# Does energy efficient lighting result in lower energy use? The evidence from a near zero energy housing development

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## Abstract

Lighting technologies have witnessed remarkable improvements in energy efficiency over the past few decades with the developments in compact fluorescent and light emitting diode technologies. But has the application of energy efficient lighting delivered a lower energy use outcome? This paper compares the domestic lighting energy use of a number of comprehensively monitored houses within two Australian housing developments constructed a decade apart. The Mawson Lakes estate was built in the early 2000's, whilst the Lochiel Park estate was designed to be nearly zero energy and was constructed in 2009-2015. Whilst the lighting technology applied at Mawson Lakes was more typical of standard construction practice at that time, strict urban design guidelines and encumbrances were sanctioned in Lochiel Park to reduce the energy used for lighting as well as other major energy services including thermal comfort and water heating.

The application of energy efficient lighting technologies at Lochiel Park has resulted in significant energy savings. Analysis of the monitored house energy data within each estate shows that the near zero energy houses use, on average, 40% less energy for lighting than those in the nearby Mawson Lakes estate. In addition, there was a reduction of average peak power drawn by the low energy housing lighting circuits of 61%. This is despite the wiring convention used in Australia which combines the ceiling and wall-mounted light fittings together with other devices such as ceiling fans and bathroom exhaust fans and heat lamps which are more prevalent at Lochiel Park. The case studies indicate that the application of energy efficient lighting technologies, in the context of contemporary lifestyles, reduces both energy end-use and peak energy loads.

**Keywords:** energy monitoring, domestic lighting, low energy houses, installed capacity, lighting power profile, peak demand

## Introduction

The provision of energy services such as lighting, thermal comfort, food refrigeration and water heating in buildings is a major contributor to anthropogenic greenhouse gas emissions, and energy efficiency programs are at the heart of mitigation strategies for many nations [1].

Energy end-use studies in various countries has found that lighting is a significant energy end-use, which typically contributes around 5~16% of total household energy use [2-6]. Lighting demand as an energy service has been growing for several centuries, particularly as the provision of light has become more convenient, readily available, and affordable [7]. Although other studies suggest total lighting energy use may have started falling in regions which have adopted energy efficient technologies [8].

### Policies

In the context of global action to address anthropogenic climate change, reducing energy demand from households has been, and remains, an important policy action [9, 10]. To date a wide range of lighting policy actions have been undertaken including the mandatory labelling of lamp efficiency, the introduction of minimum appliance efficiency standards such as the phase-out of incandescent globes, the provision of free compact fluorescent lamps (CFL) to hasten consumer transition, and the inclusion of lighting performance standards in building energy codes and standards.

In Australia, the national government introduced a phase-out of inefficient bulbs as part of a program to curb anthropogenic greenhouse gas emissions [11]; the phase-out affects the sale of lighting products with an efficiency level of less than 15 lumens per watt. In parallel the Building Code of Australia (BCA), part of the National Construction Code, introduced mandatory residential lighting requirements, which require the aggregate lamp power density of fixed lighting to not exceed 5, 4 or 3 W/m$^2$ for indoor, outdoor or garage lighting, respectively [12].

**Technological developments**

Technology change is also driving the tendency towards improved lighting efficiency. For example, the design flexibility of the light emitting diode (LED), its operational efficiency and appreciably longer effective life provide motivations away from alternative lamps. And like most mass produced consumer products, the relative cost of LED lamps is expected to fall over time as the technology matures and the market transitions.

But studies have shown that energy impacts are not just related to the efficiency of technologies, finding that energy use is also related to the demographic characteristics of building users and their lifestyle [13, 14]. From an end-user perspective, the relatively higher up-front cost of low energy lamps, the light output quality, and the convenience issues of product availability and compatibility with existing fittings, all impact the transition to low energy lighting [15, 16].

Given the various policy landscape, technology and behavioural related impacts, this study addresses the research question: does the application of energy efficient lighting deliver lower energy use outcomes? Utilising detailed energy use monitoring from two case study estates: one more typical of houses in the early 2000s, and the other a near zero energy estate; this comparison provides a strong indication of whether the application of energy efficient lighting technologies and contemporary household behaviour will deliver a lower energy use outcome.

## Literature review

The past few centuries have seen significant domestic lighting technology change from candles to gas lamps to kerosene lamps to various forms of electric lighting from incandescent lamps to fluorescent tubes to dichroic halogen lamps to LEDs. Each has provided different light qualities, environmental externalities, and consumer benefits. Examining the more contemporary lighting technologies from an efficiency perspective, LEDs deliver equivalent lux levels for one fifth the energy of incandescent or halogen lamps, and one half the energy of compact fluorescent lamps [17]. Theoretically control systems can further reduce the amount of energy wasted lighting spaces that are not occupied or already have sufficient natural light. But these savings are viewed from an engineering calculation perspective before taking into account the behaviour of building users.

