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ORIGINAL ARTICLE

Lightening the load: quantifying the potential for energy-efficient lighting to reduce peaks in electricity demand

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Abstract One of the key challenges to greater renewable electricity supplies is the temporal mismatch between non-dispatchable renewable sources and peaks in electricity demand. In addition, increased electrification coupled with the de-carbonisation of electricity generation is likely to increase the scale of demand peaks. This could force investment in carbon-intensive peaker generation or capital intensive storage capacity as well as additional transmission and distribution network capacity which may then be substantially underutilised. Whilst considerable effort has been devoted to testing a range of demand response interventions to reduce or shift consumption, less attention has been given to the ability of certain appliances to permanently reduce demand at peak through energy efficiency. In this paper, we use a published model of future energy-efficient lighting uptake together with multi-year measured lighting demand data from a sample of residential households to model the potential power (MW) and energy (MWh) reductions of a 'business as usual' rate of efficient lighting adoption. Our estimates suggest that whilst lighting comprises ~ 4% of overall New Zealand annual electricity consumption, it comprises up to 12% of evening peak electricity consumption in winter. As a result, we estimate that by 2029, more efficient residential lighting could reduce New Zealand's total annual demand by 1 TWh and reduce the highest winter evening peaks (at 17:00) by at least 500 MW (9%). The winter evening demand reduction would be roughly equivalent to avoiding the need for additional generation capacity of the scale of New Zealand's Huntly Power Stations 1–4 (coal/gas) plus the Stratford peaker plant (gas open-cycle) and has clear implications for any electricity system that is intending to transition towards ~ 100% renewable generation at least cost.

Keywords Peak electricity demand · Efficiency · Lighting · Projection · New Zealand

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Introduction

Electrification and renewable electricity generation are considered to be the two pillars of a low-carbon energy transition (Bull 2001; International Energy Agency 2019; Yuan and Zuo 2011) because an increase in the share of renewable electricity sources has significant scope to reduce energy-related greenhouse gas emissions (Long et al. 2011). However, renewables collectively constitute a less predictable generation resource (Beaudin et al. 2010; Su et al. 2014; Müller and Möst 2018) and this is especially problematic when peak residential electricity demand occurs in the morning and evening in winter in many countries (Alham et al. 2017; Muenzel et al. 2015). With increased electrification of energy services, these peaks are likely to increase leading to the need for additional peaking generation and network capacity reinforcement. Since dispatchable fossil fuel generation can be used for demand peaks as well as base demand, the high cost of providing over-capacity of renewable supplies to meet peaks in demand is one argument against entirely eliminating fossil fuels from power systems (Interim Climate Change Committee 2019; Pereira et al. 2016).

One of the key challenges to greater renewable electricity supplies is therefore the temporal mismatch between non-dispatchable renewable sources and peaks in electricity demand (Mirza et al. 2009; Müller and Möst 2018; Reddy and Painuly 2004). This means the electricity system needs to find a balance between the provision of sufficient capacity to supply demand and the risk of endangering economic profitability of energy assets, particularly when renewable generation is high (Grunewald and Diakonova 2018; Müller and Möst 2018; Transpower New Zealand Limited 2018). Resolving this may require a mix of capital intensive over-capacity of renewable supply (Denholm and Hand 2011; Lund et al. 2015), continued use of fossil-fuelled generation to meet shortfalls (Painuly 2001) and demand side management (Strbac 2008). Reducing peak demand, especially under future scenarios of greater electrification of heat and transport (Dyke et al. 2010; Pudjianto et al. 2013), is therefore a particularly important strategy for reducing the cost of integrating renewables (Energy Efficiency and Conservation Authority 2019) *as well as* reducing the need to invest in network re-enforcement caused by increased electrification per se.

Residential demand response, where consumer electricity demand is shifted and/or reduced in response to signals, is one demand side management option that could be particularly effective in countries where the residential sector is a main contributor to peak demand (New Zealand Electricity Commission 2005; Losi et al. 2015)). Several studies have explored the technical potential for residential load shifting and load curtailment to reduce peak demand (Arteconi et al. 2013; Bronski et al. 2015; and Dyson et al. 2014). These studies suggest that demand response can shift up to 20% of the annual electricity demand and 8% of peak demand without compromising comfort and service quality (Bronski et al. 2015) although the reproducibility and generalisability of many of these studies is in some doubt (Frederiks et al. 2016; Huebner et al. 2017; Srivastava et al. 2018) (Frederiks, Stenner, Hobman, & Fischle, 2016; Huebner et al. 2017; Srivastava, Van Passel, & Laes, 2018).

