How do household lighting control systems compare economically and practically?

U5801459

Abstract

With increasing electricity prices, advancing technology and the desire for greater functionality in the home, it is useful to consider the available ready-made lighting control systems. To do this three lighting control systems for residential use are compared using a typical Canberra household as a case study. These systems can be retrofitted into existing dwellings and are controlled by programmed settings, motion and manual adjustment. The focus will be on determining long term cost savings and efficiencies as well as considering implementation practicalities and environmental issues. The three systems compared are Philips Hue bulbs – networked smart colour changing bulbs, Lutron – networked dimmer switches replacing existing switches and INSTEON – dual mesh technology networking both switches and bulbs. The conclusion of the research is that none of the systems are economical in both the long and short term when evaluated against the existing system. Although the Lutron system has the lowest running costs of the three, due to its high implementation cost, the Philips Hue system is recommended to the homeowner as it is the most easily implemented without requiring professional electricians and can even be installed gradually in stages.

Contents

Provides an overview of the three systems – Philips Hue, Lutron, INSTEON - mentioning the final recommendation that none of the systems are cost effective compared to the existing system and their benefit came in functionality rather than cost. While Lutron had the lowest running costs Philips Hue is the most easy to implement.

Sets the portfolio into a world with climate change, further showing that literature has demonstrated energy savings and improvements in the quality of life with automated lighting. Automated lighting benefits are great for certain socially and culturally disadvantaged groups. The scope of the portfolio is clarified by creating a specific but meaningful research question and the analysis is placed on the spectrum of qualitative and quantitative research.

Demonstrates the underlying phenomena and drivers of price change which influence the analysis for coming decades. These trends include computing power (Moore's law), electricity price, electricity use, component cost and inflation. To confidently quantify these trends a number of data analysis techniques are used: Linear regression, Confidence intervals, Error types, Data organisation, Descriptive statistics and Population hypothesis testing.

Supplies the necessary metrics for further analysis in terms of component quantity and cost. Assumptions for further research are listed in terms of trends for electricity, power use and component replacement cost.

Examines the practicality of implementation for the three systems. This is done by using planning approaches and Gantt Charts to compare installation time and complexity. Similarly, the safety and risk of each implementation procedure is examined to determine what changes need to be made to reduce risks to an acceptable level and the corresponding cost this will entail.

Contemplates environmental considerations of energy efficiency to gain a holistic idea of emissions of the systems. Embodied energy is used to determine the energy required to manufacture each component and is calculated for an LED light and estimated for the other components, indicating energy needed to create each system.

Determines the energy use of each system not only demonstrating inefficiencies but also providing the consumption figure which can be used in evaluating running costs. An adapted energy-mass balance provides the energy usage of each component which can be used to determine energy efficiency with Sankey Diagrams.

Combines multiple stages of the analysis to determine life-cycle costs, namely implementation and running costs, which culminate in a payback period projection using both the costings and the price trends.

Discusses the chosen system in the context of society and suggests that a different case study might have resulted in a different conclusion. Lutron has the lowest running costs while Philips Hue system has the possible benefit of gradual expansion reducing up-front cost. While acknowledging that all solutions provide an improvement in functionality they are uneconomical and consideration should be given to the priorities of the home-owner.

An alphabetical Harvard reference list of journal articles, books and reliable online resources provides the evidence to support the arguments and gives the reader confidence in the conclusions drawn. Further, many sources from manufacturer specifications support the statistics used in the report providing assurance in the numerical analysis.

Introduction and Context

With 19% of the world's energy used for lighting and 6% of the world's greenhouse emissions produced as a consequence, in addition to rising electricity prices, improving lighting efficiency is in the homeowner's best interest. (Bahga & Madisetti 2014) Rapid advancements in technology have resulted in widely available home lighting automation systems that can be retrofitted into existing dwellings. It has been found that lighting automation and smart control has huge benefits increasing efficiency in the order of 40% to 60%. (Galasiu & Newsham 2009) (Enscoe & Rubinstein 2010)

In addition to the environmental and monetary benefits of improved efficiency, lighting control systems also improve the quality of life for the home user. (Brandt 2011) Lights can be programmed to adjust brightness for reading at night, turn on or off at certain times or be controlled by an individual's location, detecting the position of their smartphone. (Bellido-Outeirino2012) Another benefit of controlled lighting is that it can detect problems such as short circuits and turn itself off. Furthermore, lights can be programmed to give the appearance of occupancy, turning on and off appropriately, when in reality the homeowner can be on holiday. (Chiogna 2011) Thus, the benefits of smart lighting are wide-ranging and can be summarised in a few words: *comfort and convenience, aesthetics and ambience, safety and security and energy savings and energy management.*

A significant reason to examine lighting automation is that it has benefit for some of the most disadvantaged groups of our society. The disabled and mobility impaired may have difficulty using physical light switches. From their perspective turning on or off lights may be a difficult and trying task. Thus, motion sensing lighting or lighting that has been pre-programmed are beneficial. Further, for an individual confined to bed, being able to use a remote to alter the lighting makes a small but significant difference in the quality of life. (Brandt 2011)

The analysis in the portfolio will be focused on determining the best smart lighting approach to use when retrofitting a home, against the rubric of feasibility and cost. Of particular interest will be initial cost and lifetime upkeep costs versus cost savings driven by increased efficiency. Functionality, useability and practical considerations will also be studied. Rather than determining the benefits of a smart lighting the focus will be on the possibility of implementation. The client used as the case study in this work is a three member family in a typical semi-rural Canberra home with standard lighting and occupancy patterns.

To limit the scope of the analysis an appropriate research question was devised to provide the portfolio title. This approach increases the prospects of the research logically progressing to a non-simplistic meaningful conclusion (SUNY Empire State College 2016). Applying the methodology to the specific problem, it is recognised that the overarching theme is improving technological automation in an age of rapidly advancing computers. The topic is autonomous lighting control systems for residential dwellings. The focus is on comparing feasibility of available lighting control products with a focus on economic and practical feasibility. This leads to the final question (see figure 1).

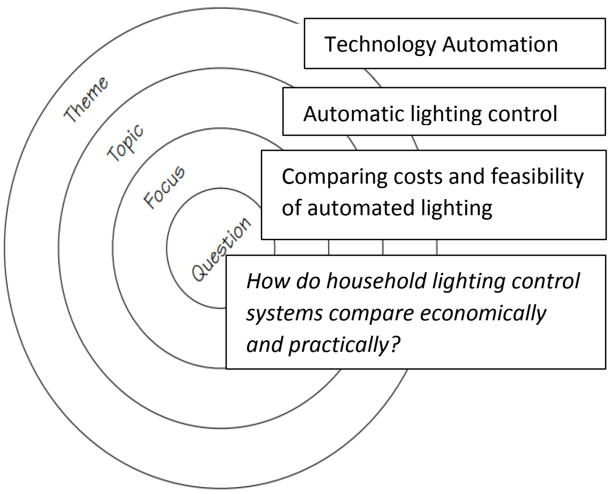

Figure 1: Crafting a Research Question

The analysis entailed in this document primarily falls into the quantitative discipline due to the focus on lifetime cost and its relation to efficiency improvements. (Denscombe 2014) The numerical nature of the data allows for impartial mathematical analysis. However when considering the results provided by the quantitative methods some qualitative judgements must be made to draw more meaningful conclusions from the analysis. Thus, while the methodologies are primarily numerical it is the quantitative judgements that help answer the research question. (Creswell 2014)

Of the readily available lighting automation systems that can be retrofitted into an existing residential dwelling there are two primary categories. (Byun & Park 2001) One approach is to replace the bulbs with network enabled LEDs (Light Emitting Diodes) which can be programed and controlled. This approach is represented by the Philips Hue system. The other major approach is instead to replace all the wall switches with networked switches which can be operated by a program. This technique is represented by the Lutron system. Both approaches have trade-offs and the final INSTEON system is used to determine if a combination of replacing switches and bulbs has greater benefits.