In observing the coal consumption of 19$^{th}$ century steam engines, Jevons [18] argued that improvements in engine energy efficiency increased the use of coal by making the technology more economically attractive, rather than delivering energy savings. This concept was taken up by Khazzoom [19] and Brookes [20] who postulated that economy-wide rebound effects, being the sum of direct and indirect effects, will absorb expected benefits and may lead to a net growth in energy use and greenhouse gas emissions. In simple terms, the theory argues that the more efficient a process becomes the more the end-users will consume the service, and for lighting this means that as lighting has become more convenient and cost effective, the greater the total energy impact.

The relationship between artificial lighting and human productivity has meant that the Jevons paradox has been demonstrated across the history of lighting technology change [7, 21]. Tsao et al. [7] examined lighting energy use across three centuries found that improvements in the efficiency facilitated lower lighting costs, greater access to lighting, greater per capita consumption of lighting, improvements in human productivity and associated increases in economy-wide energy use. Tsao et al. [7] point out that the historic rebound trend may not continue in all situations as indoor light levels near saturation (satisfies human need for light) and the price elasticity of demand closes to zero. Fouquet and Pearson [21] tracked income and price elasticity of demand for lighting over the past two centuries in the UK and found that rebound reduced as incomes grew, with rebound greater than 100 per cent during the nineteenth century, but reducing well below 100% during the twentieth century.

Detailed metering of developed world households in the 21$^{st}$ century supports this position of lower elasticity, for example a study in Sweden found lighting efficiency gains were delivered with only small levels of rebound [22]. Similarly, a German study of households found that the switch from incandescent or halogen lamps to CFL or LED technology will result in a rebound of around 6%, which suggests that significant energy savings are possible due to technology change [23].

The literature also contains substantial evidence that lighting design strategies that facilitate daylighting and encourage the use of energy efficient lighting and associated control systems can significantly reduce energy end-use for commercial buildings [24]. But as lighting is a relatively larger energy end-use in commercial buildings when compared to residential buildings, and less likely to be influenced on a daily basis by building users, this finding is not readily transferable to housing.

And although there have been many post-occupancy studies for low carbon and near zero energy homes [25-31], the energy end-use disaggregation has typically not separated lighting performance. Clearly there is a gap in the literature describing the actual performance of energy efficient lighting in low energy and near zero energy homes.

Lighting is used during periods of peak energy demand and therefore improvements in the energy efficiency of lighting may result in peak demand reductions. In heating dominated climates, winter peak loads are influenced by seasonal heating and lighting demand [6]. The Building Research Establishment [6] report noted that at least 20% of the winter electrical peak was attributable to lighting. Less is understood about the potential for lighting energy efficiency to reduce summer peak energy demand in cooling dominated climates.

The following case studies address these gaps in the literature by quantifying total energy savings and peak load reductions due to the application of energy efficiency lighting technologies in warm temperate climate near zero energy homes.

## Methodology

### Case Study: Mawson Lakes and Lochiel Park

The case study locations of Mawson Lakes and Lochiel Park, both in Adelaide (South Australia), are chosen because the first represents relatively typical local construction for the period 2000-2010, and the second represents atypical construction, being a near zero energy housing estate (constructed between 2009-2014). The contrast between the two estates is stark with Lochiel Park homes featuring the atypical application of passive design strategies, energy efficient technologies and equipment, and renewable energy technologies (e.g. solar water heating and photovoltaic systems). Further details of the Mawson Lakes homes is available at [32], and details of the Lochiel Park homes is available at [33].

Comparisons between estates, particularly across different time periods, is notoriously difficult because of the myriad of factors impacting energy consumption including local climate, household behaviour, socio-economic situation, and changes in lifestyles. In the case of the chosen case study estates, there is a noticeable difference in floor area with Lochiel Park houses having approximately 21% more conditioned floor area and approximately 30% more habitable floor area (see Figure 1). To address this issue the relevant analysis is normalised by floor area.

