was occurring at regular 15 second intervals.

Each 15-second data download (for each site) created a new time-stamped data file. Another software program was developed that extracted all of the time- and site-stamped information from all recently created files and exported them as a database at regular intervals. This database was regularly exported and de-duplicated as part of the quality control procedures, in order to more easily identify changes in a lamp’s status. The de-duplicated database was accessible via a password protected website in order to conduct real-time quality control and address any connectivity issues as soon as possible.

**Site Recruitment and Prescreening**

Recruitment guidelines were developed to ensure a fairly balanced sample. Screening criteria for households were also developed and included technical requirements (e.g., Internet access). Study parameters were explained to study participants, and approval to access lighting usage statistics was obtained. PG&E staff were involved determining a list of amenable and likely suitable homes.

Lastly, there was a final screening process in the home during the equipment installation visit (all homes successfully passed the final screening process).

**Two-Phase Placement**

The two-phase placement included the installation of up to six embedded LED replacement lamps with one set of controls in each home, covering six lamps per home. During the first phase of the placement, study participants were required to emulate a pre-Hue situation (i.e., before the controls embedded LED replacement lamps are installed). Residents of study homes were only permitted to use the pre-existing on/off switches to control the Hue lamps. This allowed for the collection of usage data associated with the fixtures under pre-Hue conditions. During the second phase, participants were permitted full control of the Hue lamps using the included software and standard on/off switches for the fixtures. The pre-Hue first phase lasted six weeks, and second phase lasted nine weeks.

The purpose of the first phase ("pre-Hue") is to determine how lamps are used during baseline conditions in rooms where the households plans to install the controls embedded LED replacement lamps (including test lamps where participants used the control features as part of phase two, and comparison lamps whose usage may be affected).

The pre-Hue phase included:

- Identification of where the household would install the primary Hue LEDs if they had purchased the system themselves (we dictated certain locations – with approval of the residents – where we were not obtaining sufficient room-type coverage among the homes; however, often the requirements of the lamps – that
they be installed in a screw-based fixture without a dimmer – dictated where they were installed);

- Identification of up to three secondary lamps whose usage patterns may be affected (increase or decrease usage) due to the use of the new technology (e.g., a living room floor lamp may be used more or less if a Hue lamp is installed in an overhead fixture);

- Installation of up to six LEDs per home (the controls logged the usage of all lamps);

- Training/explaining to the household that they were not permitted to use any of the control features of the LEDs during the first phase (this approach may have been less successful if we were recruiting from the general public); and

- Conducting a brief household questionnaire to collect descriptive information about the home and residents.

The purpose of the second phase is to measure how lamps are used after the household is able to use the controlling features of the control enabled LED replacement lamps. The second phase included:

- Leaving all installed Hue lamps in the same fixtures from the first stage;

- Training/explaining to the household to use the control features of the LEDs for the primary Hue lamps (and that they should not use the features of the secondary Hue lamps);

**RESULTS**

**FIELD PLACEMENT**

The analysis procedures and results of the field placement and technical assessment are described in this section.

**DATA ANALYSIS**

This section presents analysis and findings from the field placement component of the controls enabled LED assessment.

**SITE DESCRIPTIONS**

Table 1 shows the key characteristics of each site where the Philips Hue was installed, as well as the number of lamps – both test and secondary – installed.
### Table 1: Site Descriptions

<table>
<thead>
<tr>
<th>Site</th>
<th>Home</th>
<th>Occupants</th>
<th>Fixtures with Hue Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Three bedroom single-family detached</td>
<td>Two adults (20s), zero children</td>
<td>Four (2 test, 2 secondary)</td>
</tr>
<tr>
<td>2</td>
<td>Three bedroom single-family detached</td>
<td>Two adults (40s), two children (elementary)</td>
<td>Six (3 test, 3 secondary)</td>
</tr>
<tr>
<td>3</td>
<td>One bedroom apartment in multifamily building</td>
<td>Two adults (20s), zero children</td>
<td>Four (3 test, 1 secondary)</td>
</tr>
<tr>
<td>4</td>
<td>Four bedroom single-family detached</td>
<td>Two adults (50s), two children (teenagers)</td>
<td>Six (5 test, 1 secondary)</td>
</tr>
<tr>
<td>5</td>
<td>Two bedroom apartment in multifamily building</td>
<td>Three adults (20s), zero children</td>
<td>Six (3 test, 3 secondary)</td>
</tr>
<tr>
<td>6</td>
<td>Three bedroom single-family attached</td>
<td>Two adults (30s), two children (elementary)</td>
<td>Four (3 test, 1 secondary)</td>
</tr>
<tr>
<td>7</td>
<td>Two bedroom single-family detached</td>
<td>Two adults (30s), zero children</td>
<td>Six (3 test, 3 secondary)</td>
</tr>
<tr>
<td>8</td>
<td>Four bedroom single-family detached</td>
<td>Two adults (40s), two children (elementary)</td>
<td>Five (3 test, 2 secondary)</td>
</tr>
</tbody>
</table>

### Data Collection and Cleaning Procedures

The flowchart in Figure 5, below, illustrates the data collection and data cleaning process. Data including on/off status, brightness and color profile was collected from each lamp at 15-second intervals and stored in a snapshot database as a time stamped data point. At regular intervals the snapshot database was subjected to a de-duplication process that removed all successive redundant observations for each lamp resulting in an event database containing time periods of common usage with start and end date stamp. At the end of the study period, the event database went through a post-processing regime that created an analysis dataset with common and meaningful field names.

After the data were collected, the resulting dataset was subjected to analysis to identify errors or problematic readings. Primarily, the analysis investigated the frequency of on/off events per lamp per day and the duration of each on/off event to identify periods with usage patterns outside what could be considered normal usage. The analysis revealed that some lamps in the study experienced periods with high numbers of alternating on/off events of very short duration. From manual inspection of some of these periods it was determined that the likely cause of many of these events were periodic connectivity issues during which the bridge lost communication with the lamp, resulting in false off reading, i.e. the bridge recorded the lamp as off when it was in reality on.

Due to the way in which the data were recorded, records with lost connectivity were not able to be distinguished from true off events with 100 percent confidence because the data signatures of these events were the same as those for events were a light was turned off at the switch. Sensitivity analysis was conducted that investigated the impact on overall lamp usage when these events of differing lengths were recoded from off to on. This analysis led the study team to decide that short off events of 90 seconds or less between two on events were more likely to be connectivity issues rather than true on/off events considering normal household lamp
usage. The study team was less confident that events of greater than 90 seconds were not due to true on/off events. A decision was reached to create an automated cleaning protocol to recode from off to on, all off events of 90 seconds or less that were bounded by on events. This automated cleaning did not have a large impact on overall lamp usage over the period. Once this cleaning protocol was completed, further analysis revealed some lamps in the study that continued to have days with large numbers of on/off events. Days that were outside of what the study team deemed “normal” usage were flagged, manually inspected and removed from the analysis if deemed problematic. Seven days out of a total of approximately 4,400 lamp days were removed.
**Figure 5: Hue Data Collection and Cleaning Flowchart**

- **Data Collection**
  - Snapshot database
  - Collection daemon
  - De-duplication script (Python)
  - Event database
  - Internal web interface
  - Export to CSV
  - Post-processing
    - Date processing (e.g. DST)
    - Convert colors to common format (RGB)
    - Common record designations (on/off, white/color, etc.)

- **Quality Control**
  - Manual view of real-time data
  - Random quality inspections
  - Real-time monitoring
  - Ongoing analysis
  - Calibration of bulb colors

- **Participants**
  - Bulb
  - Bulb
  - Lightswitch
  - Bridge
  - Smartphone

- **Data Cleaning**
  - "Ravi" Analysis Dataset
  - Automated cleaning script (SPSS)
  - Database of cleaned intervals
  - Manual cleaning
  - Database of removed days
  - Manual review of lamp days outside bounds of "normal" lamp usage
  - "Clean" Analysis Dataset

- **Flowchart Details**
  - Snapshot of all bulb data
  - Bridge contacted at 15-second intervals
DATA ANALYSIS – LAMP USE AND BRIGHTNESS PROFILES

The final cleaned dataset was analyzed using IBM SPSS and Microsoft Excel. Figure 6, below, provides an illustration of the analysis process, which included the following steps:

1) The clean de-duplicated analysis dataset records were rounded to the nearest 15-second interval, and the dataset was backfilled with equal 15-second interval data.\(^5\)

2) The 15-second interval data was binned into 15-minute periods.