Background Trends

The background trends of several factors become significant due to the analysis of cost potentially spanning more than a decade. Variables such as electricity price, computing power and cost of components can vary significantly. (Commonwealth of Australia: Department of Industry, Innovation and Science 2016) This leads to the necessity of attempting to predict how each of the factors will change over time - the accuracy of this prediction has a direct impact on the quality of the analysis.

One of the rapidly changing factors over the past decade is technological advancement. Computing power has increased exponentially, continuously doubling. This has led to the price for the same computing power falling with time, leading to an increase in consumption. Now computer chips and smart devices are an integral part of daily life. This phenomenon has been dubbed 'Moore's Law'. Recently the trend of Moore's Law has reached a stage where technology has provided the space for increasing automation in the home. Home lighting control systems are growing in functionality and hence popularity. They can take information from a variety of inputs including: motion, heat, noise and sunlight sensors; along with preprogramed time settings and manual user input, they control house lights to specific brightness and even colour. (Byun et al. 2013) From Moore's Law it is clear that this trend of increasing household automation is likely to continue as computer hardware prices continue to fall and capabilities continue to increase. (Snoonian & Bowen 2005)

Electricity costs in Australia have increased despite improvements in production technology. This trend is driven by several factors. Ageing infrastructure (poles and wire and some of the power plants themselves) means more maintenance costs. Labour costs particularly with specialist contractors are rising. There is a long term increase in cost of raw materials such as coal and gas, despite the recent downturn due to the financial crisis and overproduction holding costs in check. Furthermore, more environmentally friendly energy sources such as solar and wind have raised energy prices as they are still not fully competitive in terms of cost efficiency. (Shu & Hyndman 2011)

To quantify the trends in increased electricity price and decreased technology prices and use this to estimate prices for the future, simple linear regression is used to fit a line to the data. Simple linear regression examines the statistical relationship between an independent and dependent variable. The regression can show the trend of several data points and determine if the trend is increasing or decreasing and at what rate. It can also give an indication of how well the trend can be approximated by a linear equation with the R^2 value. The ideal value is 1 while under 1 is under-fitted and over 1 is over-fitting the model to the data. (Morrison 2014)

Plotting the percentage increase in the cost of household electricity over the years from 1990 to 2014 shows an increasing exponential trend of about 5 percent a year (adjusted for inflation), (see figure 2). The exponential trend is used rather than the linear model as over longer periods greater than a decade the linear model becomes increasingly inaccurate. This is demonstrated with the difference of R^2 values which was 0.95 for the exponential and 1.32 for the linear trend line. The Lower and Upper lines around the trend line provide the 95% confidence interval for the trend. (Tushar-Mehta 2012) This shows that there is only minor uncertainty for the overall trend and with the extended length of time, lends confidence in using the trend for analysis into future decades.

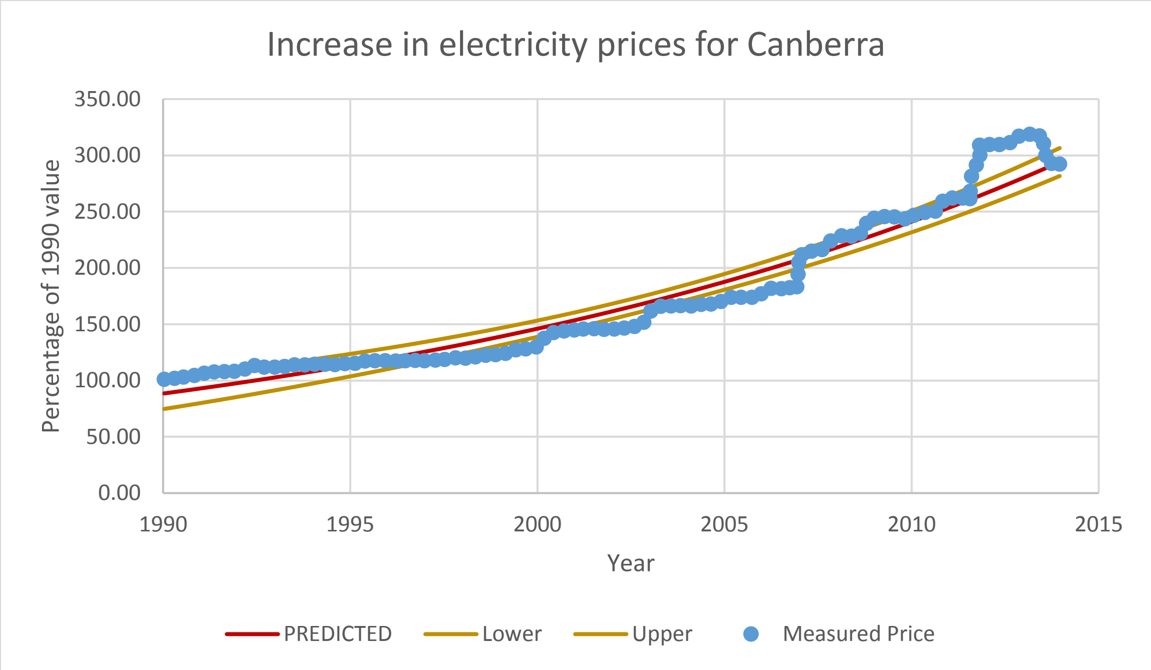

Figure 2: Trend in Canberra electricity price with confidence interval (Australian Bureau of Statistics 2014)

The data shows that residential electricity prices in Australia are trending up rapidly. The 5% annual increase is significant, especially considering it is in addition to long term inflation of 2-3% annually. This increasing energy price is also higher than average wage growth meaning that a greater portion of household income is spent on power bills. (Australian Bureau of Statistics 2011) (Australian Bureau of Statistics 2012) This means that there is greater reason for improving the efficiency of lighting which comprises about 11% of home electricity use. (Tompros et al. 2009) Thus the effect of increasing electricity cost must be taken into account in efficiency cost calculations. As the base cost of yearly power is not constant but instead increasing, a fixed percentage cost saving would save increasing amounts of capital over time. This would also shorten the payback period significantly if the trend is assumed to continue over the long term.