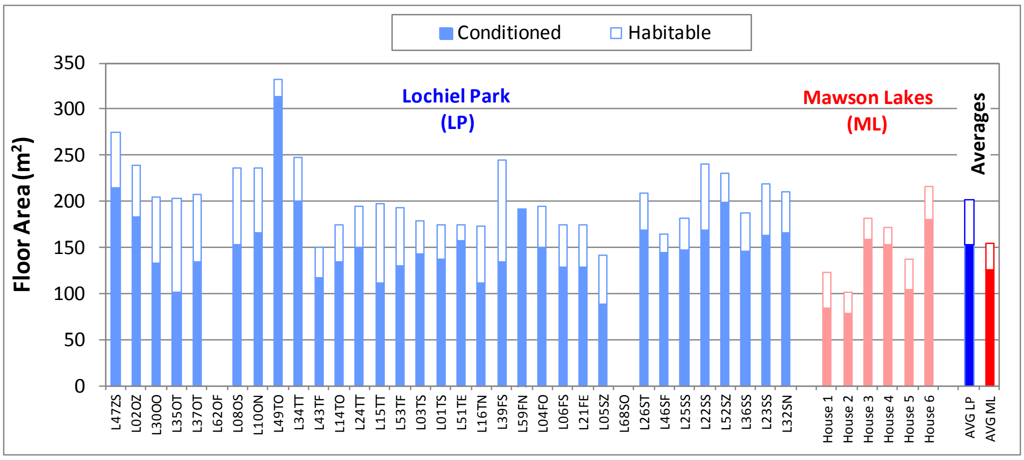



**Figure 1: Habitable and conditioned floor area of the individual and average monitored Lochiel Park and Mawson Lakes houses.**

**Lighting data**

The lighting technology and performance information utilised in this study comes from three main sources: (a) surveys of occupants; (b) appliance and equipment audits (house inspections) conducted by the authors; and (c) monitored energy end-use data.

Surveys regarding energy conservation attitudes and behaviours were administered to all Mawson Lakes residents to develop a greenhouse gas emission reduction scoresheet [32]. The results of surveys give some insight into the installed appliances and equipment.

Appliance audits were carried out in 45 Lochiel Park houses to gain an understanding of the types of energy using appliances and equipment used in modern low-energy houses. In addition to collecting the nameplate information of many major appliances, details regarding the number, type and power rating of plug-load and lighting devices were collected.

**Overview of energy end-use monitoring systems**

*Mawson Lakes*

Electricity and gas utilities monitored networks of houses within Mawson Lakes, where 50 and 140 houses had their electricity and gas monitored, respectively. Network data was made available to the authors of the scoresheet report [32]. Within these networks, six houses were monitored in detail, with disaggregation across heating and cooling, lighting, ovens, dishwashers and refrigerators. The lighting energy data was recorded in 15 minute intervals at increments of 6Wh, using a current transformer and a data logger; giving an average power resolution of 24W.

*Lochiel Park*

Each house in Lochiel Park is fitted with an 'EcoVision' brand monitoring system, which includes an in-home feedback display, a programmable logic controller (PLC), and a variety of intelligent meters and sensors [34, 35]. Each monitoring system records and displays the residents' real-time water, electricity and gas usage. Lighting energy data presented in this study is collected from a sub-set of 10 houses with disaggregation to major appliances (e.g. ovens, refrigerator, dishwasher, heating and cooling, water heating) and electrical circuits (e.g. lighting circuits).

The raw electrical energy consumption data is collected remotely each month, which is recorded at minute intervals using wattmeters with resolution of 1.25, 1 and 0.5Wh. This translates into average minute power consumptions of 75, 60 and 30W, respectively. This data is converted to 15 minute average blocks to match that of the Mawson Lakes data to facilitate a fair comparison of lighting circuit power profiles. This does not affect the energy consumption over the monitoring period, and has only a minimal smoothing effect on the average power profile, as shown in Figure 2.

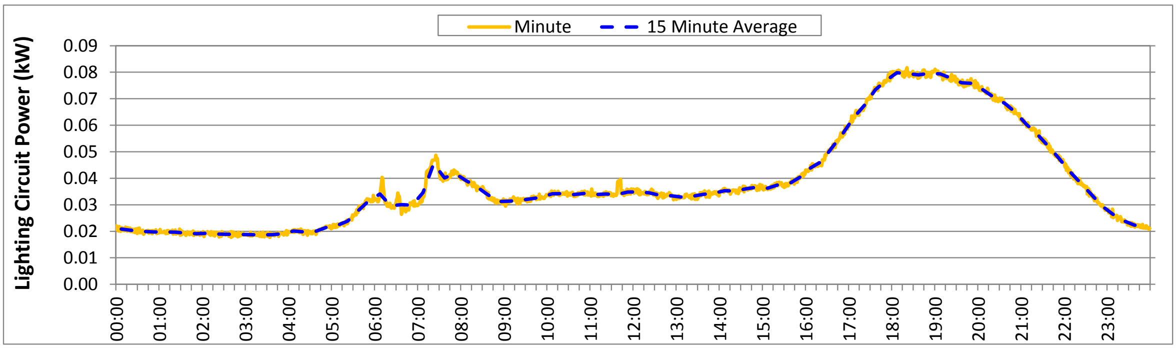
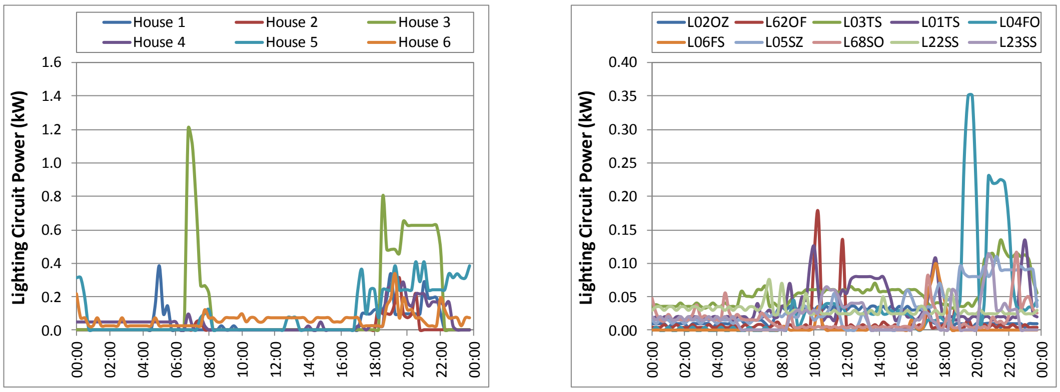