3) For each 15-minute period per lamp the following metrics were calculated:
   a. Mean percent of time “on” (versus “off”)
   b. Mean percent of full lamp brightness, when the lamp was “on” only

4) The 15-second interval data was aggregated to create a database with 15 minute intervals

5) Sunrise and sunset data were imported and each interval flagged as before or after sunrise and sunset.

6) For each lamp, for each 15 minute interval over the course of a day the following metrics were calculated:
   a. Mean percent of each 15-minute period that each lamp was “on” (versus “off”) for the entire study period
   b. Mean percent of each 15-minute period that each lamp was “on” (versus “off”) for Phase 1 and Phase 2.
   c. Mean percent of full lamp brightness, when “on”, over the entire study period
   d. Mean percent of full lamp brightness, when “on”, for Phase 1 and Phase 2.
   e. Mean percent of time in Phase 1 and Phase 2 that the 15 minute interval fell before or after sunrise or sunset

7) Lamps were assigned bins for each analysis category of interest including, site, room type, and household demographics.

8) Charts were created that mapped the average 15-minute lamp usage profile and brightness level for each lamp. In order to give insight into the impact of day length on lamp usage these charts were overlaid with the average percent of time each 15 minute period of the day fell in the night period defined as before or after official sunrise or sunset.

9) Average hours of use per day were calculated per lamp and for each analysis category, e.g.: site, room type and overall.

\(^5\) The first step was required to create a consistent dataset, as the data pulls from each Hue bridge did not occur at exact 15-second intervals, due to minor Internet speed variability.
To summarize the colors used by participants, the actual colors produced by the bulbs were grouped according to the primary (red, green, and blue) and secondary (yellow, fuchsia, and cyan) colors, called reference colors. This approach was used because the full range of possible values for the hue of a given color of light range between 0 and 65,535, and the hue values for the primary and secondary colors are spaced relatively evenly across the range of possible hues. Thus, considering the distribution of colors used in terms of the reference colors provides most of the interesting data while maintaining simplicity. For each color a bulb displayed, the closest reference color was selected as the one whose hue value was the minimum distance from the recorded hue value.

The color bins and associated hues are shown below, in Table 2. A mapping of how this was applied to the Hue application is shown below the table.
White light was similarly binned into reference colors, but at a much finer level of detail than the primary and secondary colors. The reason for this is twofold; first, the Hue bulbs themselves were designed to represent more subtle variations of white light than colored light (since white light is used so much more frequently), and second because the variation in white light can essentially be represented across a single spectrum which describes white light in terms of its “color temperature”. Warm light is associated with a yellow or red quality, whereas cold light is associated with blues. White light was therefore grouped into warmer, warm, neutral, cold, and colder. The default white light produced by the Hue bulbs is on the warm side of the spectrum, and so it is the reference color for the “warm” group. “Neutral” is the white in the middle of the color temperature spectrum, and it has the least “color”, either warm or cold.

The white color temperature bins and associated mireks are shown below, in Table 3: White Color Temperature Bins. A mapping of how this was applied to the Hue application is shown below the table.
Lastly, there is an area of the Hue spectrum that is defined by hue and saturation (part of the color groupings), but essentially produces warmer to colder white light. A visual approximation of the Hue application screen, along with the “other (white)” color bin, is shown below, in Figure 7.
Although in principle the color grouping procedure could result in colors in any group (red, yellow, green, cyan, blue, or fuchsia), in practice no recorded hue values fell into either the “Green” group or the “Cyan” group. The reasons for this are related, but for the opposite reasons, to the fine detail in which white light was captured. The Philips Hue hardware was designed to represent colored light, but in particular to represent whites and colors on the warm end of the spectrum. For this reason, the Hue bulbs can capture a wider range, and finer detail, in reds and yellows than they can in greens and blues.

The colors which the Philips Hue bulbs can physically represent are captured in the triangular portion of the CIE 1931 color spectrum (shown above in Figure 4). From the diagram, it is clear that the greenest color that can be represented is largely yellow, and the section of the triangle corresponding to cyan (a light blue) is largely represented as a cool shade of white. Philips produces an alternative bulb, the “LivingColors Iris” bulb, which is designed to faithfully reproduce the entire color spectrum, but in so-doing it is less adept at producing fine detail in white lights.

FINDINGS

The following section presents the lamp use and mean brightness profiles for all study lamps combined, for each room type, for each study site, and for each household demographic group. As described earlier each figure presents the following information derived from 15-minute interval data:

- Mean percent of time “on” in Phase 1, the “pre-Hue” phase
- Mean percent of time “on” in Phase 2, the test phase
• Mean lamp brightness when the lamp was on, expressed as a percent of full brightness. This is presented for Phase 2 only as no dimming was permitted in Phase 1.

• Mean percent of time during the analysis period that the given 15 minute interval of the day fell during nighttime hours in Phase 1 and Phase 2.

It is important to note when reviewing these figures that Phase 1 fell during the late summer and early fall months, and Phase 2 took place in late fall, a portion of which was after the switch from daylight savings to standard time. Therefore, day length was shorter during Phase 2 and as such, a portion of the change in lighting usage over the study period is due to seasonal increase in lighting usage in Phase 2.

To better understand the impact of seasonality on lighting usage we reviewed the 2010 Final Evaluation Report: Upstream Lighting Program (KEMA, 2010). The study leveraged logger data collected from over 1,700 homes in California to model average lighting hours of use for each day of the year using a sinusoidal regression model. Based on this study, in general, we would expect to see an average increase in lighting use of approximately 23 minutes per day in normal consumption between August and November. In our findings below, we find that comparison lamp usage increased approximately 26 minutes per day between Phase 1 (August/September) and Phase 2 (October/November), while test lamp usage increased by approximately 35 minutes per day.

Given that the sample size of the current study is eight homes, it is not possible to confidently state actual impact of seasonality on usage in the study homes. However, the increased average hours of use in comparison lamps is closer to what we would expect to see from seasonality alone, while the increase in test lamp usage is larger than what we would expect to see from seasonality alone. This suggests that the increase in test lamp usage is due to factors other than seasonality.

Color usage profiles are presented for all test lamps and for test lamps by room type and study site, as well.

**OVERALL ANALYSIS FINDINGS – TEST AND COMPARISON LAMPS**

The following four figures present the lamp use and brightness profiles for lamps across all study sites for all lamps, test lamps and secondary lamps respectively, as well as the color usage profile of all test lamps, combined.

Figure 8, below, presents the lamp use and brightness profile for all 41 lamps across all 8 study sites. As we would expect lamp usage was highest in the evening hours, with some additional usage in the early morning. In Phase 1 of the study that extended from August 13, 2014 to October 1, 2014, evening use peaked between 8pm and 11pm with lamps being used on average slightly less than 20 percent of the time during this period of the day. Phase 2 of the study saw greater lamp usage in the evenings with peak usage between 7pm and 10pm and lamps being in use over 20 percent of the time during this period of the day. Homes tended to use the dimming feature of the lamps in the late evening and early morning with at least some homes appearing to program lights to dim or increase over time. The average hours of use across all lamps for the entire study period was 1.48 hours per day, with 1.19 hours of use per day in Phase 1 of the study and 1.72 hours of use per day in Phase 2 of the study.

Seasonality, or decreasing day length in Phase 2 is likely the primary reason for the difference in use between Phase 1 and Phase 2. However, further investigation of
test lamp use versus secondary lamp use indicates that different usage patterns for controllable lights versus non-controllable lights may exist.

**Figure 8: All Sites – All Lamps – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile](image)

The study installed test lamps that households were allowed to fully control in Phase 2 of the study and secondary or "comparison" lamps that households were asked to use as a normal, non-controllable lamp. The purpose of these lamps was to identify if usage patterns in secondary light fixtures may be affected (increase or decrease usage) due to the use of the new technology. Figure 9 and Figure 10, below, present the lamp use profile for test lamps only across all study sites and comparison lamps only across all study sites, respectively.