Another trend that can be examined is household electricity consumption. Plotting daily kWh power use for each quarter since 2004 for the case study home suggests whether consumption will remain constant or change over time. The initial indication with a linear trend line is that consumption is decreasing at 1.22 kWh/year. However an examination of the variables behind electricity use show that much more power was used in the drought years with irrigation pumps. In the recent years less pumping is necessary due to more rain. Also other factors including replacing an electric stove with gas and better insulation reducing winter heating costs exaggerate the trend. This is an example of coverage error; with different electricity consumption in different years due to different factors, the data should not simply be directly compared.

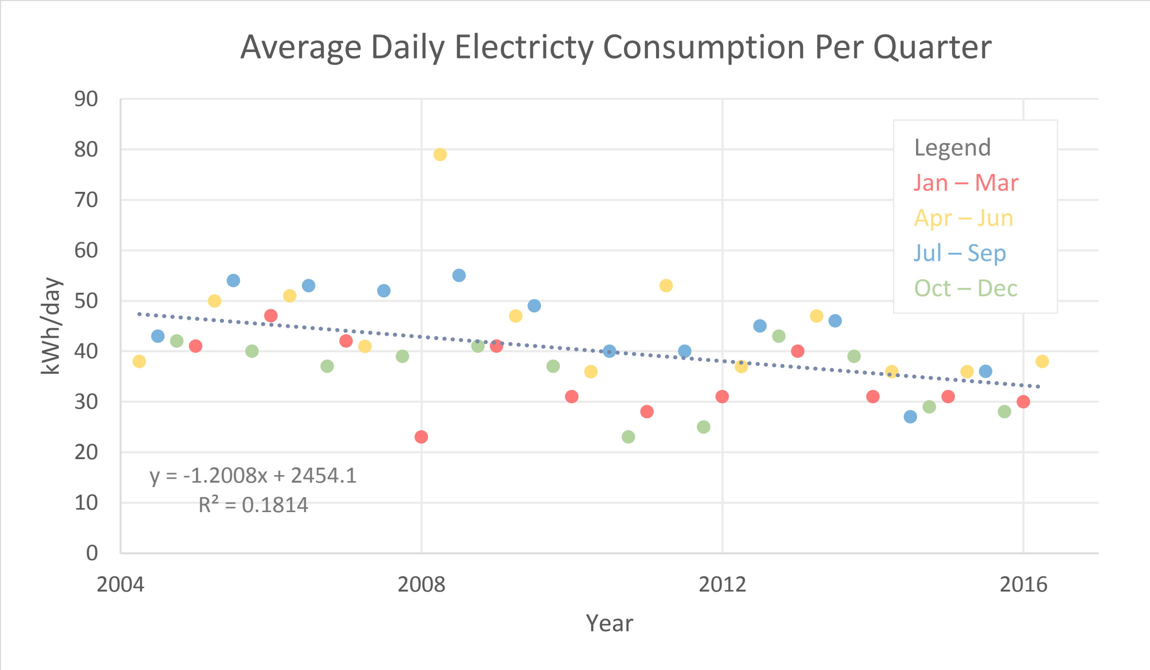

Figure 3: Case study electricity quarterly consumption with trend and seasonal differentiation

Processing errors can also appear in the organisation of data into the spread sheet. To reduce this risk different methods were used. The first was to directly enter the data from newest to oldest from the electricity bills. The other was to independently calculate the data using the quarterly consumption divided by the number of days in the billing period working from oldest to newest. Discrepancies were then checked by taking the difference and any discrepancies greater than 0.1 were checked. This method greatly reduced the possibility of error from data being out of order or error of the value itself. This is especially important as it is necessary to have confidence in the data even with variance and significant outliers.

A statistical examination of the dataset also provide some clues. The data shows a strong central tendency with the mean, mode and median all falling between 39 and 41. However the data does have a certain spread. The range is high but is a bad measure due to the high outlier. The standard deviation is a better indicator and is significant at 10. Further the spread can be seen in the quartiles plot (figure 5). Nevertheless while the variance is high, seasonal and periodic fluctuations tend to cancel out and the data can be treated as approximately falling under a normal distribution leaving the true error in the mean with a sample size of 49 at 1.43. Thus due to central tendency and the uncertainty and unpredictability of the trend the consumption is taken as a constant 40kwh/day for further analysis.

Figure 4: Descriptive statistics

Samples	49
Mean	40.1808
Mode (closest integer)	41
Median	39.61
Min	22.86
Max	78.63
Range	55.77
Standard deviation	10.0033
Error in the mean	1.43

The average daily kWh usage is well above standard for the family size and geographic location. To determine if this is statistically significant due to the large standard deviation hypothesis testing of the population was used.

Null hypothesis: there is no statistically significant difference between means of case study and population

Hypothesis: case study uses more electricity than other households of similar size

$$t = \frac{\breve{x} - \mu_o}{\frac{s}{\sqrt{n}}} = \frac{40.18 - 25}{\frac{10.00}{\sqrt{49}}} = 10.626$$

$\breve{x} = sample\ mean \qquad \mu_o = hypothesised\ population\ mean$

$s = sample\ standard\ deviation \qquad n = sample\ size$

$\text{P value} = 0.00000009$

Due to the very small P value the null hypothesis can be firmly rejected. The conclusion is that the case study usage is higher than a typical home with statistically high certainty. The reason for this is partly due to the irrigation which not only causes higher variance but also higher overall consumption. Also on careful analysis of peak and off-peak usage a large inefficient old hot water boiler is found to substantially contribute to the high consumption. A measure of 10% of household electricity used for lighting is standard. (Sustainable Victoria 2016) For a typical household this would yield 2kWh/day while for the case study it would yield 4kWh/day. While 4kWh is too high due to the other unrelated factors increasing total electricity consumption using 2kWh would ignore the overall higher case-study consumption. Therefore, an average 3kWh/day is used for later calculations.

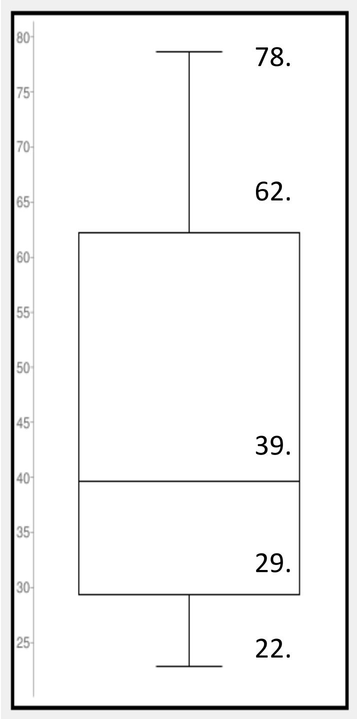

Figure 5: Quartile plot of electricity consumption for case study

Another trend which bears some influence is the trend in replacement component prices for lights. LED prices show an exponentially decreasing trend which appears linear when plotted on an exponential axis. (figure 6) Care should be taken due to shorter time period; coverage error could be present not picking up long term fluctuations with the small data set. It appears that the trend is stabilising at a reasonable value which from the data appears to be $9 US dollars. This is logical, for while manufacturing cost may decrease, transportation and retail cost are unlikely to substantially change. Nevertheless it is safe to conclude that replacement cost of components is unlikely to increase and this assumption is used in future analysis. (US Energy Information Administration 2014)