**Figure 2: Effect of converting the average Lochiel Park minute (by minute) lighting data to 15 minute averages.**

Note that both housing estates are wired to the same specification which allows ceiling and bathroom exhaust fans, as well as bathroom heat lamps, to be wired on lighting circuits. Due to limitations with monitoring equipment (i.e. the resolution of wattmeters and coarse equivalent powers), it is difficult to disaggregate lighting power from that of ceiling fans, exhaust fans or heat lamps. In addition, luminous flux was not measured and hence neither the lighting levels nor efficacy is presented here.

The Mawson Lakes lighting data, presented in this study, was monitored between April 2002 and March 2003, whilst that from Lochiel Park was monitored between January and December 2014. An example of a single day lighting circuit power profile, for both estates, is shown in Figure 3.




**(a) Mawson Lakes (31-03-2003)** **(b) Lochiel Park (31-12-2014)**

**Figure 3: 15 minute lighting circuit power profiles of monitored house within both estates.**

## Lighting technology and circuit details

*Mawson Lakes*

Although no appliance audits were performed nor were records kept of the number or types of lighting technologies used within Mawson Lakes homes, the surveys indicate that 47.2% of respondents believed they were using energy-saving lighting - the author's believe halogen dichroic low-voltage down lights, typically installed in new homes at that time, were deemed by respondents to be energy-efficient in the survey, and this may hence be misleading given modern energy-efficient lighting technologies. The surveys also showed that 81.9% of respondents did not have ceiling fans installed and of those that did, the mean was 2.8 fans per household [32], likely installed in bedrooms. This, in addition to the fact that these houses were constructed well before the phase out of inefficient light bulbs, justifies the authors assumptions that the majority of lights used are incandescent and or halogen down lights and that very few ceiling fans are included on these lighting circuits.

*Lochiel Park*

The lighting systems installed at Lochiel Park predominantly use compact fluorescent lamps (CFL), with a smattering of light emitting diodes (LED) usually on stairwells, and linear fluorescent lights mostly used in the carport or garage. The appliance and equipment survey found that Lochiel Park homes on average have 41 fixed internal lights, 6 portable lights and 10 outdoor lights. A breakdown of the quantity and installed capacity of fixed, portable and outdoor/shed lights for each individual household is shown in Figure 4. Lochiel Park houses were required to have ceiling fans fitted to each living space and bedroom.