A similar pattern of usage is revealed across the two lamp groups in both phases. In Phase 1, both lamp groups have very similar usage profiles with some minor variation. After moving into Phase 2, while the profiles remained similar there were some interesting deviations. Firstly, there is an increase in morning usage among the test lamps from Phase 1 to Phase 2 that did not occur in the secondary lamp group. In Phase 2, test lamps are showing more use in the later evening than the secondary lamp group, and the difference between Phase 1 and Phase 2 usage is more pronounced in the test lamp group.
Figure 9: All Sites – Test Lamps – Lamp Use and Dimming Profile

Figure 10: All Sites – Comparison Lamps – Lamp Use and Dimming Profile
Table 4, below, presents the average hours of use per day of test and secondary lamps. Over the entire study period test lamps were used on average 1.46 hours per day and comparison lamps were used on average 1.52 hours per day. Usage among test lamps was lower in Phase 1 (1.13 hours per day) than among secondary lamps (1.28 hours per day), while in Phase 2 test lamp usage increased to (1.72 hours per day), slightly more than comparison lamps (1.71 hours per day).

While seasonality is likely the cause of most variation from Phase 1 to Phase 2, differences in load shapes and hours of use between the test and secondary light groups suggest that there are may be differences in lamp usage attributable to households being able to control the test lamps. In particular, the greater proportional increase in use between Phase 1 and Phase 2 in test lamps, and increase use in the morning and late evening which are times that would be less effected by day length changes suggest that households may have used the test lamps more frequently because of the additional functionality. While there may be greater lamp use among the test lamps it is important to note that there appeared to be significant use of the dimming function of the lamps, which may offset, to an extent, any electricity consumption related to increased usage.

<table>
<thead>
<tr>
<th>LAMP GROUP</th>
<th>PHASE 1: HOURS OF USE/DAY</th>
<th>PHASE 2: HOURS OF USE/DAY</th>
<th>FULL STUDY PERIOD: HOURS OF USE/DAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Lamps</td>
<td>1.13</td>
<td>1.72</td>
<td>1.46</td>
</tr>
<tr>
<td>Secondary Lamps</td>
<td>1.28</td>
<td>1.71</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Table 5, below, shows the use of dimming across all test lamps during Phase 2 of the study period. As shown, dimming was used 18.5 percent of the time a lamp was “on”, across all test lamps. The proportion of time the lamps were dimmed to different levels of brightness is also shown.

<table>
<thead>
<tr>
<th>BRIGHTNESS</th>
<th>Test Lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>&lt; 100%</td>
<td>81.5%</td>
</tr>
<tr>
<td>&lt; 20%</td>
<td>5.4%</td>
</tr>
<tr>
<td>20-40%</td>
<td>1.8%</td>
</tr>
<tr>
<td>40-60%</td>
<td>5.0%</td>
</tr>
<tr>
<td>60-80%</td>
<td>4.5%</td>
</tr>
<tr>
<td>80-99.9%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Overall color usage among test lamps during the second phase of the study period is shown below in Figure 11, for both morning and evening timeframes. As shown, the default white color is used the majority of the time across all lamps (69.3% in mornings and 66.7% in evenings). Other white temperatures are used to varying

---

6 Mornings: 2am – 2pm; Evenings: 2pm – 2am.
degrees. Color is infrequently used in the mornings (3.7% on average across all test lamps), but accounts for 6.7 percent of on-time in evenings, across all lamps.

In both morning and evening periods, reddish colors accounted for the majority of color usage. In the mornings, yellowish colors were used nearly as frequently as red. In both morning and evening timeframes, blue and fuchsia colors were used very infrequently.

**Figure 11: All Sites – Test Lamps – Color Usage**

In this section, we present the lamp use and brightness profiles, as well as the color profiles, for each room type in which test lamps were installed. Table 6 below
PG&E’s Emerging Technologies Program presents each room type that had a lamp installed, the number of test lamps in each room type, and the average hours of use per day in Phase 1, Phase 2 and over the entire study period. It is important to note that there were fewer lamps installed in some rooms and therefore the hours of use in these rooms may not be indicative of normal usage. Dining rooms for example show significantly higher usage, however this was largely cause by the single dining room lamp in one home.

**Table 6: Room Types and Characteristics**

<table>
<thead>
<tr>
<th>Room Type</th>
<th>Number of Lamps</th>
<th>Phase 1: Hours of Use/Day</th>
<th>Phase 2: Hours of Use/Day</th>
<th>Overall: Hours of Use/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>9</td>
<td>1.28</td>
<td>1.91</td>
<td>1.63</td>
</tr>
<tr>
<td>Bedroom</td>
<td>11</td>
<td>0.54</td>
<td>0.87</td>
<td>0.72</td>
</tr>
<tr>
<td>Dining Room</td>
<td>2</td>
<td>4.26</td>
<td>6.57</td>
<td>5.60</td>
</tr>
<tr>
<td>Bathroom</td>
<td>1</td>
<td>0.7</td>
<td>0.84</td>
<td>0.78</td>
</tr>
<tr>
<td>Office</td>
<td>1</td>
<td>0.44</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Kitchen</td>
<td>1</td>
<td>1.40</td>
<td>2.04</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Table 7 shows the use dimming across all test lamps, by room type. As shown, bedroom lamps and living room lamps were dimmed most frequently (37.8% and 20.3% of “on” time during Phase 2). Lamps in dining rooms, bathrooms, offices, and kitchens were infrequently dimmed (although this is in part due to relatively few sample points in these room types, at homes where dimming was used less frequently across all lamps).

**Table 7: Use of Dimming – Test Lamps, By Room Type (Phase 2)**

<table>
<thead>
<tr>
<th>Room Type</th>
<th>100%</th>
<th>&lt; 100%</th>
<th>&lt; 20%</th>
<th>20-40%</th>
<th>40-60%</th>
<th>60-80%</th>
<th>80-99.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>79.7%</td>
<td>20.3%</td>
<td>10.7%</td>
<td>1.8%</td>
<td>3.8%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Bedroom</td>
<td>62.2%</td>
<td>37.8%</td>
<td>5.2%</td>
<td>3.6%</td>
<td>14.2%</td>
<td>11.9%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Dining Room</td>
<td>94.5%</td>
<td>5.5%</td>
<td>0.3%</td>
<td>1.0%</td>
<td>0.4%</td>
<td>3.0%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Bathroom</td>
<td>99.4%</td>
<td>0.6%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Office</td>
<td>98.7%</td>
<td>1.3%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Kitchen</td>
<td>99.4%</td>
<td>0.6%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

**Living Rooms**

Figure 12, below, presents the lamp use profile for all test lamps installed in living rooms. Test lamp use increased in the evening and overnight between Phase 1 and Phase 2. The increased overnight usage is associated with decreased lamp brightness with lights on overnight on average being at approximately 50 percent brightness. This could be due to one or more households utilizing the lamp as a security lamp. There appears to be significant use of dimming in some households in the morning and evening when the lamp is on, with some minor dimming events when lamps are
on during the day. The average hours of use of lamps in living rooms across the study period was 1.63, with the average hours of use increasing between Phase 1 and Phase 2 from 1.28 to 1.91 hours per day.

**Figure 12: Living Rooms – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile in living rooms.]

Figure 13 shows the disposition of lamp output color, when on, averaged across all test lamps in living rooms. As shown, the default color was used 84.1 percent of the time on average in the morning period, and 70.3 percent of the time in the evening period (on average). Color was used very infrequently in the morning (1.8% on average), but accounted for 6.6 percent of evening usage across lamps. Red was the most frequently used shade in the morning and evening (1.6% and 6.1% on average, respectively).
**Figure 13: Living Rooms – Test Lamps – Color Usage**

![Color Usage Chart]

**Bedrooms**

Figure 14, below, presents the lamp use profiles of all bedroom test lamps. Bedroom lamps show increases in both morning and evening usage between Phase 1 and Phase 2 with the increase in morning usage being particularly pronounced. The increase in morning usage could be due to households using the controllable lamps as a light alarm which increases the morning on time of lamps that would otherwise have been off when the household was sleeping. The increase in evening light is difficult to distinguish from a seasonal increase due to shortening day length. There is a significant use of the dimming function of the test lamps in bedrooms,
particularly in the early morning where it is used to increase brightness of the lamp and in the evening where it is used to decrease brightness of the lamp. On average, when on, bedroom lamps where always dimmed to some extent. Average hours of use of bedroom test lamps was less than 1 hour over the entire study period. Hours of use increased from Phase 1 to Phase 2 from 0.54 hours to 0.87 hours.

