Sustainability Whitepaper

Whitepaper
Sustainability

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Table of contents

personal wireless lighting

Executive summary

Smart connected lighting systems like Philips Hue exhibit energy savings due to smartness. This is often countered with the argument of energy losses in standby mode. A study was performed by Signify on 1.6 million 9W Hue lamps in european Philips Hue systems with granted user consent, measuring the on time and dimming settings of connected and the on time of non-connected light sources used as a control group (emulated by Hue lamps controlled solely by wall switches). Comparable energy consumption was demonstrated in the winter, even using conservative 0.5W value for the standby and longer on time of the smart devices compared to the non-connected benchmark. During summertime, considerable energy savings of 33%, 37%, 28% for, respectively, white, white ambience and white color ambience lamps, even with the conservative 0.5W standby. In addition, the findings demonstrate the users enjoying the flexibility of the lighting settings

1. Introduction

Wireless lights, such as Philips Hue, offer users the ability to control their lights through smart technologies, allowing them to customize their lighting to fit specific needs. This controllability requires a standby power to keep the wireless connection active to receive and timely respond to control commands. The versatility in lamp control like using schedules, dimmability, and specific hue settings has its impact on the energy consumption. In this white paper, we explore energy consumption of wireless connected lights in comparison to lights that are manually controlled through conventional on-off wall switches.

A study was conducted by Signify to understand the power consumption of Philips Hue lamps from user's usage patterns, using anonymized log data from real-world usage. Traditional usage patterns of lights that are manually controlled through wall switches were also examined as a reference point. By analysing the power consumption of these lights in the field, we can gain insights into how wireless lights impact energy consumption and identify opportunities for optimization.

In chapter 2, the origin of the lamp usage patterns is explained. Usage patterns are derived from Hue system log data. First, the characteristics of the Philips Hue lamps are explained. Then, the nature of the data and its collection methods are described. In addition, the assumptions and models in combination with the necessary data transformations are highlighted to obtain the usage patterns and calculate the related power consumptions.

The third chapter details the specifics of applying the approach of chapter 2 towards the installed Philips Hue systems in the world. It details the considerations around lamp data filtering, usage profile extractions, and power consumption calculations. It also describes how the data for the reference group of non-connected lamps is obtained (3.3). Finally, it is described how these inputs are used to translate these to energy consumption under the different conditions.

In chapter 4, the results are discussed of the power and energy consumption of the lights as a function of the different light settings reflecting the consumers behavior.

Finally, chapter 5 summarizes the impact on total energy consumption of connected lighting. It demonstrates that the power saved through the smart controls more than compensates for the energy needed to enable the versatile controllability of connected wireless lighting.

2 Methodology to derive lamps' consumed power

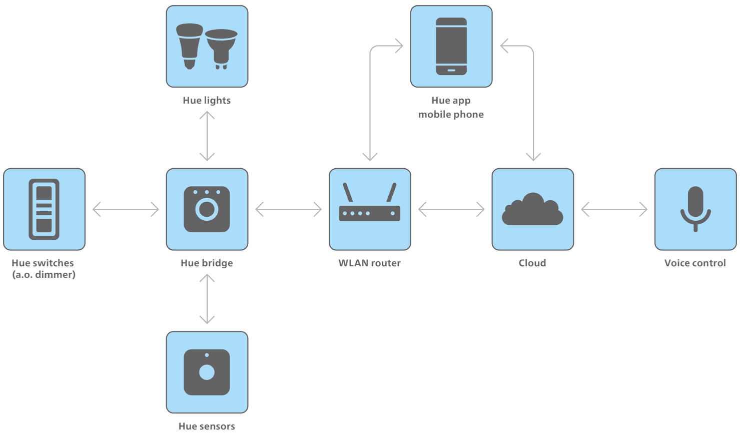
The Philips Hue system characteristics paragraph (2.1) describes the details on the Philips Hue system and the approach how light setting data is collected. Section 2.2 describes how the power consumption of lamps is derived as a function of the light settings. In section 2.3, the selected lamp types and their power characteristics are described

2.1 Philips Hue system characteristics

There are multiple ways to control a light in the Philips Hue system. The consumer can control their lights through a mobile phone app or via a voice command on a connected voice platform like Amazon Alexa or alike. The lights can also easily be configured to interact with sensors or to obey rules like being off at daytime and on during evenings. In addition, each light can be tailored in terms of brightness or other light settings in a manual or automated way.

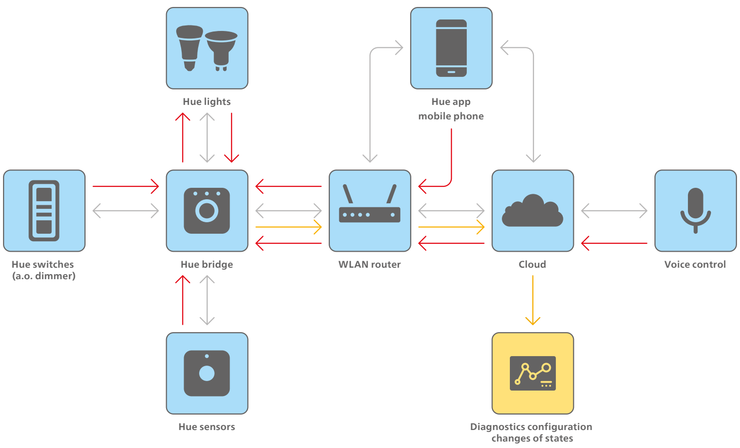
The Philips Hue system relies on a central bridge device which co-ordinates behaviour within the lighting system and provides the internet connected devices such as voice controls or mobile phone apps with a connection to the lighting network. The Philips Hue bridge contains a rule engine which processes control inputs from smart switches, sensors, mobile apps, and voice assistants and translates those triggers into control commands to the lights. With appropriate consent from the user, the Philips Hue bridge generates data logs of control events of the lights, which are then relayed to the Philips Hue cloud from the Philips Hue bridge.