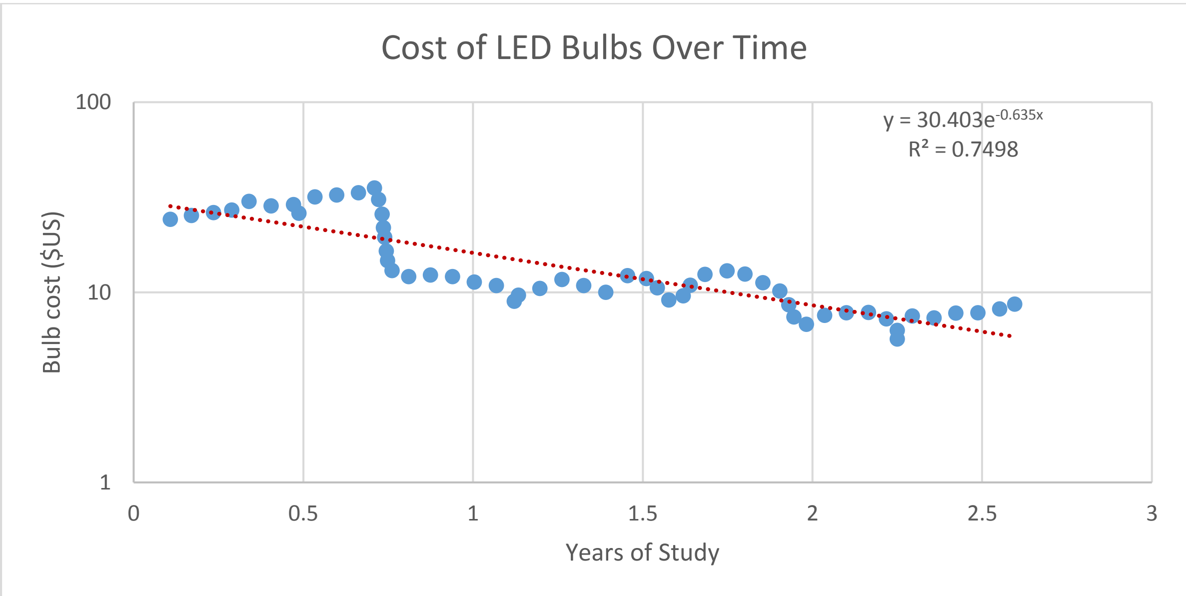

Figure 6: LED bulb cost lighting trend in US dollars on an exponential axis (Brian et al. 2014)

Specifications

The analysis has a focus on cost and for the results to be meaningful it is necessary to determine a baseline on which the comparisons can be based. Thus, all analysis in the portfolio conforms to the following assumptions:

- Residential Canberra family home - 30 lights (including lamps), 25 switches (from case study)
- Analysis commencing 2016 with inflation of 3% per annum (Trading Economics 2016)
- Wage growth similar to inflation 2 – 3% per annum (Australian Bureau of Statistics 2011)
- Electricity price increasing 5% more than inflation per annum; yielding exponential trend
- Electricity usage requirements for lights constant over time for all systems compared
- Current electricity usage for lights 3kWh/day
- Cost of replacing components including LEDs constant with adjustment for inflation
- Standard LED bulbs will be 10 Watts full brightness unless otherwise specified
- A minimum of 10 motion detectors will be present for all systems

The three systems being examined are the Philips Hue, Lutron and INSTEON lighting control systems. (figure 7) The Philips Hue lighting system replaces existing bulbs with wireless connected colour changing bulbs which can be controlled by switches, phone, motion and pre-programmed settings. (Philips 2016a) The Lutron system works by replacing the existing light switches with wireless connected dimmer switches that can similarly be controlled either directly, wirelessly or with motion sensors. (Lutron 2016a) Finally, the INSTEON system works by using dual mesh technology combining both replacing dimmer switches and replacing some lights, all of which can be controlled similarly to the other two systems. (INSTEON 2016a) All systems have a central bridge or hub which, when connected to a router, acts as a hub between the internet and Wi-Fi phone control and the separate network of lights and switches.

The Philips Hue system has the advantage of multiple colours and easy self-installation but is expensive for the components. The Lutron system has more complex implementation needing to replace wall switches and change wiring, but then has the advantage of having multiple switches in addition to remote control, as well as cheaper replacement of lights. INSTEON has the advantage of combined technology for convenience, offset by more complex installation and higher cost as well as having more potential for problems.

Figure 7: Component cost for the three lighting control systems

Philips Hue (Philips 2016f) (Apple 2016) (Officeworks 2016)		**Lutron** (Amazon 2016) (Reduto 2016)		**INSTEON** (SmartHome 2016) (Nodal Australia)	
Component	Price (for 1)	Component	Price (for 1)	Component	Price (for 1)
1 Bridge	$60	1 Bridge	$80	1 Bridge	$65
30 Smart Lights	$50	30 LEDs	$10	20 Smart Lights	$30
8 dimmers	$25	25 dimmers	$55	10 LEDs	$10
6 tap switches	$50	10 motion sensors	$20	20 dimmers	$50
10 motion sensors	$40	2 roof motion sensors	$55	10 motion sensors	$35
Total	$2460	Total	$2065	Total	$2115

Implementation

There are two aspects to be considered in terms of the feasibility and practicality of implementation. The first is how long will the practical implementation take, how difficult is it and are any special tools or skills needed leading to any additional costs? The second consideration is safety: both during implementation and in minimising long term risk.

Planning approaches and Gantt charts are useful to determine how long a sequence of events will take and how to optimise this use of time and consequently are a vital tool for project planning. In this context the Gantt charts are used to compare the total installation time and gain insight into three lighting systems (figure 8). The red line shows the critical path for each of the systems and is 8 hours, 9 hours and 11 hours for the Philips Hue, Lutron and INSTEON systems respectively.