**Figure 14: Bedrooms – Lamp Use and Dimming Profile**

Color usage across all bedroom test lamps is shown below, in Figure 15. On average, the default white color was used slightly more than half of the time in both the morning and evening periods (52.3% and 51.3%, respectively). Warm temperatures of white were frequently used in the mornings (33.9% on average) and evenings (18.4% on average). Cold temperatures were rarely used in the mornings (3.8% on average), but were often used in the evenings (15.6% on average). Across all bedroom test lamps, colors were used on average 5.4 percent of the time in mornings, with red (2.1%) and yellow (2.8%) most frequently used. In the evenings, bedroom test lamps displayed color 9.5 percent of the time across test lamps. Reddish colors accounted for the majority of evening color usage (7.6%).
Dining Rooms

Figure 16 presents the lamp use profile for the 2 dining room test lamps in the study. In both sites test lamp usage increased significantly in the morning and evening between Phase 1 and Phase 2 of the study. One of the sites also showed significant usage during the day in the dining room in both Phase 1 and Phase 2, with a large increase between the two periods as depicted in the figure. The hours of use for the 2 dining room lamps were significantly higher than other rooms with on average 5.6 ours of use per day over the entire study period. The high usage is attributable to one site in particular. Hours of use increased from 4.26 hours per day to 6.57 hours
per day from Phase 1 to Phase 2. There was some use of dimming in the morning hours at one site.

**FIGURE 16: DINING ROOMS – LAMP USE AND DIMMING PROFILE**

Morning color usage in dining rooms shows that the “Other (white)” color bin was used a significant amount of the time on average across all test lamps (31%), as shown below in Figure 17. The warmest temperatures of white were also used frequently across dining room lamps in the morning (10.6%), and color was used eight percent of the time across lamps. Among colors, red shades were the most frequently used in the mornings in dining rooms. One of the dining room test lamps was set to turn on gradually and mimic a sunrise, the bulk of which falls within the “Other (white)” colors. In the evenings, the default white was used the vast majority of the time (85.1%) on average across dining room lamps, with hardly any color usage (1.5%).
**Figure 17: Dining Rooms – Test Lamps – Color Usage**

**Bathrooms**

Figure 18 shows the lamp use profile for the single bathroom test lamp in the study. The pattern of usage is typical of what we would expect to see in a bathroom with a spike in usage in the early morning and a smaller spike in the late evening with intermittent use throughout the day. There was no significant change between Phase 1 and Phase 2 aside from a shift in usage to the earlier hours in the morning in Phase 2, which was probably due to a schedule change at the household. There are two small dimming spikes depicted in the figure during low usage periods of the day, but overall dimming was used very little in the bathroom at this household.
Color usage for the one test lamp installed in a bathroom was minimal, as shown below in Figure 19. In the mornings, reddish color was used 0.3% of the time, and the default white color was used the remainder (including the entire evening period). Bathroom visits are generally short and light color may not be important.
Aside from some additional usage in Phase 2, the single office lamp in our study did not experience any significant changes in usage between Phase 1 and Phase 2 as shown below in Figure 20. Likewise, average daily hours of use was virtually unchanged between Phase 1 (0.44) and Phase 2 (0.45). There was no substantive use of dimming in this room. While this may indicate that offices are not suited for the lamps functionality, it is important to note that there was only one office light in the study.
The one test lamp installed in an office was never set to a color other than the default white, including non-default color temperatures.

**Kitchens**

The single kitchen lamp in our study experienced an increase in usage in Phase 2 in the late evening as shown in Figure 21, below. The lamp was not dimmed during Phase 2. Average hours of use increased between Phase 1 and Phase 2 from 1.40 hours per day to 2.04 hours per day. Similarly to the office lamp, it is important to note that there was only one kitchen light in the study.
The one test lamp installed in a kitchen was never set to a color other than the default white, including non-default color temperatures.

**SITE-LEVEL ANALYSIS FINDINGS – TEST-LAMPS**

The following section presents lamp use information for each study site. Table 8 below details the average hours of use per day for each study site, which will be discussed in more detail with the subsequent load and dimming profiles for each site.
Table 8: Average Hours of Use by Study Site

<table>
<thead>
<tr>
<th>Site</th>
<th>Phase 1: Hours of Use/Day</th>
<th>Phase 2: Hours of Use/Day</th>
<th>Overall: Hours of Use/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>2.58</td>
<td>2.35</td>
<td>2.46</td>
</tr>
<tr>
<td>Site 2</td>
<td>1.71</td>
<td>2.22</td>
<td>1.98</td>
</tr>
<tr>
<td>Site 3</td>
<td>0.35</td>
<td>1.80</td>
<td>1.18</td>
</tr>
<tr>
<td>Site 4</td>
<td>0.08</td>
<td>0.69</td>
<td>0.42</td>
</tr>
<tr>
<td>Site 5</td>
<td>0.46</td>
<td>0.96</td>
<td>0.74</td>
</tr>
<tr>
<td>Site 6</td>
<td>0.46</td>
<td>0.68</td>
<td>0.59</td>
</tr>
<tr>
<td>Site 7</td>
<td>1.53</td>
<td>1.79</td>
<td>1.68</td>
</tr>
<tr>
<td>Site 8</td>
<td>2.86</td>
<td>4.13</td>
<td>3.58</td>
</tr>
</tbody>
</table>

Table 9 shows the use of dimming at each site, across all lamps within the site. Site 2, Site 3, Site 4, and Site 5 all used dimming relatively frequently (18.3% - 54.0% of “on” time during Phase 2). In particular, Site 2 and Site 3 used dimming nearly half of the time across all of their installed lamps. Conversely, Site 6, Site 7, and Site 8 dimmed their lamps very infrequently, and Site 1 used dimming some of the time (7.3%). As shown, there exists significant variation in the use of the dimming feature of connected LEDs across homes in this study.

Table 9: Use of Dimming – Test Lamps, By Site (Phase 2)

<table>
<thead>
<tr>
<th>Site</th>
<th>100%</th>
<th>&lt; 100%</th>
<th>&lt; 20%</th>
<th>20-40%</th>
<th>40-60%</th>
<th>60-80%</th>
<th>80-99.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>92.7%</td>
<td>7.3%</td>
<td>0.2%</td>
<td>0.0%</td>
<td>6.1%</td>
<td>0.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Site 2</td>
<td>46.0%</td>
<td>54.0%</td>
<td>26.0%</td>
<td>1.6%</td>
<td>15.2%</td>
<td>8.2%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Site 3</td>
<td>52.0%</td>
<td>48.0%</td>
<td>6.8%</td>
<td>6.9%</td>
<td>8.9%</td>
<td>20.6%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Site 4</td>
<td>78.9%</td>
<td>21.1%</td>
<td>2.0%</td>
<td>2.5%</td>
<td>6.9%</td>
<td>5.7%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Site 5</td>
<td>81.7%</td>
<td>18.3%</td>
<td>4.4%</td>
<td>6.2%</td>
<td>4.6%</td>
<td>2.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Site 6</td>
<td>99.2%</td>
<td>0.8%</td>
<td>0.2%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Site 7</td>
<td>99.3%</td>
<td>0.7%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Site 8</td>
<td>99.3%</td>
<td>0.7%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Site 1

Site 1 is a three bedroom detached single family residence occupied by two working adults in their twenties with no children. Figure 22 presents the lamp use profile for Site 1.

Over the Phase 1 period of the study Site 1 had some lamp usage during every period of the day with increased usage in the evening. During the Phase 2 period there was a reduction in lamp usage overnight and during the day. Lamp use increased in the early to mid evening, most likely due to decreasing day length. Overall average hours of use decreased from Phase 1 to Phase 2 from 2.58 hours per
day to 2.35 hours per day. Dimming was used in this household at times during the evening but on average, the household did not dim the lights below approximately 90% brightness.

**Figure 22: Site 1 – Test Lamps – Lamp Use and Dimming Profile**

Average morning and evening color usage across all test lamps at Site 1 is shown below in Figure 23. Site 1 only used the default white color in the mornings. On average and across all Site 1 lamps, color was used seven percent of the time in the evenings, with reddish shades accounting for nearly all color usage (6.9%). Colder whites were used 1.8 percent of the time in the evenings on average across lamps.
Site 2

Site 2 is a three bedroom detached single-family residence occupied by two working adults and 2 elementary school aged children. Figure 24 presents the lamp use profile for Site 2.

As depicted in the figure, there were some significant changes in usage between Phase 1 and Phase 2 of the study at this site. Site 2 increased lamp usage between 7am and 8am in the morning, possibly due to bedroom lights being used as light alarms which is indicated by the gradual change in brightness in the morning hours.
There was a decrease in lamp use in the evening which is counter to what we see in other homes due to seasonality. Lastly, there was increased lamp usage overnight due to one lamp being left on at low brightness, potentially as a security light. Also of note is the extensive use of brightness control in this household when lamps were on. Brightness control was used in the morning to increase brightness and in the evening to dim the lights. This occurred both in bedrooms and in the living room at this site. Overall average hours of use increased from Phase 1 to Phase 2 from 1.71 hours per day to 2.22 hours per day. A large portion of this increase can be attributed to one lamp being left on overnight.