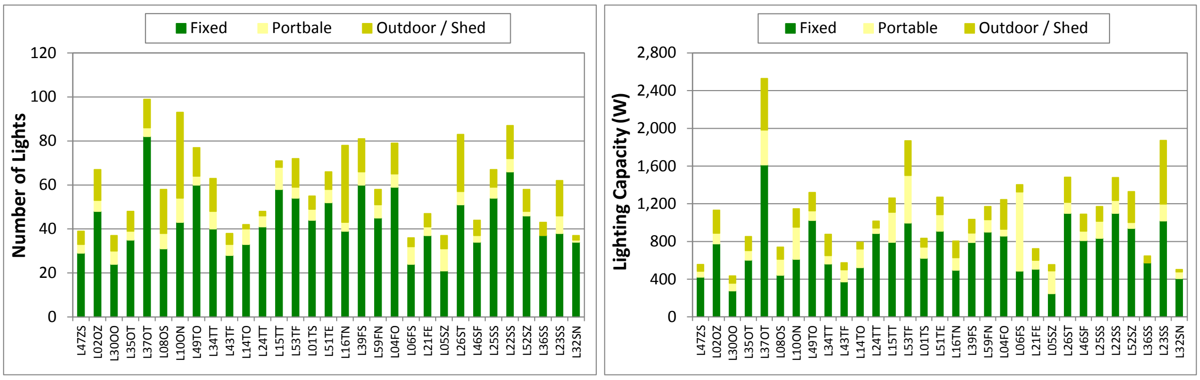



**Figure 4: Quantity (left) and installed capacity (right) of lights in audited Lochiel Park houses.**

The appliance audit and survey also revealed that the fixed indoor lighting capacity ranges from 247W to 1,613W; the average being 726W. This is shown as a function of habitable floor area in Figure 5a, together the subsequent BCA requirement for new houses (i.e. a density of 5W/m$^2$). Figure 5b shows the individual household indoor fixed lighting densities. The energy density ranges from 1.35 to 7.8, with a mean of 3.56, which is well below the current regulatory requirement. They also show that a small number of houses (i.e. 5 of 31) exceed the current energy density requirement, which is due to these houses being completed before this lighting requirement was mandated.

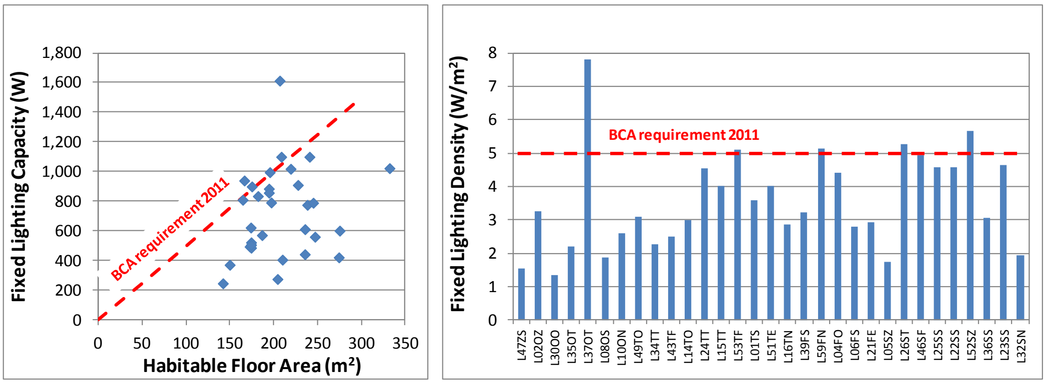



**Figure 5: Fixed lighting (a) installed capacity vs. floor area, and (b) energy density, of the audited Lochiel Park houses. The dashed line represents the 2010 BCA requirement of 5W/m$^2$.**

**Do these monitored houses represent their respective estates?**

*Mawson Lakes*

Given the relatively high completion rate, 60%, of the surveys administered within the Mawson Lakes households, it is assumed that the survey findings are be reasonably representative of the population at Mawson Lakes [32]. In addition, the average networked Mawson Lakes utility data was assumed to be representative of the entire estate. This network average closely matches that for the average of the six monitored houses for the majority of the year, with the exception of summer period, where the average electrical consumption of the sub-set is nearly 50% larger than the network average in some of the summer months. From the perspective of lighting energy use, the house sample is assumed to be sufficiently representative of the Mawson Lakes estate.

*Lochiel Park*

The sub-set of detailed monitored houses is representative of the Lochiel Park estate across a range of relevant factors, as shown in Figure 6 and Figure 7. The former shows the monthly estate wide average total electricity demand for the estate as a column with an error bar that represents one standard deviation of this; the point represents the monthly average of the 10 detailed houses. Similarly, Figure 7 shows the average household habitable floor area, installed fixed lighting capacity and energy density of these houses, along with the estate wide standard deviation (error bars) and the average of the 10 detailed monitored houses (points). These figures demonstrate that across the various house characteristics, the average of the 10 houses, where the lighting data is obtained, is relatively close to the average of the estate, and falls well within one standard deviation, giving confidence that the lighting data presented here is representative of the houses within the estate.