Figure1: Different methods on how a light can be controlled in Philips Hue system.



To fully appreciate the usage patterns, we have considered several data logs. Since all data to control the lights goes through the bridge, the diverse types of logs originating from the bridge are considered as depicted in Figure 2. These data are logged under the condition that the consumer has given consent.

Figure2: Trigger processing in the bridge for controlling lights (red lines) and data collection for analysis (yellow line).



The *diagnostics data* tracks when a light becomes offline since the echo request of the bridge towards the lights are no longer confirmed by the lights through an echo response. The messages logging the absence of the echo response, which come along with a timestamp, are an indication that a light has been turned off by a main voltage switch. Similarly, when a light is powered, then there is a separate log message along with a timestamp which is an indication of a light being turned on by a main voltage switch. This data can be used to analyse Philips Hue lights that are used just as if they were traditional non-connected lamps controlled by a mains switch. When also fulfilling the requirement that the lights are not controlled by any other control method, this lamp subset is used to represent non-connected lamp usage (see chapter 3.3).

The bridge keeps track of the *configuration* of the Philips Hue system in the home. The latest configuration gives a view on the setup of the Philips Hue system. Configuration consists of information such as:

- Which lamps and accessories are connected to the bridge as part of the Philips Hue system.
- Mapping between the lamps and the rooms set up by the user.
- Which mobile device apps are configured with the bridge.
- Which features of the Philips Hue system are configured.

These data logs give context where lights and other component are positioned in the home and what type of rules are configured to operate the lights automatically.

Change of state data refers to all the light control messages along with a timestamp. It provides information on the origin of the control command, and it details the requested light setting. From here we extract control information about the connected lights such as:

- Stand by power (on-off)
- Brightness setting level (0-100%)
- Color setting (x, y CIE chromaticity)
- Color temperature (correlated color temperature)

As a result, there is knowledge which light has which specific light setting for which duration.

In the next section, it is explained how these light settings are converted into power consumption.

2.2 Determining power consumption of lamps

The lamps' power consumption depends on the light settings and can vary from the standby power when the lamp is off but still controllable to the full rated power at full brightness.

Being able to determine the power consumption at a given combination of control settings required direct measurements of the lamps themselves. First, the segregation of lamps into types and models was required due to the difference in hardware compositions of lamps (see chapter 2.3). The range for light settings, LED parameters, and electrical efficiency differs from one product to another. This then also results in power consumption differences. Then, for each of a selected set of lamp models, the power consumption was recorded by measuring the respective lamp at a sample set of type-specific lighting control settings .
These samples are used as a basis to build a mathematical model and look up tables for power consumption per lamp model as a function of its light settings. Which in turn serves as the reference lookup for power calculation for the analysis on a larger dataset.

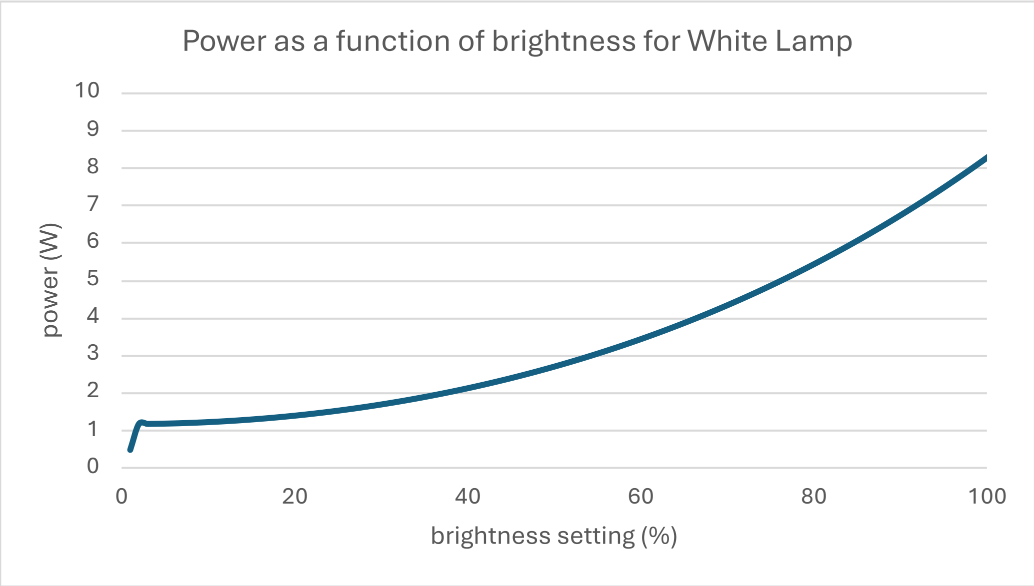
We have measurements of power for any given settings for selected lamp models. Based on the type of lamp, specific combination of settings allows to determine the power draw of a given lamp.
Common to all the types of connected lamps, is the power consumed when the lamp is in its 'off' state which is represented by the standby power. This depends on the hardware components present in the lamps which are required to be active all times to receive any commands. This is required as the commands are sent wirelessly. For the purposes of this study, a conservative value of 0.5 Watts is used whilst standby power for current generation Philips Hue products varies between 0.15 and 0.5 watts depending on the product.
Also common to all the connected lamp types, the power consumption in the 'on' state also includes the power for keeping the radio antenna and microcontroller necessary for control active.

2.3 Selected lamp types and their power consumption

A range of lamps are selected to get a fair representation of the installed field. Three types of lamps were considered, which differ in their power consumption as a function of their light settings. See below to know what the setting configurations for each type of lamp are.

White Lamp:
A white lamp has a LED composition which emits a predefined white tone (i.e. correlated color temperature) of 2700K. For such a white lamp, the power usage values are only a function of the lumen brightness setting, which ranges from 1 to 100%. The 100% value links to the rated power of the product while the 1 value links to a light in its off state consuming only the standby power of the radio.