**Figure 24: Site 2 – Test Lamps – Lamp Use and Dimming Profile**

When turned on, lamps at Site 2 were the default white less than half the time (42.0% in the mornings and 48.0% in the evenings, on average). In the mornings, the warmer white color temperature was used more than one-third of the time on average (34.0%), and the colder white color temperature was used 19.8 percent of the time across lamps. Red and yellow shades were used less frequently (2.5% and 0.3% on average, respectively), and blue and fuchsia were never used in the morning. In the evenings when lamps were on, Site 2 used the colder white color temperature 45.9 percent of the time on average, and almost never used color (0.1%).
Site 3

Site 3 is a one bedroom apartment occupied by two working adults in their twenties. Figure 26 presents the lamp use profile for Site 3.

This site experienced a significant increase in lamp use from Phase 1 to Phase 2, as well as extensive use of the brightness control functions of the lamps. Lamp use increased most significantly in the early morning and evening hours. In the morning in particular lamp usage went from close to zero percent to lamps being on 20 percent of the time between 6:30am and 7:30am. Brightness control was also
utilized most in the morning and evening hours, but brightness was also controlled often throughout the day. When the lamps were on during the day, on average they were at between 80 percent and 90 percent brightness. Overall usage increased between Phase 1 and Phase 2 with average hours of use at the site increasing from 0.35 hours to 1.8 hours.

**Figure 26: Site 3 – Test Lamps – Lamp Use and Dimming Profile**

Average color usage across all lamps at Site 3 is shown below in Figure 27. As shown, the default white was used, on average, 21.8 percent of the time across lamps. Warmer white accounted for 34.5 percent of test lamp on-time at Site 3 (on average across lamps), and colors were used 16.0 percent of the time a lamp was turned on (with the vast majority reddish colors; 14.6%). In the evenings, Site 3 relied on the default white more than half of the time across lamps (55.7%), and frequently used the colder white temperature (17.3% on average). Color was seldom used in the evenings (3.2% on average), with red colors making up the majority.
Site 4

Site 4 is a four bedroom detached single-family residence occupied by two working adults and two teenage children. Figure 28 presents the lamp use profile for Site 4.

During Phase 1, the test lamps at this site saw very little overall usage with close to no usage during the day and minimal usage in the evening hours. During Phase 2, when the household was able to control the test lamps evening usage of the lamps increased dramatically relative to Phase 1 usage. Morning and daytime usage of the lamps in Phase 2 remained very low. The household did use the brightness control
functionality of the bulbs, particularly in the evening. During the morning and daylight periods, there are changes in average brightness, but these readings should be discounted because the lamps were rarely on. Overall, usage of the lamps increased between the two periods with average hours of use increasing from 0.08 hours to 0.64 hours.

**Figure 28: Site 4 – Test Lamps – Lamp Use and Dimming Profile**

The morning and evening average color usage disposition across lamps at Site 4 is shown below in Figure 29. In the mornings, the default white, warmer whites, and warm whites were each used on average one-quarter of the time the test lamps were on, across lamps. Lamps were set to a color 8.7 percent of the time in the morning on average across test lamps (yellow: 7.5%; blue: 1.2%). In the evening when lamps were on, the default white color was used 3.1 percent of the time, averaged across test lamps. Warmer white accounted for 34.6 percent of color temperature usage across lamps, with both warm and cold whites accounting for slightly less (22.1% and 25.1%, respectively. On average, lamps were set to a color when turned on 7.2 percent of the time in the evenings at site 4, across test lamps.
Site 5

Site 5 is a two bedroom apartment occupied by three working adults in their twenties. Figure 30 presents the lamp use profile for Site 5.

Site 5 saw an increase in lamp usage overall between Phase 1 and Phase 2 with average hours of use increasing from 0.46 hours to 0.96 hours. As depicted below, the majority of this increase occurred in the evening as well as overnight. Additionally, there was a shift in usage pattern in the morning to earlier hours which may have been due to a schedule change in the household. Closer inspection of the
lamps in the home revealed that increased usage was largely attributable to lamps installed in the living room and to a lesser extent the bedroom. Interestingly some lamps were on all night over some portion of Phase 2, which may have been due to a lamp being left on accidentally for a period of days, or being used as a security light. Brightness controllability was used during Phase 2 in the mornings and evenings, almost all of which is accounted for by the bedroom lamp.

**Figure 30: Site 5 – Test Lamps – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile]

Figure 31 shows that in the morning across all test lamps at Site 5, the default white was used 96.2 percent of the time when a lamp was on (averaged across all test lamps). Colder white color temperature was used 2.8 percent of the time lamps were on in the morning, on average, and color was rarely used (0.1%). In the evening, color was used 25.0 percent of the time, on average across lamps (nearly entirely reddish colors). The default white was used 70.8 percent of the time, on average across test lamps.
Site 6

Site 6 is a three bedroom detached single-family residence occupied by two working adults and 2 elementary school aged children. Figure 32 presents the lamp use profile for Site 6.

Whereas most sites in the study experienced differing patterns of usage between Phase 1 and Phase 2 of the study, Site 6 and the following site, Site 7, both showed relatively consistent usage between the two periods with very little use of dimming. As depicted below, the usage patterns between the two periods in Site 6 are almost
identical with some additional usage in the late evening in Phase 2 of the study. The brightness controllability function of the lamps was virtually unused with a small change in brightness registering for the average brightness at approximately 11pm which is due to an isolated instance of dimming in one room. The average hours of use for this site changed minimally from 0.46 hours per day on average to 0.68 hours per day.

**Figure 32: Site 6 – Test Lamps – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile](image)

The lamps installed at Site 6 were never set to a color other than the default white, including non-default color temperatures. The user reported difficulty using the application as the reason for not using the color features of the Hue.

**Site 7**

Site 7 is a two bedroom detached single family residence occupied by two working adults in their thirties. Figure 33 presents the load and dimming profile for Site 7.

Similarly to Site 6, Site 7 displayed relatively consistent usage between the two periods with very little use of dimming. Usage between the two periods in Site 7 are almost identical with some additional usage in the early evening in Phase 2 of the study, likely attributable to decreasing day length. Again, the brightness
controllability was virtually unused. The average hours of use for this site changed minimally from 1.53 hours per day on average to 1.79 hours per day.

**Figure 33: Site 7 – Test Lamps – Lamp Use and Dimming Profile**

The lamps installed at Site 7 were never set to a color other than the default white in the morning, and were set to a colder white temperature in the evening less than one percent of the time, on average across lamps. The user reported difficulty using the application as the reason for not using the color features of the Hue.

Site 6 and Site 7 occupants both expressed some frustration with the functionality of the product and had difficulty using the software at times. Despite this, we have kept these sites in the study because they do indicate that there are constraints to the usability of the product experienced by some users.

**Site 8**

The final site in the study, Site 8 is a four bedroom detached single-family residence occupied by two working adults and 2 elementary school aged children. Figure 34 presents the lamp use profile for Site 8.

Similar to both Site 6 and Site 7, this household did not make any significant use of the brightness controllability of the test lamps during Phase 2. There is a pronounced increase in usage throughout the day with a prominent spike in the early morning.
On closer inspection of all lamps in the home, this was mostly due to increased usage in the dining room of the home. The average hours of use for this site changed minimally from 2.86 hours per day on average to 4.13 hours per day.