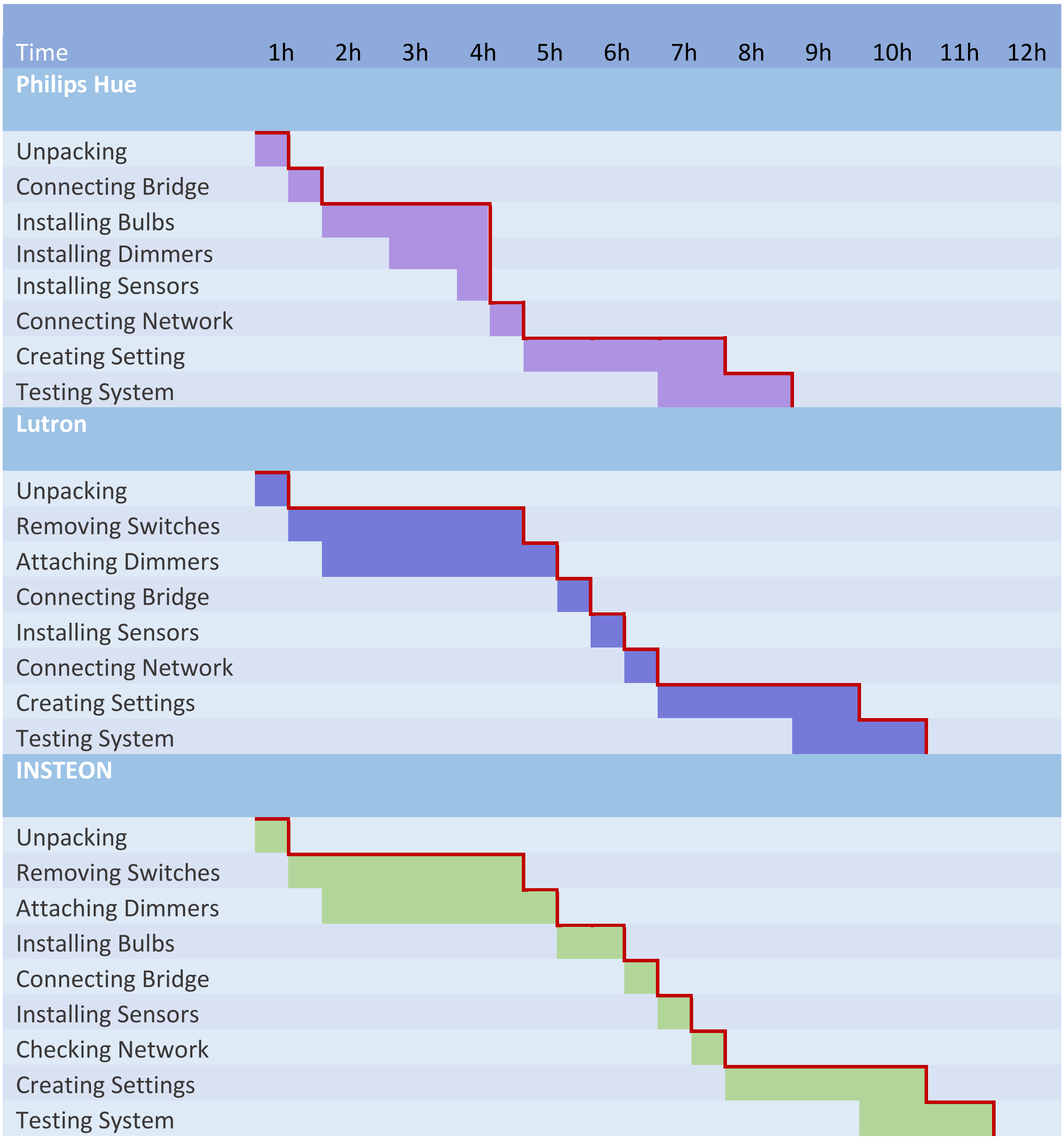

Figure 8: Implementation time for each system in hours

Interestingly, despite the added complexity of the INSTEON system which combines both wireless lighting control and wireless controlled dimmer switches, the critical path time is only 3 hours more than for the Philips Hue and 2 hours more than for the Lutron. Also it is now clear that the most significant activities in terms of time are removing switches and attaching dimmers as well as creating pre-programmed settings. While settings can be created by the homeowner, removal and replacement of switches may require a qualified electrician who may bill in part by the number of hours worked. This becomes both a safety and a cost concern.

The two broad risks and safety considerations for the systems are the safety of people and the risk of system damage. For both these cases this can be further broken down into safety and risk during installation and over the lifetime use of the system. A risk matrix was used to determine the types of risk for each system and their relative severity. (Glendon, Clarke, & McKenna 2006)

Figure 9: Risk matrix for the three systems plotting risks against likelihood and severity

	Risk Severity			
	Negligible	**Marginal**	**Critical**	**Catastrophic**
Certain				
Likely				
Possible	Broken bulb during installation (All systems)	Short circuit during installation or during use resulting in damage (All systems)	Electrocution during installation (Lutron and INSTEON)	
Unlikely			Electrocution during installation (Philips Hue)	
Rare				Electrical Fire (All Systems)

Making a number of alterations to the installation procedure will minimise the severity and reduce the likelihood of the risks, increasing personal and system safety. To minimise the risk of breaking bulbs and shattering glass, care should be taken during unpacking and children and pets should be kept out of the house during the process (minimising the risk by isolation). Also wearing protective gear such as covered shoes minimises the severity of risk. To reduce the likelihood of short circuit during installation and electrocution, power should be switched off (eliminating the risk) while reducing the risk in the long run can be achieved by engineering controls of reducing the fuse value if appropriate. Use of an electrician to install dimmer switches means reduced risk of electrocution for both the more experienced installer and later homeowner when power is turned on. Electrical fire can be minimised by checking all wiring is done correctly by an electrician substituting the risk and installing smoke alarms as engineering controls. Thus all the risks have been minimised or eliminated, particularly those with the greatest severity.

Due to safety considerations and despite the cost an electrician is necessary for both the Lutron and INSTEON systems. This cost could be roughly estimated by the time to replace the switches; the estimate is $800 for the Lutron system and slightly less for the INSTEON system $700 due to there being less switches, but still the same call out fee. (Homewyse 2016)

Environmental Considerations

In all the lighting systems the environmental impact of the initial production must be compared with the energy savings and reduced emissions over the lifetime of the product. The standard LED is a direct component in the Lutron and INSTEON systems and the core of the more advanced INSTEON and Philips Hue bulbs; LED energy production cost is compared to the lifetime energy use. Embodied energy which constitutes the sum of all the energy required to produce the item is used to estimate production cost. As energy inputs correlate strongly with greenhouse emissions, comparing embodied energy to lifetime energy savings shows the total energy savings or loss.

The material embodied energy for the bulb of 14.14MJ (figure 10) is fairly close to the 15.59MJ embodied energy from literature. With the addition of a complex machining and assembly process, it rises to 60MJ and packaging brings it to 130MJ; with an additional 1.6MJ for transportation the total is 132 MJ. However this is still fairly insignificant compared to total lighting energy usage of 1760MJ with the 95% confidence interval ranging from 1660MJ to 2120MJ. This value is much less than incandescent (15100MJ) and compact fluorescent (3950MJ) (bulbs adjusted for differing lifetimes) suggesting that overall the LED is the most environmentally friendly bulb type despite a higher manufacturing cost than Incandescent (42.2MJ). (Navigant Consulting 2012)

Figure 10: Material embodied energy of an LED (Navigant Consulting 2012)

NAME	MATERIAL	MASS (G)	EMBODIED ENERGY (MJ)
GLASS BULB	Glass	10.7	0.13589
CONNECTORS	Gold plated copper	0.5	0.05
ARRAY (9 LEDS)		1.5	0.810
LOCAL HEAT SINK RING	Aluminium	5.7	0.969
HEAT SINK OUTER CONE	Aluminium	18.1	3.007
INNER HEAT SINK CYLINDER	Aluminium	13.1	2.227
EDISON BASE INSULATOR	Acrylic, polycarbonate	4.2	0.378
INNER INSULATOR	Acrylic, polycarbonate	6.6	0.594
PRINTED CIRCUIT BOARD		10.2	5.508
EDISON BASE AND LEADS	Tin, plated steel	12.2	0.4636
TOTAL		**82.7**	**14.14**

The embodied energy for each system in terms of manufacturing is roughly estimated. The rule of thumb that the embodied energy for an electronic product containing circuitry is 12 times the embodied energy of its mass in fossil fuels. This results in a figure of 540MJ/kg which is used for all components except for the lights. (Ciceri, Gutowski, Garetti 2010) For the LEDs the figure of 130MJ calculated above is used and scaled for smart lights which have more weight and circuitry (figure 11).