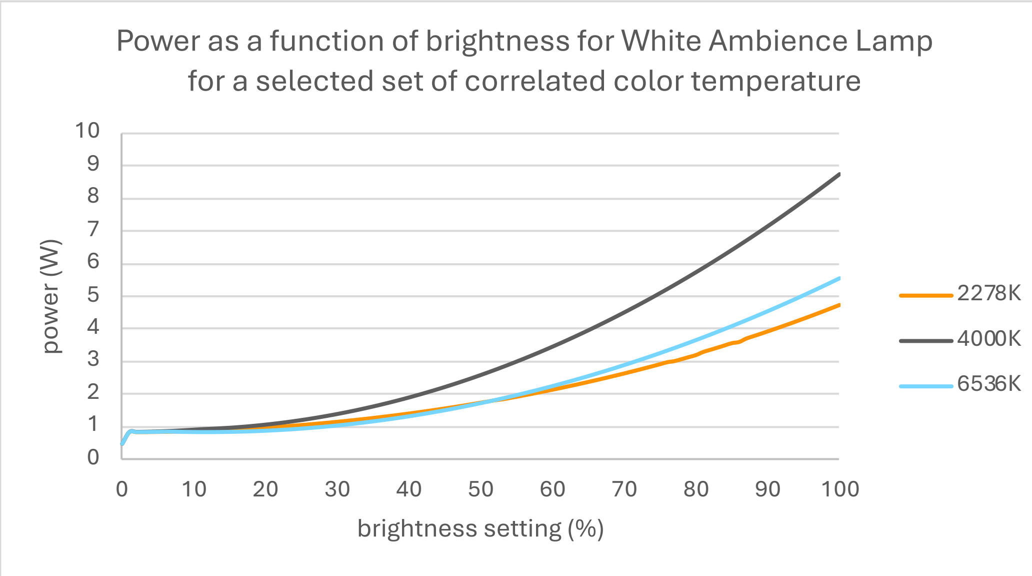
Figure 3: Measured power consumption as a function of the lumen brightness setting for a Philips Hue white light lamp (E27, White, 9W bulb). Value at the brightness setting 0 represents the Lamp 'off' state where it consumes standby power.



Based on the lumen brightness of a white lamp, the power consumed by the lamp model is determined. Since these characteristics vary per white lamp model, the correlations between power value and lumen brightness setting are determined for each lamp which is used in this study.

White ambience lamp:
A white ambiance lamp has a LED composition which allows to tailor the white tones. In the Hue case, the light can typically vary between 2200K and 6500K correlated color temperatures. Each of these correlated color temperatures have their own lumen brightness-power consumption dependencies. The power usage values are still a function of the lumen brightness setting, which ranges from 1 to 100% but is unique for each chosen correlated color temperature. In the below figure some examples of power consumption at a given correlated color temperature are presented.

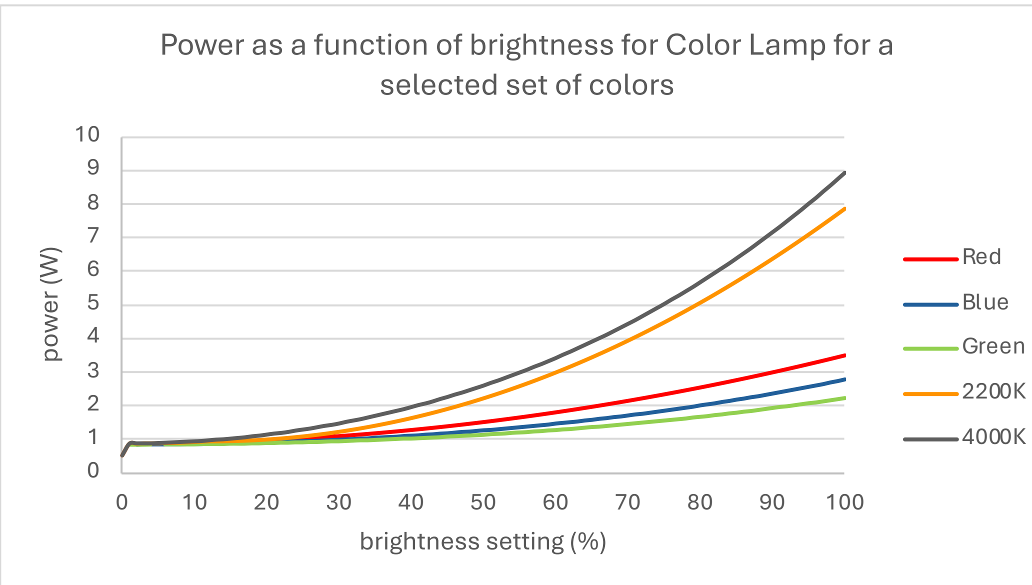
Figure 4: Measured power consumption as a function of the lumen brightness setting for a Philips Hue white ambiance light lamp at three different correlated color temperature settings. (E27, white ambiance, 9W bulb). This graph includes the power-brightness correlation of the range in white tones (2278K and 6536K). In addition, the more common white tone of 4000K is included. Value at the brightness setting 0 represents the Lamp 'off' state where it consumes standby power.



Based on the lumen brightness and the CCT settings of a white ambience lamp, the power consumed by the lamp model is determined. Since these characteristics vary per white ambiance lamp model, the correlations between power value versus lumen brightness and correlated color temperature settings are determined for each lamp which is used in this study.

White color ambience lamp:
A white color ambiance lamp has a LED composition which allows any color setting in the color gamut. The range of color setting is determined by the LED colors determining the gamut size. In this case the Philips Hue light can typically be set between 2200K and 6500K correlated color temperatures as white tones similar as in the white ambiance lights. On top of this, the lights can also present any color within the color gamut. The white tone or color appearance is in this case characterized by the x, y CIE chromaticity values. As a result, each of these x, y combinations have their own lumen brightness-power consumption dependencies. The 'x' values range from 0.15 to 0.7, the 'y' values range from 0.04 to 0.7. The power usage values are still a function of the lumen brightness setting, which ranges from 1 to 100% but is unique for each chosen x, y combination. In the below figure some examples of power consumption at a given x, y combinations are presented.