**Figure 34: Site 8 – Test Lamps – Lamp Use and Dimming Profile**

Test lamps at Site 8 were never set to a color in the morning period, and there was minimal color temperature change (as shown in Figure 35, below). In the evenings, color was used 11.6 percent of the time on average across all lamps when on (nearly all reddish shades). The default white color was most frequently used in the evenings.
HOME AND HOUSEHOLD TYPE USAGE ANALYSIS FINDINGS – TEST LAMPS

In this section we present lamp usage grouped by the demographic characteristics of the site. For this purpose we have separated the sites into four groups described in Table 10 below.
Table 10: Site Demographic Groupings

<table>
<thead>
<tr>
<th>Demographic Group</th>
<th>Number of Sites</th>
<th>Phase 1: Hours of Use/DAY</th>
<th>Phase 2: Hours of Use/DAY</th>
<th>Overall: Hours of Use/DAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Children – Detached Home</td>
<td>2</td>
<td>1.95</td>
<td>2.02</td>
<td>1.99</td>
</tr>
<tr>
<td>No Children – Attached Home</td>
<td>2</td>
<td>0.41</td>
<td>1.38</td>
<td>0.96</td>
</tr>
<tr>
<td>Elementary Age Children – Detached Home</td>
<td>3</td>
<td>1.98</td>
<td>2.86</td>
<td>2.47</td>
</tr>
<tr>
<td>Teenage Children – Detached Home</td>
<td>1</td>
<td>0.08</td>
<td>0.69</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 11 shows the use of dimming across the demographic segments represented by the homes in this study. As shown, dimming was used more heavily in the attached homes without children and the homes with teenage children. This may suggest heavier usage of connected LED features among younger adults and teenagers, but it is difficult to draw conclusions given the sample sizes (and significant variation across sites).

Table 11: Use of Dimming – Test Lamps, By Demographic Groupings (Phase 2)

<table>
<thead>
<tr>
<th>Site</th>
<th>Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Children – Detached Home</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>&lt; 100%</td>
</tr>
<tr>
<td></td>
<td>&lt; 20%</td>
</tr>
<tr>
<td></td>
<td>20-40%</td>
</tr>
<tr>
<td></td>
<td>40-60%</td>
</tr>
<tr>
<td></td>
<td>60-80%</td>
</tr>
<tr>
<td></td>
<td>80-99.9%</td>
</tr>
<tr>
<td>No Children – Attached Home</td>
<td>96.4%</td>
</tr>
<tr>
<td></td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td>0.6%</td>
</tr>
<tr>
<td>No Children – Attached Home</td>
<td>64.4%</td>
</tr>
<tr>
<td></td>
<td>35.6%</td>
</tr>
<tr>
<td></td>
<td>5.8%</td>
</tr>
<tr>
<td></td>
<td>6.6%</td>
</tr>
<tr>
<td></td>
<td>7.1%</td>
</tr>
<tr>
<td></td>
<td>13.0%</td>
</tr>
<tr>
<td></td>
<td>3.1%</td>
</tr>
<tr>
<td>Elementary Age Children – Detached Home</td>
<td>82.1%</td>
</tr>
<tr>
<td></td>
<td>17.9%</td>
</tr>
<tr>
<td></td>
<td>8.5%</td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>4.9%</td>
</tr>
<tr>
<td></td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>1.4%</td>
</tr>
<tr>
<td>Teenage Children – Detached Home</td>
<td>78.9%</td>
</tr>
<tr>
<td></td>
<td>21.1%</td>
</tr>
<tr>
<td></td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td>2.5%</td>
</tr>
<tr>
<td></td>
<td>6.9%</td>
</tr>
<tr>
<td></td>
<td>5.7%</td>
</tr>
<tr>
<td></td>
<td>4.1%</td>
</tr>
</tbody>
</table>

No Children – Detached Home

The first demographic group contains two households (Site 1 and Site 7), living in detached single-family residences consisting of working adults with no children. Figure 36 presents the lamp use profile when all test lamps in this demographic group are combined.

Across all lamps in this group we see very little variance in usage between the two study periods aside from some additional usage in the early evening in Phase 2, which is most likely attributable to decreasing day length. We can also see that the brightness control functionality of the lamps was not utilized significantly in these homes and when it was it was in the evening hours. The average hours of use between the two study periods did not change a great deal with average daily hours of use increasing slightly from 1.95 hours per day to 2.02 hours per day.
No Children – Attached Home

The second grouping contains two households (Site 3 and Site 5), living in apartments and consisting of working adults in their twenties with no children. Figure 37 presents the lamp use profile when all lamps in this demographic group are combined.

In contrast to the first grouping, the homes in this grouping used the test lamps with greater frequency in Phase 2 of the study period with pronounced increases in the morning and evening. While some of the evening use increase is attributable to changing day length, it appears that there is increased use not influenced by day length, particularly in the morning and late evening. In addition, this group utilized the brightness control functionality heavily during Phase 2. In particular these homes used this function to brighten lights in the morning and dim lights in the evening. Interestingly, there are 2 brightness spikes in the morning indicating two different morning brightening regimes between the two homes in the group. Average hours of use in Phase 1 and Phase 2 were lower than the first group with 0.08 hours of use in Phase 1 and 0.69 hours of use in Phase 2.
Elementary Age Children – Detached Home

The third demographic group contains three households (Site 2, Site 6 and Site 8), living in detached single-family residences, consisting of working adults with elementary age children. Figure 38 presents the lamp use profile when all lamps in this demographic group are combined.

The homes appeared to increase usage in the test lamps in Phase 2 of the study period with increased usage in the morning and through the day. On further inspection, the increased daytime usage was attributable to one home in the group primarily. This group utilized the brightness control functionality extensively during Phase 2. Similar to Group 2, these homes used this function to brighten lights in the morning and dim lights in the evening. Average daily hours of use for this group were 1.98 hours of use in Phase 1 and 2.86 hours of use in Phase 2.
The final demographic grouping consists of one site, Site 8. This site is a detached single-family residence, consisting of working adults with teenage children. Figure 39 presents the lamp use profile when all lamps in this demographic group are combined. This figure is identical to Figure 28.

As mentioned above, during Phase 1, the test lamps at this site saw very little overall usage with close to no usage during the day and minimal usage in the evening hours. During Phase 2, when the household was able to control the test lamps, evening usage of the lamps increased dramatically relative to Phase 1 usage. Morning and daytime usage of the lamps in Phase 2 remained very low. The household did use the brightness control functionality of the bulbs, particularly in the evening. During the morning and daylight periods, there are changes in average brightness, but these readings should be discounted because the lamps were rarely on. Overall, usage of the lamps increased between the two periods with average hours of use increasing from 0.08 hours to 0.64 hours.
MARKET STUDY

The results of the market study are presented in this section. The majority of the findings come from the manufacturer in-depth interviews, as studies related to lamps with embedded control technologies are not presently available.

LITERATURE REVIEW

The first stage of the literature review was the identification of easily-comparable EM&V studies. One evaluation report was found to be applicable to the goals of this study. The study found that when dimmers are installed on fixtures and incumbent technologies are replaced by LEDs (at the same time), operating hours of the lamps increases overall. The study also noted that there is a lot of variability in how dimmers affect usage patterns, that dimming reduces energy usage and thus greater operating hours may be offset, and that the majority of observed energy savings were due to lamp replacement (from an incumbent technology to LEDs), and not controls-related (Cadmus, 2013).

The literature review also encompassed a review of comparable products. Fourteen companies, including Philips, are or soon will have LEDs with embedded controls for sale to the U.S. market. Below, in Table 12, is information related to all of these
products, including the price of a comparable starter kit (which includes a bridge, if applicable, and a number of connected LEDs) and an overview of key features.