Figure 11: Total embodied energy for each system

Component	Weight	Quantity	Energy/Item	Embodied Energy
Philips Hue				
Bridge (Philips 2016a)	235g	1	130MJ	130MJ
Smart lights (Philips 2016d)	180g	30	200MJ	6000MJ
Motion sensor (Philips 2016c)	82g	10	40MJ	400MJ
Tap switch (Philips 2016b)	90g	6	50MJ	300MJ
Dimmer (Philips 2016e)	70g	8	40MJ	320MJ
TOTAL				7150MJ

Lutron				
Bridge (Lutron 2016a)	272g	1	150MJ	150MJ
Lights basic (Navigant Consulting 2012)	80g	30	130MJ	3900MJ
Motion sensors (Lutron 2016c)	80g	10	40MJ	400MJ
Motion sensor roof (Lutron 2016d)	250g	2	140MJ	280MJ
Dimmer switches (Lutron 2016a)	113g	25	60MJ	1500MJ
TOTAL				6230MJ
INSTEON				
Bridge (INSTEON 2016a)	142g	1	80MJ	80MJ
Lights basic (Navigant Consulting 2012)	80g	10	130MJ	1300MJ
Smart lights (INSTEON 2016c)	176g	20	200MJ	4000MJ
Motion sensors (INSTEON 2016d)	114g	10	60MJ	600MJ
Dimmers (INSTEON 2016b)	60g	20	30MJ	600MJ
TOTAL				6580MJ

The result has a very high error due to not taking into account different materials and less complexity in certain components such as dimmers when compared to bridges. Nevertheless the calculation gives an estimate which suggests that all the systems are approximately similar in environmental energy impact and the most harmful components to manufacture are the lights which in all systems make up the majority of the total: 84%, 63% and 81% for Philips Hue, Lutron and INSTEON systems respectively.

Energy Usage

Each of the systems is fairly complex with multiple components drawing varying amounts of power for differing periods of time (figure 12). To untangle this mess of energy flows and build up a figure for total energy use for each of the systems the techniques of energy mass balance and Sankey diagrams are used. The power usage of the motion sensors are not included as they run off batteries which are specified by the manufacturers to last in excess of a decade. (Steiner, Blakeley & Miller 2014)

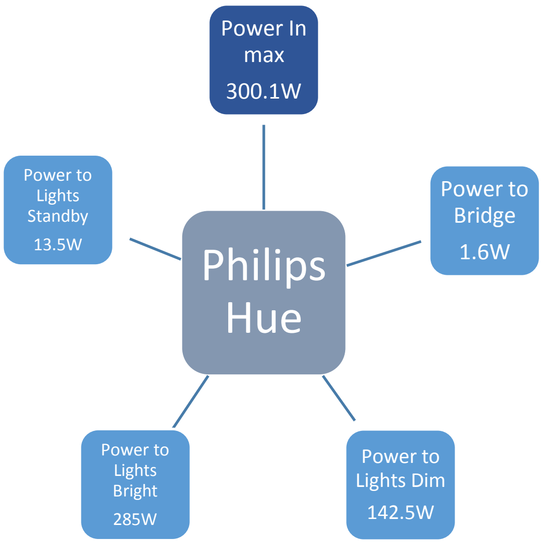

Figure 13: Energy balance for the Philips Hue system

Figure 12: Energy usage for components of each system

Philip Hue (Philips 2016a) (Philips 2016d)	
Bridge	1.6W
Bulbs Standby	0.45W * 30
Bulbs Bright	9.5W * 30
Bulbs Dim	4.75W * 30
Lutron (Lutron 2016a) (Lutron 2016b)	
Bridge	1.3W
Switch	0.5W * 25
Bulbs Bright	10W * 30
Bulbs Dim	5W * 30
INSTEON (INSTEON 2016a) (INSTEON 2016b) (INSTEON 2016c)	
Bridge	1.5W
Lights Standby	0.5W * 10
Switches Standby	0.75W * 25
Wireless Bright	8W * 20
Wall Bright	10W * 10
Wireless Dimmed	4W * 20
Wall Dimmed	5W * 10

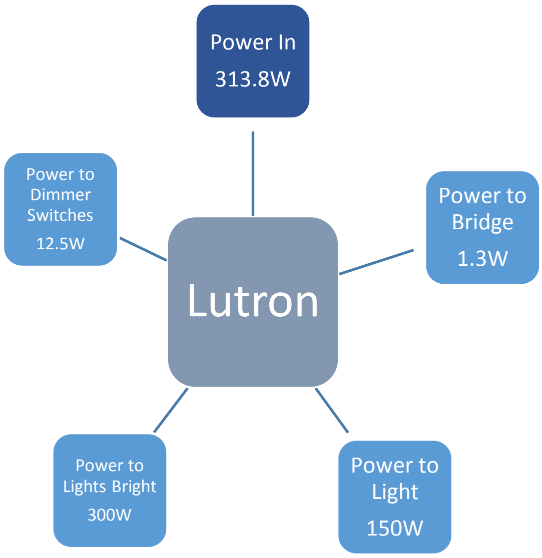

Figure 14: Energy balance for the Lutron system

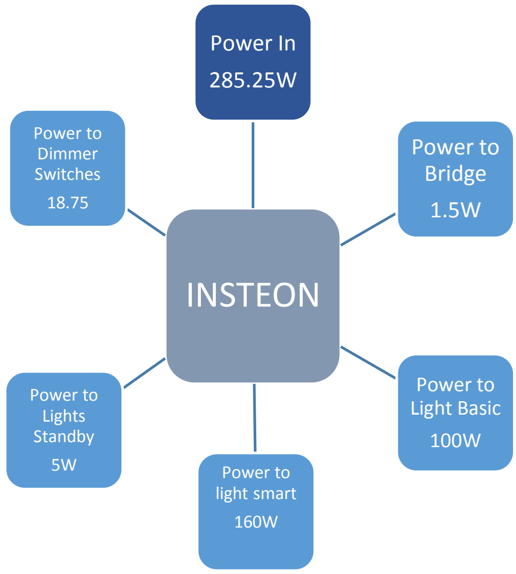

Figure 15: Energy balance for the INSTEON system

From the energy balance diagrams it is clear that the maximum power usage varies between 285.25W for the INSTEON system (figure 15) to 300.1W for the Philips Hue system (figure 13) and 313.8W for the Lutron system (figure 14). However maximum power use is not a good indicator as it assumes that all house lights are on and are at full power. Instead a more useful measure for analysis is to reinterpret these figures into power use per day. Assumptions must be made of use for the bulbs in both bright and dim settings as an average. The figure of 2 hours use on average per light was arrived at. This is because certain lights might only be used for a few minutes each day while others are used for over 8 hours. Literature also suggested a value of 3 hours but due to the number of lamps used for short times in the case study, this was too high. (Sustainable Victoria 2016)