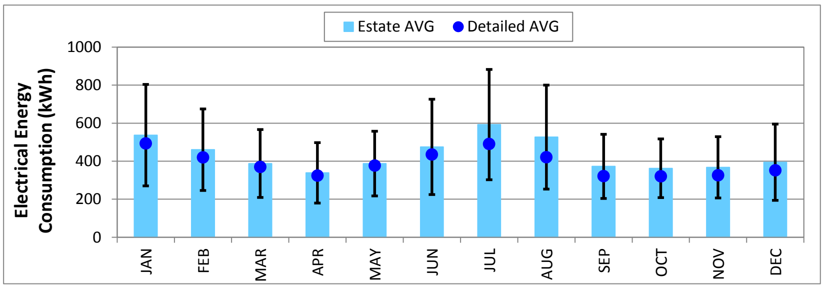



**Figure 6: Average estate-wide and 10 detailed monitored house monthly electrical energy use.**

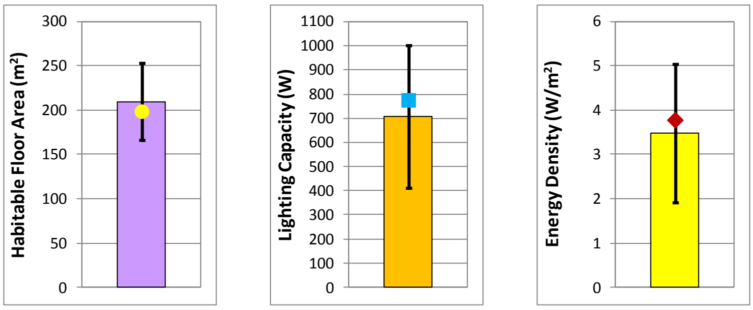



**Figure 7: Average detailed monitored house (points) vs. average audited house (columns) floor area, installed fixed lighting capacity and indoor lighting density.**

## Lighting performance of monitored houses

### Energy consumption

The annual electrical energy consumed by lighting circuits of the detailed monitored houses within both the Lochiel Park and Mawson Lakes housing developments, is shown in Figure 8. The figure shows that despite the wide variety in both estates, the average Lochiel Park house use 40% less lighting energy than the average Mawson Lakes house; 326.5 kWh to 547.5kWh. This is despite the Lochiel Park houses being 30% larger in size (habitable floor area), which suggests that the lighting technologies employed in these homes provide the service more efficiently than for Mawson Lakes.

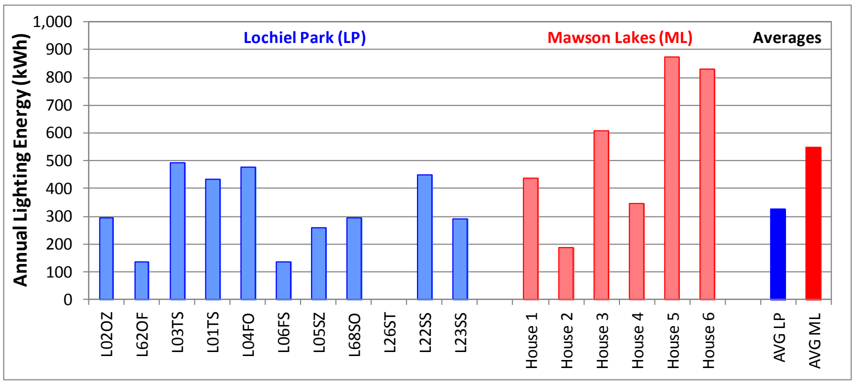



**Figure 8: Individual and average annual lighting circuit energy per development.**

Figure 9, which normalises the lighting energy by habitable floor area, verifies the significant improvement in performance and shows that on average the Lochiel Park houses use half of the lighting circuit energy per floor area than those of Mawson Lakes. Further research to confirm lighting use patterns for each estate is necessary to confirm the relative importance of efficiency to the end result.

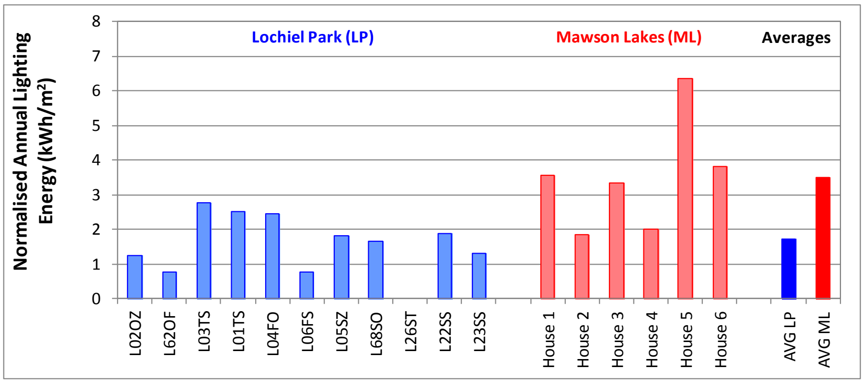



**Figure 9: Individual and average normalised annual lighting circuit energy per development.**

Although a significant reduction of lighting circuit energy has been demonstrated, it is difficult quantify how much of this is due to the use of efficient lighting technologies alone. Power profiles (signatures) of lighting and ceiling / bathroom exhaust fans are unknown and likely vary from appliance to appliance and house to house. It should be noted that the Lochiel Park houses have more ceiling fans per home, compared to those in Mawson Lakes, and therefore a larger portion of the total lighting circuit energy may be accounted for by fans. Also, the lighting energy reductions achieved in the Lochiel Park houses may be due to improved daylighting (i.e. house orientation, window placement, skylights), and this impact cannot be quantified without lighting power signatures patterns.