<table>
<thead>
<tr>
<th>COMPANY</th>
<th>PRODUCT</th>
<th>PRODUCT SPECIFICATION OVERVIEW</th>
<th>COMPARABLE PRICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips</td>
<td>Hue</td>
<td>Hub required; Zigbee/WiFi connectivity; App-controlled; White light and color.</td>
<td>A19 starter kit (includes hub, 3 connected A19 LEDs): $199.95 (additional A19 LEDs: $59.95)</td>
</tr>
<tr>
<td>Stack</td>
<td>Alba</td>
<td>Hub required; WiFi; App-controllable, daylighting, occupancy sensors allow for non-controlled automation; White light only.</td>
<td>BR-30 starter kit(^7) (includes hub and 2 BR-30 LEDs): $150.00 (additional BR-30 LEDs: $60/each)</td>
</tr>
<tr>
<td>GE + Wink</td>
<td>Link</td>
<td>Hub required; Zigbee/WiFi connectivity; App-controlled; White light only.</td>
<td>No starter kit available. Hub: $49.99 A19 LEDs: $14.97/each</td>
</tr>
<tr>
<td>TCP</td>
<td>Connected by TCP</td>
<td>Hub required; WiFi connectivity; App-controlled; White light only.</td>
<td>A19 starter kit (includes hub, 2 connected A19 LEDs): $69.95 (additional A19 LEDs: $19.97/each)</td>
</tr>
<tr>
<td>Belkin</td>
<td>WeMo</td>
<td>Hub required; WiFi connectivity; App-controlled; White light only.</td>
<td>A19 starter kit (includes hub, 2 connected A19 LEDs): $99.99 (additional A19 LEDs: $29.99/each)</td>
</tr>
<tr>
<td>iLumi</td>
<td>Color Tunable LED Smartbulbs</td>
<td>No hub; Bluetooth connectivity; App-controlled; White light and color.</td>
<td>No hub required. A21 connected LEDs: $89.98/each</td>
</tr>
<tr>
<td>Insteon</td>
<td>Insteon</td>
<td>Hub required; Radio frequency (RF) communication; App-controlled; White light only.</td>
<td>No starter kit available. Hub: $99.99 A19 LEDs: $29.99</td>
</tr>
<tr>
<td>Lifx</td>
<td>Multicolor Smart LED</td>
<td>No hub; WiFi connectivity; App-controlled; White light and color.</td>
<td>No hub required. A19 connected LEDs: $99/each</td>
</tr>
<tr>
<td>Samsung</td>
<td>Bluetooth-enabled Smart LED</td>
<td>No hub; Bluetooth connectivity; App-controlled; White light only.</td>
<td>No information available at this time.</td>
</tr>
<tr>
<td>Tabu</td>
<td>Lumen LED Color Smart Bulb; LuMini LED</td>
<td>No hub; Bluetooth connectivity; App-controlled; White light and color.</td>
<td>No hub required. A19 connected LEDs: $69.99/each</td>
</tr>
<tr>
<td>Google/Lighting Sciences Group</td>
<td>TBD</td>
<td>No information available at this time.</td>
<td>No information available at this time.</td>
</tr>
<tr>
<td>AwoX</td>
<td>StriimLIGHT</td>
<td>No hub; Bluetooth or WiFi connectivity; App-controlled; White light only; Lamps have built-in speakers for playing music.</td>
<td>No hub required. A19 connected LEDs: $39.99/each</td>
</tr>
<tr>
<td>Torchstar</td>
<td>N/A</td>
<td>Hub required; Radio frequency (RF) or WiFi connectivity; App-controlled; White light and color.</td>
<td>A19 starter kit (includes hub, 3 connected A19 LEDs): $69.99 (additional A19 LEDs: $13.99)</td>
</tr>
<tr>
<td>LG</td>
<td>Smart Lamp</td>
<td>No hub; Bluetooth connectivity; App-controlled; White light only.</td>
<td>No information available at this time.</td>
</tr>
</tbody>
</table>

\(^7\) BR-30 LEDs are the only currently available lamp type from Stack, but they will be introducing a full line of lamp styles in 2015.
MANUFACTURER IN-DEPTH INTERVIEWS

In-depth interviews were conducted with five corporate level representatives from manufacturers who produce LEDs with embedded controls. Respondent and firm background information is presented below, in Table 13 (they are anonymous to ensure that respondent confidentiality is maintained).8

<table>
<thead>
<tr>
<th>#</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Director of Product Development</td>
<td>Founder, CEO</td>
<td>Product Manager</td>
<td>Product Manager</td>
<td>Co-founder and CEO</td>
</tr>
<tr>
<td>Years</td>
<td>6.5 yrs</td>
<td>1 yr</td>
<td>10+ yrs</td>
<td>10+ yrs</td>
<td>3 yrs</td>
</tr>
<tr>
<td>Product Availability</td>
<td>Currently available for sale</td>
<td>Pre-order, begins shipping Q1 2015</td>
<td>Currently available for sale</td>
<td>Currently available for sale</td>
<td>Currently available for sale</td>
</tr>
<tr>
<td>Other LEDs?</td>
<td>All LEDs have embedded controls</td>
<td>All LEDs have embedded controls</td>
<td>Full line of LEDs without controls</td>
<td>Full line of LEDs without controls</td>
<td>All LEDs have embedded controls</td>
</tr>
<tr>
<td>Standard Controls?</td>
<td>Does not produce standard lighting controls</td>
<td>Does not produce standard lighting controls</td>
<td>Produces standard lighting controls</td>
<td>Does not produce standard lighting controls</td>
<td>Does not produce standard lighting controls</td>
</tr>
<tr>
<td>Non-LED products?</td>
<td>Produces many non-LED products</td>
<td>Only produces LEDs with embedded controls</td>
<td>Produces many non-LED products</td>
<td>Produces many non-LED products (lighting only)</td>
<td>Only produces LEDs with embedded controls</td>
</tr>
<tr>
<td>Other Connected Devices?</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Below we present findings from the in-depth interviews with connected LED manufacturers.

TARGET MARKET

Four respondents reported that the residential consumer market is the primary overall target market for this product, particularly consumers who fit a typical early adopter profile. One respondent was unable to answer (proprietary). Two respondents provided more specific information related to the target market for their product. Both report that younger people are easier targets (18-35 for one, 18-45 for the other), as they are generally more amenable to high tech devices. Only one mentioned that their product was more successful among more affluent consumers.

Three respondents also believe that these products are well suited for the commercial sector. Two of these respondents already market their product to

---

8 Representatives from Philips were unavailable to assist in this part of the research during the data collection phase, and thus are not included as a respondent for this assessment.
commercial customers, and one will be rolling out a commercial line of products soon. Sectors within the commercial market that may be particularly suited for these products include the hospitality sector (cited by all three respondents), retail (two respondents), offices, and healthcare (one respondent each).

A common theme discussed with each respondent is that the product is similar to any new, high tech product, and is characterized by high first cost and interest among early adopters.

REASONS FOR PRODUCING LEDS WITH EMBEDDED CONTROLS

Respondents were asked why their company decided to produce LEDs with embedded controls. Three respondents cited a gap in the market unfilled by then-available products. The other two (whose companies produce a range of lighting products) saw a market that was growing and wanted to fill a need for their consumers.

The three respondents who cited a gap in the market elaborated further. The idea for one of the products started with the smartphone, which they believed created an opportunity to change the way people interact with the world around them, including how they use their lighting. The idea for one of the other products started with the identification of excessive electrical lighting in an office building with sufficient sunlight. They compared the lack of adaptable controls in the office’s lighting systems with their cell phone screen, which could adjust to the brightness, and determined that lamps should have embedded control functionality (this company’s product not only embeds on/off and dimming controls, but also photocells and occupancy sensors). The last firms’ representative said that their product was in direct response to huge market potential, and that building a flexible system would allow for consumers to enter to connected space via lighting, but with potential to expand (this company produces many other connected devices, and teams with other manufacturing companies to offer a range of connected products).

All of the respondents believe that LEDs with embedded controls are serious lighting solution. All mentioned that the color aspect of certain companies’ lamps are essentially a novelty component of the product. One noted that color is nice in certain cases, such as retail display lighting, and two noted that it is used for certain occasions within the home (e.g., holidays, etc.). One respondent whose product includes RGB color rendering LEDs mentioned that the color TV and, later, the 3D TV were both seen as novelty items when they were first entering the market.

Four of five noted that color temperature tuning is an important feature of connected LEDs as it allows customization within the white light spectrum.

SALES AND PRICING

Respondents were unable to estimate 2014 sales (proprietary information). All respondents claim that sales will grow over the next five years (typical of a new market).

Respondents reported that product cost was associated with different functionality profiles (e.g., active vs. passive controls, color, LED quality, etc.), but that variability also had to do with the fact that the product line is very new on the market. All respondents believe that prices will go down for the products available today, but that new products will likely be introduced over the course of five years that may outperform the current set, and would be priced appropriately. Reportedly, price will
decline due to sales volumes. According to two respondents, the price will decline
due to sales volumes of competitors, too, because those drive material costs down.

FUTURE PLANS

Respondents were asked questions about their company’s future plans related to
LEDs with embedded controls. All respondents believe that their company will be
producing a product similar to their current product in five years. Three mentioned
that there will be improvements to the product line that might make it seem different
(no central hub, incorporation of occupancy sensing, and incorporation into more
robust home automation systems).

Three of the five manufacturers produce other connected devices beyond lighting.
One produces connected electrical sockets, home security cameras, and light
switches, and they team with other companies to offer a range of connected
appliances (e.g., coffee maker, slow cooker). Another produces motion sensors and
wall plugs, and the third has partnered to launch a connected thermostat.

All of the manufacturers agreed that whole home automation is a likely end point of
these types of products. They believe that interoperability is the key – many
manufacturers producing products that are tied together. One mentioned new
construction as a likely target market for a packaged home automation approach.