Sankey Diagrams are a good way of determining how to optimise design and see how usage of various components relate. The graphical size of their paths are related to the numerical size of the quantity being represented. For each of the systems the energy consumption over the period of a day is broken down into components of use. The first division is into baseline power consumption which remains constant over the course of the day and power use by the lights when they are on. Baseline power consumption consists of the bridge and also having lights or switches on standby and communicating with the network waiting for commands. The lighting power consumption is also broken up into lights at full power or lights, dimmed by 50%, a common dimming metric. (Tompros 2009) (Doulos & Tsangrassoulis & Topalis 2008)

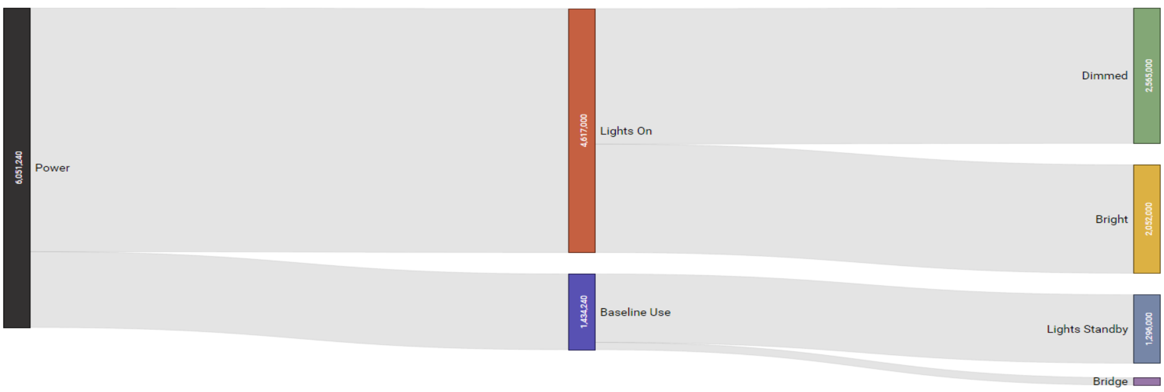

Figure 16: Sankey diagram in joules for energy usage for a day of operation for the Philips Hue system

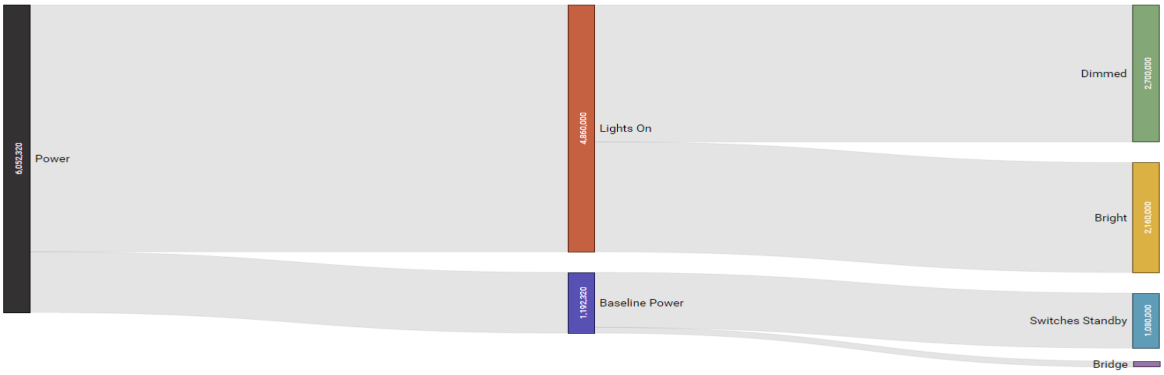

Figure 17: Sankey diagram in joules for energy usage for a day of operation for the Lutron system

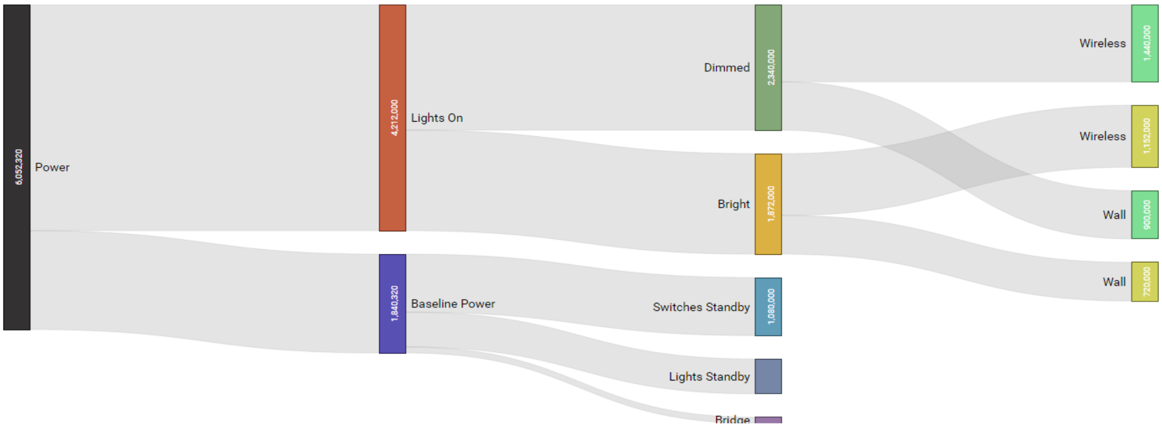

Figure 18: Sankey diagram in joules for energy usage for a day of operation for the INSTEON system

Comparison of sizes of total power flows shows that all three systems use a similar number of Joules for each day of operation: Hue 6051240 (figure 16), Lutron 6052320 (figure 17) and INSTEON 6022320 (figure 18). Converted to kWh/day the usage is: 1.6809, 1.6812 and 1.672866667 respectively. At first it appears they have similar efficiencies, however on closer analysis this is not the case. Comparing the baseline power as a fraction of the total power consumption is revealing: Hue - 0.237, Lutron - 0.197 and INSTEON - 0.306. This shows that the Lutron dimmer switch system is the most efficient with more of the energy going into useful light. The Philips Hue has a moderate baseline load but the INSTEON has a massive baseline load as a fraction of total power use. This is a result of combining two systems (wireless switches and lights) both with standby power draw and the result is 30% of the power is not used to provide light. This inefficiency is concerning and is a detriment to the INSTEON system when compared to the others.

The main reason for all the systems' high baseload power draw is the ZigBee communications network protocol which all components work on. Unlike a wireless router through which all signals pass, the ZigBee network has all components constantly connecting to each other so if one component fails the signal can be passed by another component. This also extends the range of the network with other components acting as bridges to the signal but has the disadvantage of all components having to remain on standby. (Chen et al. 2011)

This application of the Sankey diagrams and energy balance has highlighted the importance and clarified the scope of the final end goal of comparing total electricity consumption and cost, as opposed to overall improvement in efficiency. This is important because efficiency can include energy used per lumens produced. In contrast, the total electricity consumption will take into account the use of energy for both lighting and the baseline power load which will determine the consumer cost.