Figure 5: Measured power consumption as a function of the lumen brightness setting for a Philips Hue white color ambiance light lamp at different x, y combinations. (E27, white color ambiance, 9W, bulb). This graph includes the power-brightness correlation of the primary colors. In addition two examples of different white tones are included. Value at the brightness setting 0 represents the Lamp 'off' state where it consumes standby power.



3 Field data collection

Philips Hue operates a large fleet of connected lights installed in consumer homes in many countries around the world including the full European Union. With appropriate consumer consent, we collect anonymized diagnostic data on the status and configuration of these lights via our Philips Hue bridge (for more details, see chapter 2.1).

3.1 Data parsing

For the purposes of this study, we sampled data logs from a subset of our Philips Hue lights during two 7-day periods in January 2022 and August 2022. A total of 1.6 million lights were included in this sample set representing 108 million control events. We conducted this study of lights exclusively in the Europe region. The subset was arrived at based on user consent, by selecting certain representative light bulbs for which accurate power consumption models were built and based on availability of reliable data without gaps caused by connectivity disruptions.

Lamp model selection
Philips Hue lamps come in various sizes and types. Our analysis focuses on subset of lamp form factors which represent largest part of the European installed base. The selected lamp types are summarized in the table below.

Table 1: Hue lamp devices chosen for the analysis:

Model ID	Lamp description	Base type	Form factor	Max lumen output	% of Lamps under analysis
LTA001	Hue ambiance lamp	E27	A19	806lm	49%
LCA001	Hue color lamp	E27	A19	806lm	25%
LWA001	Hue white lamp	E27	A19	806lm	26%

** color lamp stands for the white color ambiance lamp types.*

These lights are tagged depending on the ways of controlling the lights and lights setting at a given period. There are three main types of controls.
The first type refers to a change in light settings via an app or other way in which there is a direct intervention from the consumer. The second type refers to a change in light settings via some way of automation. For example, through rules configured in the bridge or motion sensors being part of the Philips Hue system. The third type refers to lights controls as would be normal for legacy lamps via the main voltage switch.

Power consumption calculations
The lamps which are primarily controlled by the first or second type of interaction, are considered connected lamps. For the connected lamps, power consumption calculations use the methodology as explained in the previous chapter. The state information contains the relevant lamp state parameters: brightness and, if supported, CCT and/or color point. Further, with the state information available, getting the burning hours and standby hours are straight forward. When the lamp is in 'on' state, then it is burning. The time of this state measured in hours, would be the burning hours. Similarly, when the lamp is 'off' then the time consumed is standby hours. For smart lamps such as Philips Hue, power is still consumed during the standby time. Hence this measure is also important for power consumption calculation.

The third type of control represents usage via main voltage switch. This is one of the considerations made while selecting the reference group of lamps; see chapter 3.3 for more details.

3.2 Energy consumption calculations for connected lamps

The light setting - power conversion approach, as described in the previous chapter, holds the mapping between a state and power measured during the state for a particular model of lamp. This information can be extended to rest of the lamps of the same model. With the state information, burning hours and the power lookup, we can derive the energy by multiplying the burning hours and the respective mapped power value. To get the total energy, this is then added to the energy consumption during the standby time. See below for a more detailed view on this.

For a selected lamp L, let S be the set of states the lamp was in during our analysis window,
where S Í All states possible for a lamp. And s_i Î S is an individual state, where *i* uniquely identifies a lamp.
T is a function of s, which returns the time taken spent by the lamp in the state in hours.
P is a function of s, which returns the power consumption of the lamp in the state in Watts.
This is based on the power lookup.

$$burningEnergy\ (s_i) = T(s_i)\ x\ P(s_i)$$

$$standbyEnergy\ (s_i) = T(s_i)\ x\ 0.5$$

$$overallBurningEnergy\ (S) = \sum burningEnergy\ (s_i)$$

$$overallStandbyEnergy\ (S) = \sum standbyEnergy\ (s_i)$$

$$totalEnergy\ (L,S) = overallBurningEnergy\ (S) + overallStandbyEnergy\ (S)$$

The energy is calculated in Watthours.

3.3 Reference Group of Lamps

In order to draw conclusions on the impact on total energy consumption of a connected lamp, a reference group needed to be created to represent the legacy non-connected case. Since Philips Hue lamps report to the bridge in the ‘on’ state also when controlled by the mains voltage switch, we were able to identify a reference group based on Philips Hue products used exclusively in this manner as a representative proxy for non-connected lamp usage.

From our field data collection sample we were able to identify 80 000 devices which were only controlled by the mains voltage switch during the observation periods.

For this reference group emulating the non-connected lights, a mean number of operating hours is derived, based on the messages logging the presence and absence of the echo response (see chapter 2.1).