EVALUATIONS

A summary of the findings from this technology assessment is presented below in a
numbered list:

1. Hours of use increased more for the test lamps than the comparison lamps between
   Phase 1 and Phase 2, possibly indicating that installation of connected LEDs would
   lead to greater operating hours and possibly energy consumption (relative to
   standard LEDs). This analysis accounted for changes in hours of use due to
   seasonality.

2. The possibility of increased energy consumption based on hours of use among test
   lamps may be offset by frequent use of the dimming features. The results indicate
   that dimming was frequently used among test lamps installed in bedrooms and living
   rooms (approximately 38% and 20% of “on” time, respectively).

3. There appear to be situations where increased usage occurred in the test lamp, and
   decreased usage in the comparison lamp (which was only controlled via the standard
   wall switch) – this suggests usage of connected LEDs may impact the use of other
   lamps within a room. In these cases, some portion of the usage is moving from one
   lamp to the other, and does not necessarily reflect net increase in usage overall.

4. Color functionality was used heavily by some households, and not at all by others.
   Color usage was most prevalent in sites with young adults and no children, and the
   site with teenage children.

5. Color was more frequently used in the evenings in living rooms and bedrooms, and
   more frequently in the morning in dining rooms (on average, across test lamps).
   Color was almost never used in bathrooms (it was never used in the office or kitchen.
where test lamps were installed, but this was more to do with the household not using the color functionality across any of their lamps).

6. White light color temperature tuning is another benefit of this technology, and was used extensively by Site 2, Site 3, and Site 4. Color temperature has been a barrier to efficient lighting adoption (both for fluorescent and LED technologies), and the ability to tune the temperature to satisfy your particular temperature needs is a benefit of this technology (this was mentioned by four of five manufacturers interviewed for the market study component of this assessment).

7. Brightness controllability was used significantly at Site 2, Site 3, Site 4, and Site 5 (for other sites it was rarely used). This could be a driver of sales based on the wants and needs of the end-user.

8. Some end-users were frustrated with the way the lamps were controlled by their cell phones. Both the new method of using a phone to turn on/off or adjust lighting and issues with the user interface were barriers to using the control features of the system. These may be barriers to the adoption and use of connected LEDs, and affected the amount that study participants used the feature set of the Hue. These issues may manifest themselves in the residential mass consumer market, and thus savings from the connected aspect of smart-phone controlled LEDs may not exist for all purchasers.

9. Lamp connectivity issues impact the usability of the lamps themselves. This is a potential barrier, although there are a number of manufacturers using a variety of different wireless connectivity protocols (e.g., WiFi, zigbee, Bluetooth), so improvements in this area are likely achievable by manufacturers.

10. Lamps must be installed in fixtures controlled only by on/off switches (not dimmers). Furthermore, lamps must be powered “on” at the switch in order to control them via the application (lamps may be turned “off” via the application). If a fixture is turned “off” by the switch, the lamp receives no power and thus cannot be controlled remotely.

11. Product cost is generally high for products in this category, but cost is expected to decline significantly in the near-term.

12. Connected LEDs offer a way to overcome drawbacks of currently available lighting hours of use meters. Traditional lighting monitoring equipment typically relies on photocell readings to determine the on/off status of a lamp, where ambient light can create false “on” readings due to installer error. Connected lamps allow for a higher degree of certainty regarding the on/off status and other characteristics of the lamp, such as light color or brightness, because the status data is continuously communicated to a centralized hub. However, connectivity issues – mentioned above in the ninth finding – may disrupt data collection and/or require implementing data cleaning procedures.

**FINANCIAL ANALYSIS**

The return on investment of purchasing and using LEDs with embedded controls was not an intended outcome of this research. Prices for this nascent product category is generally very high. Because the category is so young, price is highly variable based on the product feature set as evident in Table 12. While variation in price for this technology category is attributable in part to differences in feature sets across
products, it is also dependent on material costs (LEDs and communication hardware) and other factors, such as target market.

The findings indicate savings will vary based on the control strategies enabled by the product, demographics of the users and usability of the controls.

**RECOMMENDATIONS**

The findings from this assessment suggest that further study in the area of connected LEDs is warranted at this time. There exist a range of available products at different price points and with different feature sets, and manufacturers are supporting the products as serious lighting solutions. Furthermore, the results of the market study suggest that the user experience with connected LEDs may change in the near-term, with more manufacturers producing connected LEDs that adjust to the user and do not require as much user input (e.g., via a smartphone). Manufacturers believe that connected LEDs are the future of residential – and perhaps commercial – lighting, and not just a novelty item.

Additionally, this assessment shows that usage changes with the introduction of application-controlled connected LEDs. A more robust study, in terms of the number of homes and total number of lamps, may be able to address whether energy savings from the use of dimming (or color) offsets any potential increase in energy consumption due to increases in hours of use.

It is also recommended that PG&E consider opportunities for additional human-centric studies related to the color tuning aspect of connected LEDs. This feature alone would help to alleviate an efficient lighting market barrier that precedes the introduction of LEDs into the residential mass market (consumer dissatisfaction with fluorescent and LED light quality).

Until further study of this technology group, it is not recommended that PG&E adopts a new measure category for this technology into the energy efficiency program. However, since connected lamps may be a good entry point into the efficiency market for consumers, and since they allow for tuning of color temperature to suit the needs of consumers, it is recommended that these lamps be considered for residential and targeted commercial energy efficiency programs as part of the existing LED measures.
APPENDICES

TEST AND SECONDARY LAMP COMPARISON

LIVING ROOMS

Figure 40: Site 1 – Living Room Test Lamp – Lamp Use and Dimming Profile

Figure 41: Site 1 – Living Room Comparison Lamp – Lamp Use and Dimming Profile
**Figure 42: Site 2 – Living Room Test Lamp – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile](image)

**Figure 43: Site 2 – Living Room Comparison Lamp – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile](image)
Figure 46: Site 4 – Living Room Test Lamp – Lamp Use and Dimming Profile

Figure 47: Site 4 – Living Room Comparison Lamp – Lamp Use and Dimming Profile
**Figure 48: Site 5 – Living Room Test Lamp – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile over Pacific Time.]

**Figure 49: Site 5 – Living Room Comparison Lamp – Lamp Use and Dimming Profile**

![Graph showing comparison lamp use and dimming profile over Pacific Time.]

Pacific Gas and Electric Company
Figure 50: Site 7 – Living Room Test Lamp – Lamp Use and Dimming Profile

Figure 51: Site 7 – Living Room Comparison Lamp – Lamp Use and Dimming Profile
Figure 52: Site 8 – Living Room Test Lamp – Lamp Use and Dimming Profile

Figure 53: Site 8 – Living Room Comparison Lamp – Lamp Use and Dimming Profile
BEDROOMS

Figure 54: Site 1 – Bedroom Test Lamp – Lamp Use and Dimming Profile

Figure 55: Site 1 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile
Figure 56: Site 3 – Bedroom Test Lamp – Lamp Use and Dimming Profile

Figure 57: Site 3 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile
**Figure 58: Site 5 – Bedroom Test Lamp – Lamp Use and Dimming Profile**

**Figure 59: Site 5 – Bedroom Comparison Lamp – Lamp Use and Dimming Profile**
**Figure 62: Site 8 – Bedroom (1) Test Lamp – Lamp Use and Dimming Profile**

**Figure 63: Site 8 – Bedroom (1) Comparison Lamp – Lamp Use and Dimming Profile**
**Figure 64: Site 8 – Bedroom (2) Test Lamp – Lamp Use and Dimming Profile**

![Graph showing lamp use and dimming profile](image)

**Figure 65: Site 8 – Bedroom (2) Comparison Lamp – Lamp Use and Dimming Profile**

![Graph showing comparison lamp use and dimming profile](image)
DINING ROOM

**Figure 66: Site 3 – Dining Room Test Lamp – Lamp Use and Dimming Profile**

**Figure 67: Site 3 – Dining Room Comparison – Lamp Use and Dimming Profile**
BATHROOM

FIGURE 68: SITE 5 – BATHROOM TEST LAMP – LAMP USE AND DIMMING PROFILE

FIGURE 69: SITE 5 – BATHROOM COMPARISON LAMP – LAMP USE AND DIMMING PROFILE
Figure 70: Site 7 – Office Test Lamp – Lamp Use and Dimming Profile

Figure 71: Site 7 – Office Comparison Lamp – Lamp Use and Dimming Profile
REFERENCES