*Comparison with other studies*

Although international comparisons are difficult due to factors including climate, culture, building typology and socio-economic impacts, the following comparisons highlight significant differences in lighting energy end-use. A Norwegian research has found annual average energy use for lighting at around 1,050 kWh/year or around 8.8 kWh/m$^2$/year [36], representing the impact of available sunlight and local building typology. In the United Kingdom average energy use is much lower than Norway at around 508 kWh/year, or around 6.7 kWh/m$^2$/year [37]. In Australia, a country with more available sunlight, the figures for both Mawson Lakes and Lochiel Park (3.4 and 1.7 kWh/m$^2$) show an expected lower average lighting energy use per floor area, although the total average lighting energy use for Mawson Lakes is similar to that of the UK due to the larger average floor area.

## Power profiles

*Peak lighting circuit power demand*

Figure 10 summarises the individual and estate average peak lighting circuit power demand (15 minute blocks) throughout the monitoring period, showing that the combination of energy efficient lighting technologies and daylighting strategies can on average reduce the peak lighting circuit power by 61%, from 1,080W to 412W. This is despite the higher penetration of ceiling fans in the Lochiel Park houses. It is not expected that the power demanded by bathroom exhaust fans and heat lamps should significantly vary between both housing estates.

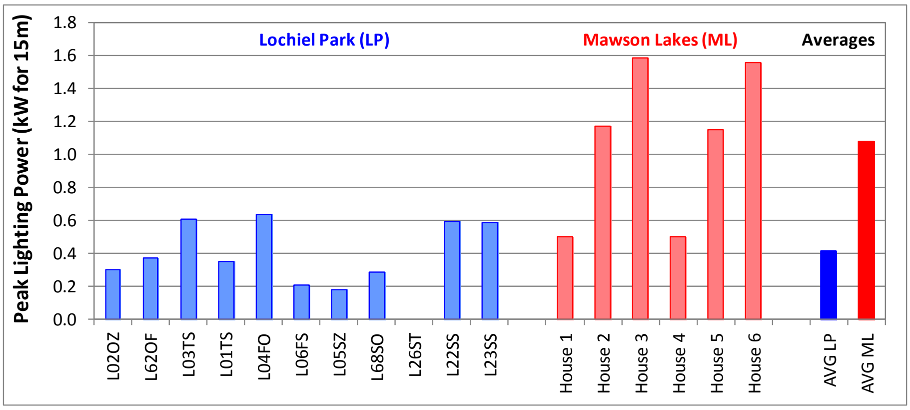



**Figure 10: Individual and average peak lighting power drawn (15 minutes) per development.**

Although the introduction of energy efficient lighting technologies has clearly significantly reduced the peak lighting circuit power, it is not clear what impact this has on total household peak power demand, and what the contribution of lighting circuits is on the peak demand of the monitored houses.

*Lighting circuit contribution to peak power demand*

Table 1 summaries the contribution of lighting circuit devices / appliances during peak power demand events throughout each respective monitoring periods. The information shows that peak events occur at different times of the day and on different days throughout the year, with about half of these occurring in both summer and winter; the exception is House 6 from Mawson Lakes whose peak demand occurs during Spring where the combined air conditioners and electric domestic water heater make up about 94% of the house’s peak electrical demand. Overall, lighting devices do not significantly impact on the peak electrical demand of both sets of houses, and surprisingly there is one house in each data set

(L06FS and House 3) that does not use their lighting circuit / appliances during their peak demand event. On average there is a clear reduction of the contribution between the developments, where the Lochiel Park houses contribute just over 1% to peak demand, whilst those in Mawson Lakes contribute to about 2.9%.

Figure 11 shows the average daily lighting circuit power demand of the monitored house for each estate in summer and winter, as these are the seasons in which peak electrical demand events occur. Each figure also shows the estate annual average daily profile as dashed lines. The profiles indicate a time difference of about one hour between the annual average peaks, as well as both the summer and winter peaks. The figures show a significant reduction in the peak for each season, with the average summer peak power demanded by the Lochiel Park lighting circuits reduced by 52.8% compared to Mawson Lakes, whilst those in winter and for the full year are reduced by 63.6% and 64.3%, respectively. The smaller reduction in summer could reflect the higher use of ceiling fans in Lochiel Park, and that reducing waste heat from inefficient lights may also reduce these cooling loads.