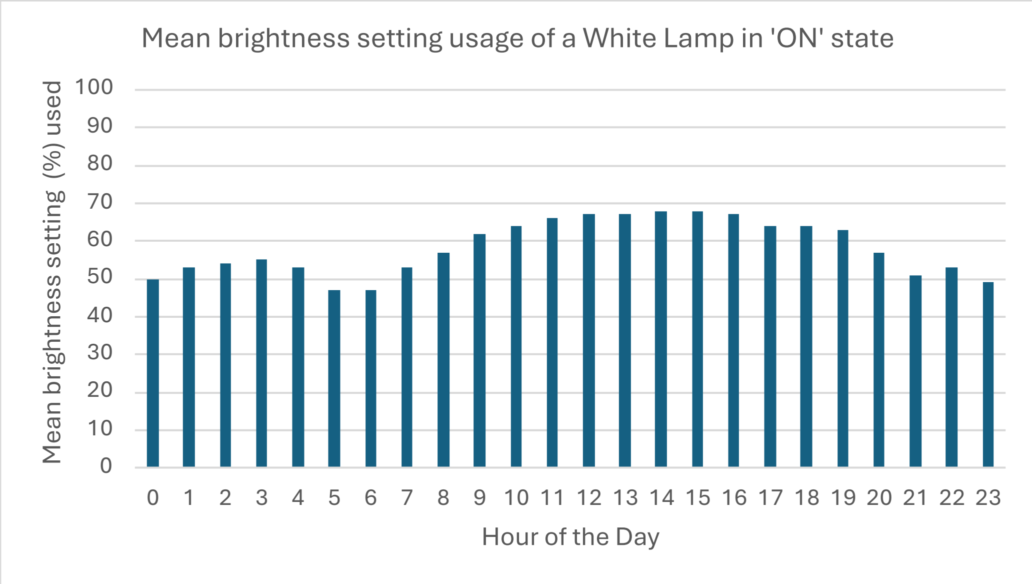
For calculating the energy consumption of the non-connected lights we use a theoretical reference lights with equivalent peak lumen per watt performance to the connected lights in the study in addition to a theoretical light with an more efficient lumen per watt performance. The calculation is done based on consuming the peak power consumption continuously while the light is powered on since these products do not have controllability. The energy consumption for those non-connected lights is then obtained by multiplying the number of mean operating hours with the lamp’s full rated power.

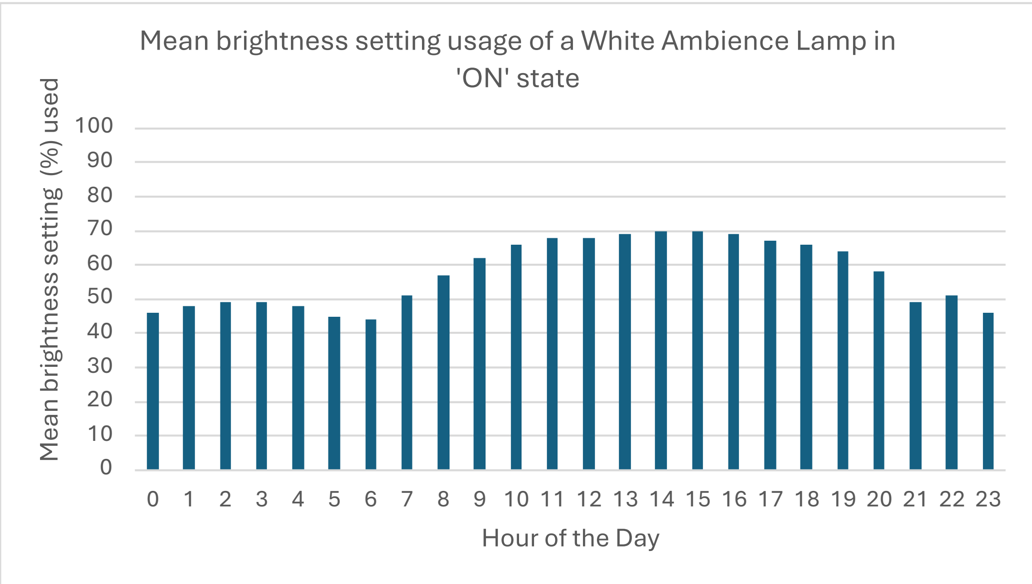
4. Results and Discussion

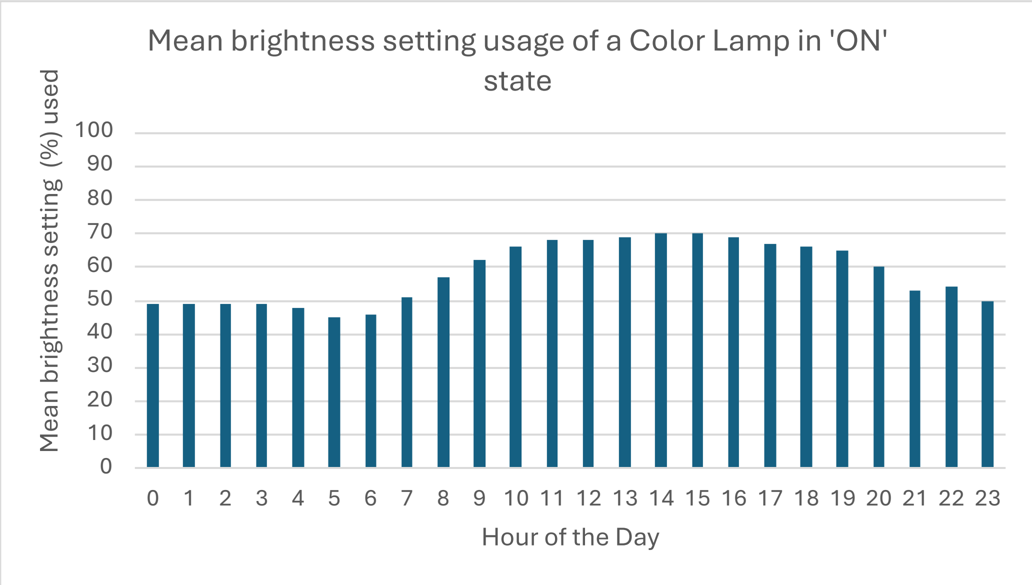
4.1 Versatility of Hue lamps usage

In the first part of this chapter, attention is given on how versatile a Philips Hue system is being used. The duration of lights being at a specific dim level for the three lamp families is presented in the graph below.

Figure 6: Mean brightness level in use as function of the hours in the day. In these three graphs it is presented for the white, white ambiance, and the white color ambiance lamps.