Overall Cost

To determine the overall cost of the system over the long term it is necessary to consider all the lifetime costs the consumer will face as well as how the cost of running the system changes over time. Lifetime costs is an important way to organise and consider the yearly cost for each system, whereas payback period combines these results with earlier trend predictions to give long term predictions for running cost and total cumulative cost.

Lifetime cost for the consumer begins with the initial purchase cost and the installation cost. Then ongoing costs of system upgrades, replacing lightbulbs and replacing failed components also need to be considered. Purchasing prices and installation cost by the electrician have already been calculated and discussed. The upgrade cost is considered to be replacing the bridge once per decade and is approximated as $100 dollars split over 10 years. This is necessary to get full functionality from the replacement later generation bulbs. The replacement cost of the bulbs themselves is assumed to be constant (as covered in the background trends section) due to manufacturing efficiencies. The lifetime hours of the bulbs were used to approximate how many bulbs will fail in a given year. The standard 10W bulb has 50000 hour lifetime while the INSTEON smart bulb has 25000 hour lifetime and the Philips Hue only 15000 hours. This is to be expected as with increased bulb complexity there is an increased risk of failure. Further due to the high replacement cost for individual Philips Hue Bulbs, coupled with short lifetime, results in a substantially larger cost than the other systems. The final ongoing cost is replacement of failed components other than lights. This cost is particularly high for the INSTEON system due to its complex dual mesh technology being highly at risk. (SmartHome 2016a) Disposal costs are equal for all systems but will not be considered in the payback period.

Figure 19: Initial and ongoing costs for each system

Costs	**Philips Hue**	**Lutron**	**INSTEON**
Purchase Cost	$2460	$2065	$2115
Installation Cost	$0	$800	$700
Upgrade Cost (replacing bridge)	$10 / year	$10 / year	$10 / year
Replacing Lightbulbs (54750 hours yearly use)	$136.875 / year	$10.95 / year	$29.20 / year
Replacing Components other than bulbs due to failure	$100 / year	$40 / year	$250 / year
Disposal Cost	$20	$20	$20

The payback period for all three systems and the existing lighting system is plotted, taking into account varying electricity prices but with constant consumption and replacement costs. Inflation is neglected and costs are in $2016 dollars as wage growth is assumed to cancel out inflation.

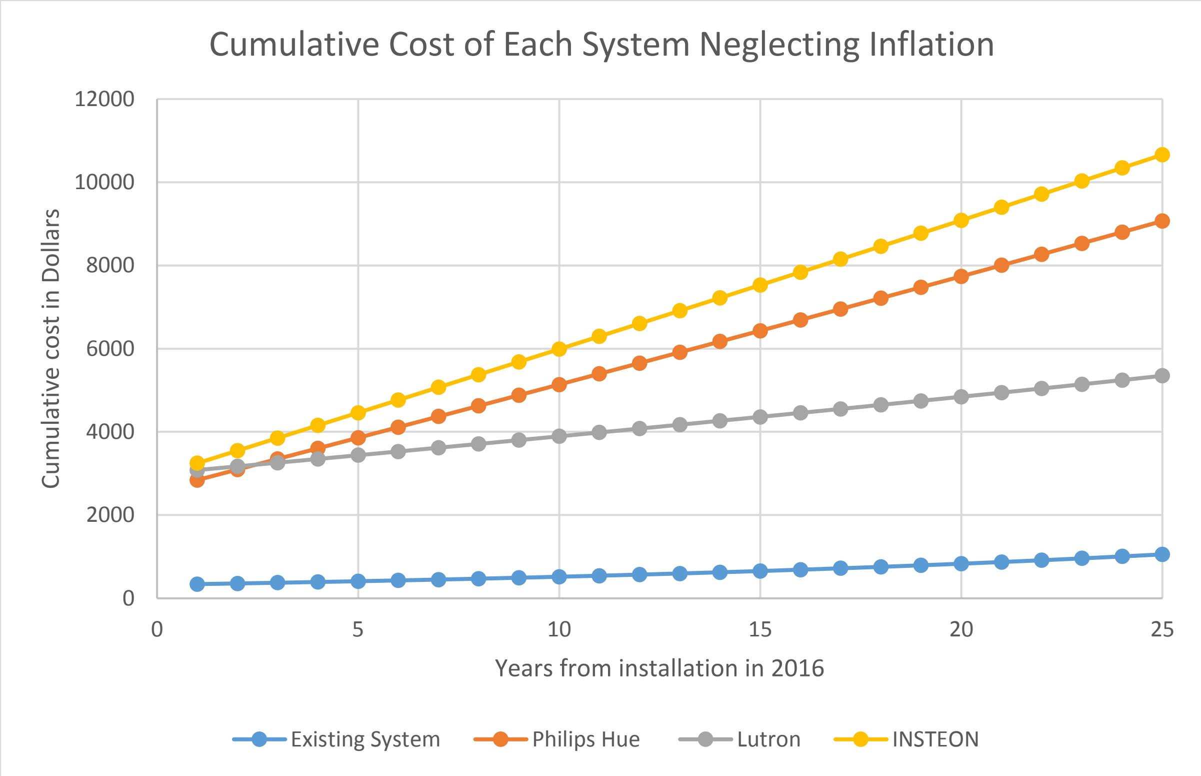

Figure 20: Payback period for each lighting control system and the existing system over the next two and a half decades

As can be seen from the graph (figure 20) none of the systems will ever be more cost efficient than the existing system due mainly to the installation cost but also running cost, which offsets cost savings in electricity consumption. The Lutron system is more cost efficient over a long period due to the reduced replacement cost for bulbs. The Philips Hue rapid rise is due to the high cost of replacing bulbs while the greatly increasing trend of the INSTEON system is due to the high failure rate of components.

Conclusion and Recommendations

Taking the long term view, the analysis shows that the Lutron system is the most cost efficient of the three smart systems but if total cost is the concern, the homeowner should stick with existing lighting. The INSTEON system, while theoretically a good idea, is let down by its implementation causing higher running and maintenance costs which overshadow the greater functionality. The Philips Hue system's cost is also substantial but if the desire is for functionality as opposed to cost then this would be the best system for the homeowner. Further, as installation can be done without an electrician, it is possible to create the system by adding a few lights at a time to the network over a period of years, thus decreasing the initial cost to only a few hundred dollars as opposed to a couple of thousand. Hence, it is clear from the analysis that despite rising electricity prices, smart lighting systems should not be purchased on the basis of cost savings due to running costs but should rather be considered if the desire is for greater functionality and more diverse control mechanisms. A final consideration is that the results and recommendations are heavily influenced by the case-study and may not be applicable in all situations. For example, for households without smartphones the functional benefits of the systems would be greatly reduced. Nevertheless, for many households, automated lighting control systems are worth considering, particularly the Philips Hue.

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