**Table 1: Peak power demand events and contribution of lighting circuits on peak demand.**

| Estate | House | Peak Power (kW) | Date | Time | Lighting Power (kW) at peak | Contribution of Lighting at peak |
|---|---|---|---|---|---|---|
| Lochiel Park | L02OZ | 4.290 | 16/01/2014 | 14:45 | 0.045 | 1.05% |
| | L62OF | 5.920 | 16/01/2014 | 19:15 | 0.024 | 0.41% |
| | L03TS | 6.987 | 02/02/2014 | 16:45 | 0.105 | 1.50% |
| | L01TS | 9.279 | 14/07/2014 | 10:15 | 0.050 | 0.54% |
| | L04FO | 6.413 | 07/02/2014 | 18:15 | 0.195 | 3.04% |
| | L06FS | 4.377 | 11/08/2014 | 07:30 | 0.000 | 0.00% |
| | L05SZ | 3.135 | 24/08/2014 | 11:00 | 0.023 | 0.74% |
| | L68SO | 7.118 | 14/12/2014 | 00:00 | 0.132 | 1.85% |
| | L22SS | 7.071 | 23/07/2014 | 16:30 | 0.025 | 0.35% |
| | L23SS | 6.996 | 11/08/2014 | 21:45 | 0.045 | 0.64% |
| | **AVG** | **6.159** | N/A | N/A | N/A | **1.01%** |
| Mawson Lakes | House 1 | 7.560 | 20/01/2003 | 19:45 | 0.312 | 4.13% |
| | House 2 | 4.704 | 12/07/2002 | 17:45 | 0.192 | 4.08% |
| | House 3 | 10.608 | 22/12/2002 | 08:30 | 0.000 | 0.00% |
| | House 4 | 8.904 | 07/01/2003 | 17:15 | 0.024 | 0.27% |
| | House 5 | 8.208 | 30/07/2002 | 18:45 | 0.456 | 5.56% |
| | House 6 | 13.320 | 04/10/2002 | 23:45 | 0.456 | 3.42% |
| | **AVG** | **8.884** | N/A | N/A | N/A | **2.91%** |

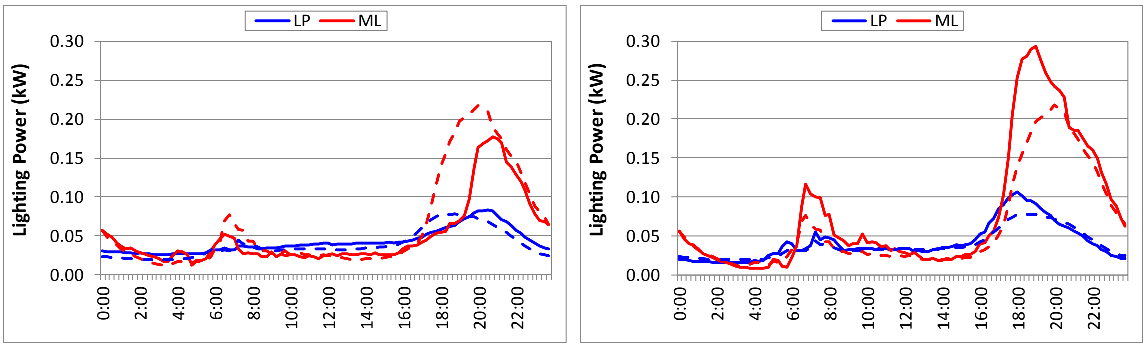



**Figure 11: Average daily Lochiel Park (LP) and Mawson Lakes (ML) lighting circuit power profiles for (left) summer and (right) winter; the dashed lines represent the year-long daily average.**

## Conclusions

Lighting energy efficiency has been a key policy action in the context of addressing anthropogenic climate change.  This paper has highlighted some of the numerous lighting policy changes worldwide and in Australia, with the policy goal of curbing residential greenhouse gas emissions.

Given questions raised in the literature about the likely rebound effect from improving the energy efficiency and therefore cost efficiency of providing lighting energy services, this study set out to determine whether the application of energy efficient lighting technologies in a residential setting would lead to a reduction in energy use.  The comparison between the two nearby residential estates shows that the application of energy efficient lighting technologies combined with improved daylighting strategies significantly reduces the energy used for lighting energy services by about 40%. Further research to compare lighting use patterns for each estate is necessary to confirm the relative importance of efficiency to the end result.

Also noticeable was a significant reduction in peak power demand of the lighting circuits of about 61%, with benefits found across all seasons.  And although the impact of lighting on total peak energy demand is relatively small, the related reduced internal heat load from improved lighting energy efficiency may also contribute to a lower summer cooling peak energy demand.

In light of the recent mandatory lighting performance requirements established by the Building Code of Australia, the installation and operation of energy efficient lighting technologies should result in a reduction in household energy use. The impressive energy savings presented here are magnified when normalised by floor area, as new houses are typically designed and built larger than ever before. The experience of Lochiel Park also shows that the mandatory building energy regulatory standards could be improved beyond the current $5W/m^2$ requirement for indoor lighting, leading to further total and peak energy demand savings.

## Acknowledgments

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