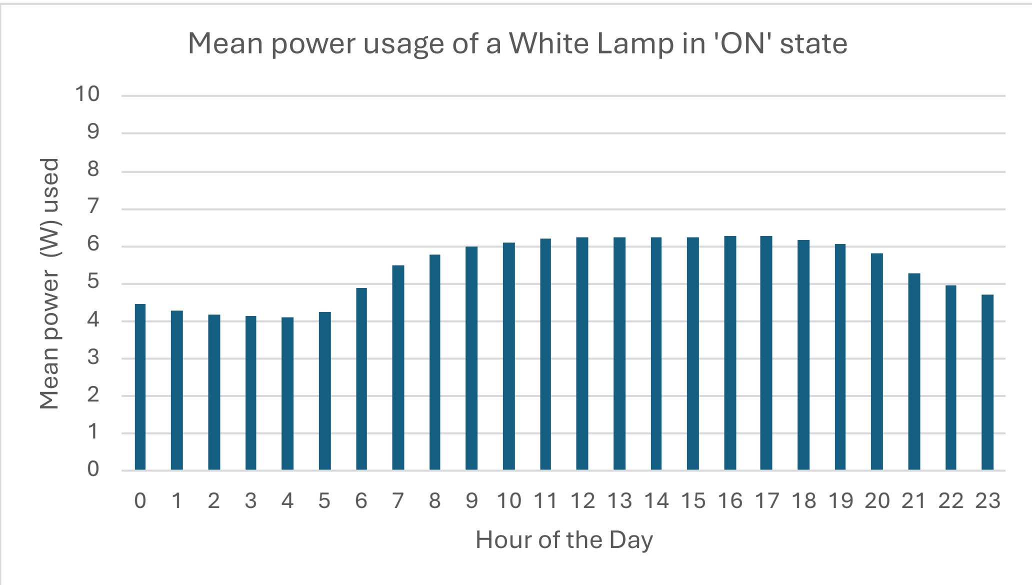


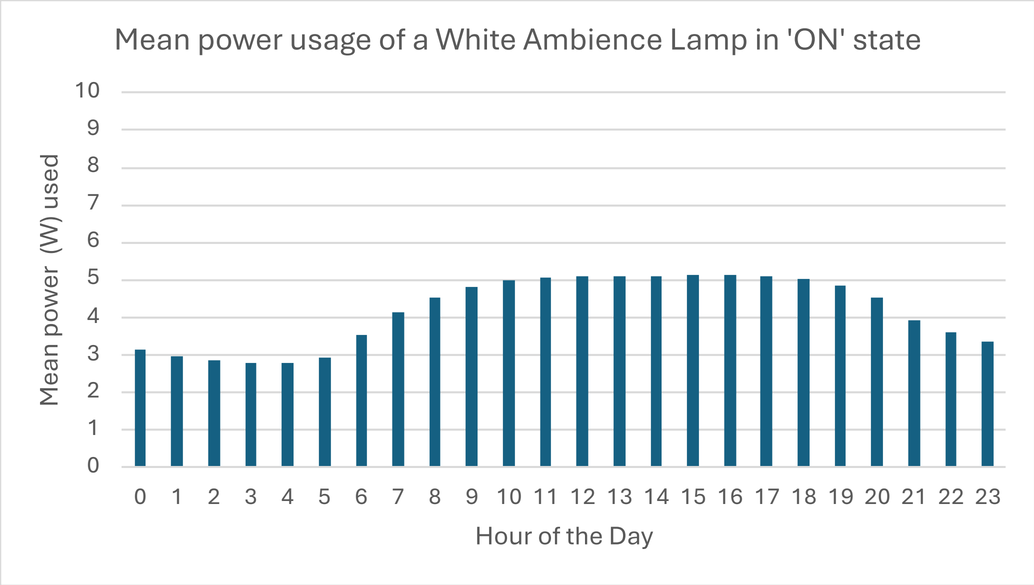


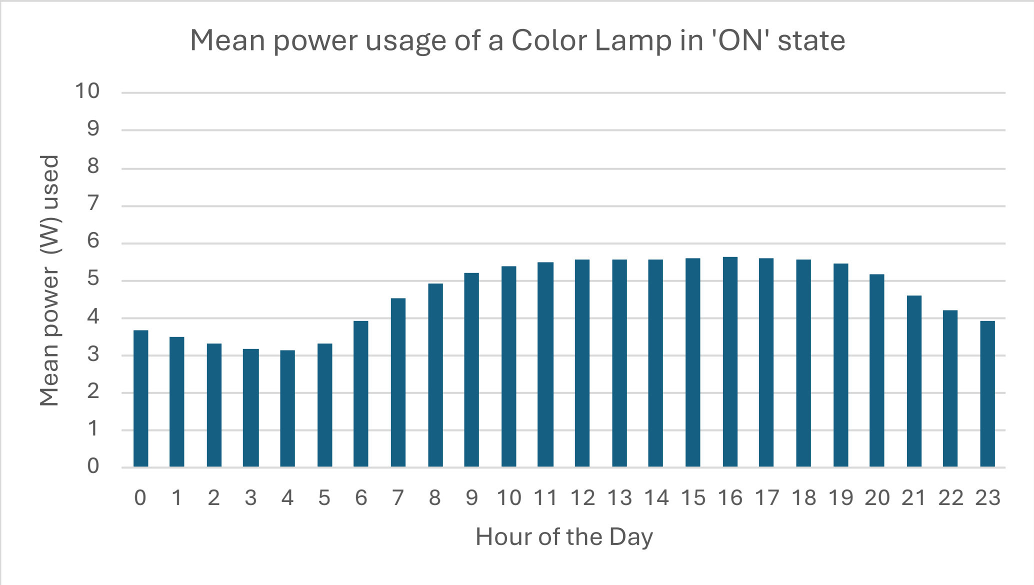


Clearly, consumers take advantage of using the dimming possibilities of connected lamps. This also results in an mean power consumption as can be seen in the next graph.

Figure 7: Mean power level in use as function of the hours in the day. In these three graphs it is presented for the white, white ambiance, and the white color ambiance lamps.

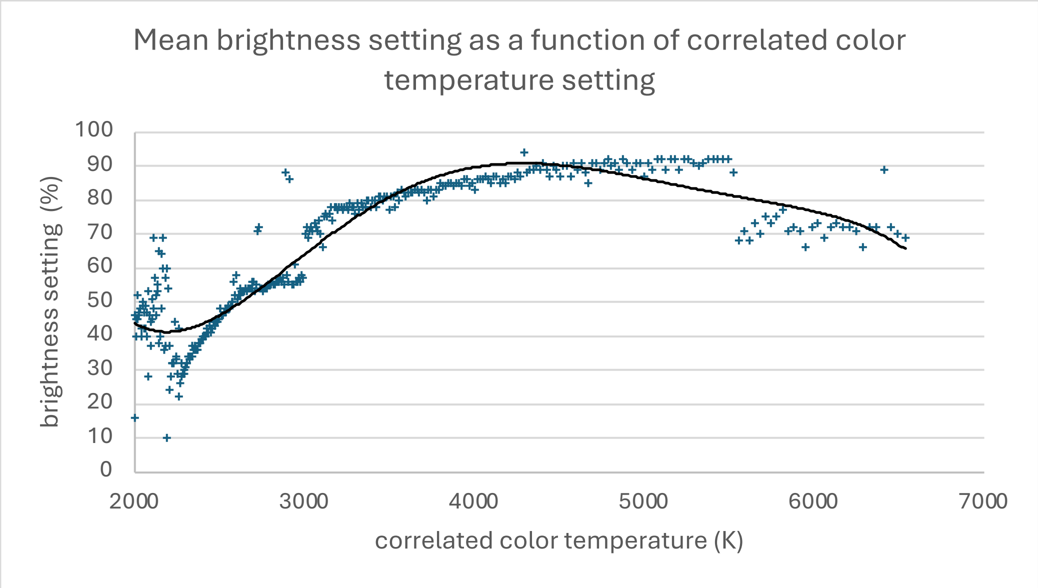



Mean power usage of a White Ambience Lamp in 'ON' state
Mean power (W) used
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the Day


Mean power usage of a Color Lamp in 'ON' state
Mean power (W) used
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the Day

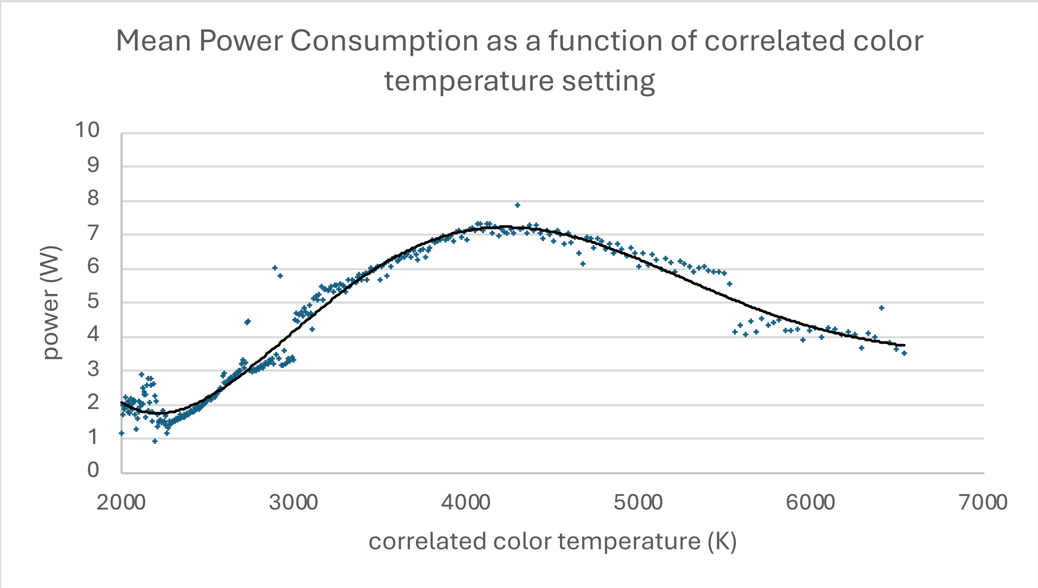
In addition, the consumer can control lamps with white ambiance capabilities the white tones. These white tones are commonly represented by the correlated color temperature. Typically, lights at lower correlated color temperatures come along with stronger dimming setting as can be seen in the graph below.

Figure 8: Mean brightness settings as a function of the correlated color temperature for the connected lamps with white ambiance capabilities in its on state.



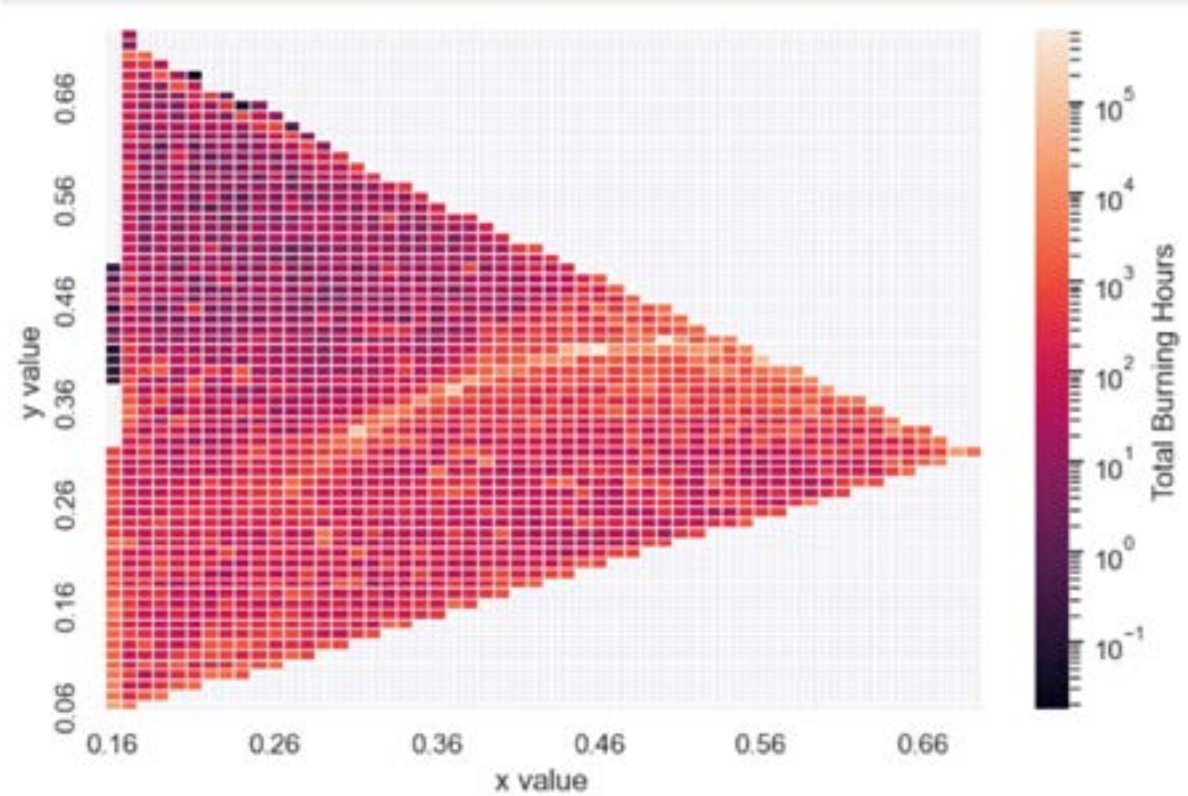
These different white tone settings also come along with their own specific conversion into power consumption as can presented in the next graph.

Figure 9: Mean power consumption values as a function of the correlated color temperature for the connected lamps with white ambiance capabilities in its on state.



Moreover, the lights with color capabilities can also be used in a more saturated color state. The frequency of usage is plotted in the x, y CIE chromaticity diagram in the graph below.

Figure 10: Total burning hours usage in a week as a heat map as function of light settings using the CIE chromaticity x, y coordinates.



Next to these differences in power consumption, it is observed that there are shorter burning hours of lights controlled by a motion sensor as opposed to lights being controlled by an on-off switch in similar conditions in the home (like in a hallway). This is attributed to the saved time in terms of burning hours. With motion sensors, we observe the lamps are burning for 75% of the time compared to such a regular usage.

4.2 Energy consumption results

In the table below, there is a summary of the actual mean energy consumption of connected lamps typically in a day.

Table 2: Measurement of mean power and energy consumption per day as measured in two periods in the year.

		on state		off state	
period of recording	9 W connected hue lamp types	mean power consumed per hour	mean duration in a day	mean power consumed per hour	mean energy consumption in the day
January 2022	White White Ambience White and Color Ambience	5.61 W 4.32 W 4.91 W	4.39 hrs 5.34 hrs 5.39 hrs	0.5 W 0.5 W 0.5 W	34.41 Wh 32.38 Wh 35.75 Wh
August 2022	White White Ambience White and Color Ambience	5.37 W 4.14 W 4.67 W	2.53 hrs 3.08 hrs 3.48 hrs	0.5 W 0.5 W 0.5 W	24.32 Wh 23.22 Wh 26.51 Wh

The daylight differences in winter and summer for Europe in having lights on are reflected in our observations. In comparing this with LED white lamps with comparable light performance, it indicates that the opportunities to have more freedom in light settings (like dimming) balances out the costs of standby power as can be seen in Table 3.

Table 3: The energy consumption of connected lamps compared with the energy consumption of an 8W & 9W non connected white lamp from reference group.

	on state		off state				
9 W connected hue lamp types	mean power consumed per hour	mean duration in a day	mean power consumed per hour	mean energy consumption in the day (9 W connected lamp)	non connected mean 'on state' duration	non connected energy consumption 8 W equivalent	non connected energy consumption 9 W equivalent
White White Ambience White and Color Ambience	5.37W 4.14W 4.67W	2.53hrs 3.08hrs 3.48hrs	0.5W 0.5W 0.5W	24.32 Wh 23.22 Wh 26.51 Wh	4.09 hrs 4.09 hrs 4.09 hrs	32.72 Wh 32.72 Wh 32.72 Wh	36.81 Wh 36.81 Wh 36.81 Wh

In table 3 we compared the actual measure power of the connected light in the study compared to a theoretical non-connected equivalent bulb with the same peak lumen output. For the purposes of comparison we include a theoretical product with the same peak lumen per watt performance (9W) and a theoretical non-connected products with a more efficient lumen per watt performance (8W).

Moreover, as observed, there is a tendency to use the connected lights for a shorter duration in the day in comparison to the duration observed for the control group (see chapter 3.3).

5. Conclusions

This study clearly indicates that the additional control possibilities of connected lights like Philips Hue significantly alter end user behaviour. The study demonstrates two changes which work to reduce the total energy consumption compared to equivalent non connected lights:

1. When the lamp is “on” and delivering light, its setting and hence power consumption varies and is on mean average using 41-56% of its maximum rated power depending on light capabilities.

2. Connected lights are “on” and delivering light for fewer hours in the day than their non-connected equivalents.

Further the study shows that the “standby power” that a connected lamp consumes when not delivering light is easily outweighed by the savings of the above effects even with conservative “standby power” values. The study showed mean average energy savings of 28-37% reduction when compared to an equivalent wattage non-connected light. Further efforts to reduce “standby power” will further increase the energy consumption benefits of connected.

As a result, the energy consumption of smart light usage tends to be comparable or more favourable in comparison to non-connected LED lights. The versatility in control outweighs the costs of energy for smart control.

Overall, the study provides valuable insights into the energy consumption of connected lights like Philips Hue, and highlights the benefits of smart control in terms of energy efficiency. Consumers can customize their lighting to fit their specific needs and preferences, while still maintaining a comparable or more favourable energy consumption than non-connected LED lights.