On the other hand, whilst the ability of energy efficiency to reduce overall electricity consumption has been widely discussed (IEA 2018; Ministry of Business, Innovation, and Employment 2017; Mori et al. 2011; Saidur 2009; Tonn and Peretz 2007; Worrell et al. 2003), its role in reducing the temporal mismatch between supply and demand and thus contribute to demand side management is less studied (Gellings 2009). Clearly, energy efficiency has significant potential to reduce peaks when those peaks are driven by electricity uses which are open to efficiency gains (Buonocore et al. 2016; International Energy Agency 2012; McNeil et al. 2019; Worrell et al. 2003) and especially in the residential sector in countries where household electricity contributes disproportionately to demand peaks. In these circumstances, more efficient household appliances could permanently reduce demand both overall and, crucially, at peak times. In particular, efficient appliances that reduced demand during annual peaks in electricity system demand could (a) reduce the transmission and distribution network capacity needed in any electricity system, (b) reduce the need for emission-intensive peaking plants and (c) reduce the over-capacity needed in a fully renewable system. As an example, energy-efficient lighting technologies such as light emitting diodes (LED) have rapidly reduced in price and provide a significant reduction in electricity demand for the same luminescence (Schubert 2014). However, despite the apparent benefits, there has been limited work on quantifying the role of energy efficiency in reducing demand peaks (Arteconi et al. 2012; Bronski et al. 2015; Dyson et al. 2014).

In response, this paper models national scenarios of energy-efficient lighting uptake and quantifies the resulting reduction in demand during peak demand periods. Specifically, we combine national forecasts of energy-efficient lighting uptake in New Zealand with detailed time-of-use data on residential lighting demand to quantify the potential reduction in winter peak demand. We then estimate the contribution this could make to overall system demand reduction in order to explore the value of strategically chosen energy efficiency programmes in reducing both fossil fuel use and network capacity requirements in renewable-dominated electricity systems. The main innovation of this paper is quantifying the reduction in future electricity demand resulting from the uptake of energy-efficient lighting.

This paper is organised as follows. The next section provides further context on the New Zealand energy and electricity supply system. We then introduce the data and methods used to estimate the technical potential for residential lighting to reduce peak demand at different seasons of the year. "Results" presents the findings of our analysis, and "Discussion and conclusions" situates our findings in the broader literature on demand-side management. The final section draws implications for policy both in New Zealand and internationally and identifies areas of further work.

New Zealand context

New Zealand is a particularly interesting case to investigate the potential for lighting efficiency to reduce annual peak demand because electricity makes up 24% of New Zealand's total energy consumption (15% in the UK, 14% in the USA) and in recent years has ranged between 80 and 85% renewable electricity (Department for Business, Energy, and Industrial Strategy 2019; Ministry of Business, Innovation, and Employment 2018; U.S. Energy Information Administration 2019) with the aim of 100% renewable electricity in normal conditions by 2035 (New Zealand Productivity Commission 2018). Renewable generation is dominated by hydro, with wind and geothermal also contributing. Hydro is generally dispatched first to meet demand peaks but can suffer from low hydro inflows in autumn and early winter. As with many high latitude and temperate nations, energy demand in New Zealand is highest in winter and in the absence of international interconnections, support to meet winter peaks is therefore currently needed from fossil-fuelled generators (Khan et al. 2018).

In this paper, we quantify the potential effect of energy-efficient lighting on reducing annual demand peaks in New Zealand. We do this by combining detailed time-of-use data of residential lighting demand (Anderson et al. 2018) with national-level energy demand data (Energy Efficiency and Conservation Authority 2017a) and a published future lighting technology uptake scenario (EnergyConsult PTY LTD 2015).

New Zealand's electricity demand is highest overall in winter and there are two peaks daily, morning and evening, throughout the year, although much more pronounced in winter (Fig. 1). Daily average demand in 2017 varied between 3.8 GW (summer early morning) and 6.2 GW (winter evening) and the relative size and 'peakiness' of winter demand is a challenge for the integration of non-dispatchable renewable generation at significant scale (Ministry of Business, Innovation, and Employment 2019).

Figure 2 uses the latest available New Zealand Energy End Use Database (Energy Efficiency and Conservation Authority 2017a) to show total electricity consumption for New Zealand by sector in 2015 and the contribution to overall consumption by different household appliances. Thus, the residential sector was estimated to be responsible for 32% of total electricity consumption in 2015 and residential lighting made up 4% of this total. Since lighting use is concentrated in winter due to less daylight hours (Table 1) and occurs at times that are likely to correspond to peak demand periods, its contribution to peak winter demand is likely to be much larger than 4%. As a result, the introduction of energy-efficient lighting in New Zealand homes is likely to reduce peak electricity demand by much more than 4%.

Data and method

We use several data sources to estimate the potential effect of increasing energy efficiency in residential lighting on national peak electricity demand. These sources are described below in more detail and comprise:

- A published future New Zealand residential lighting technology uptake scenario for 2015 to 2029 (EnergyConsult PTY LTD 2015) to provide annual

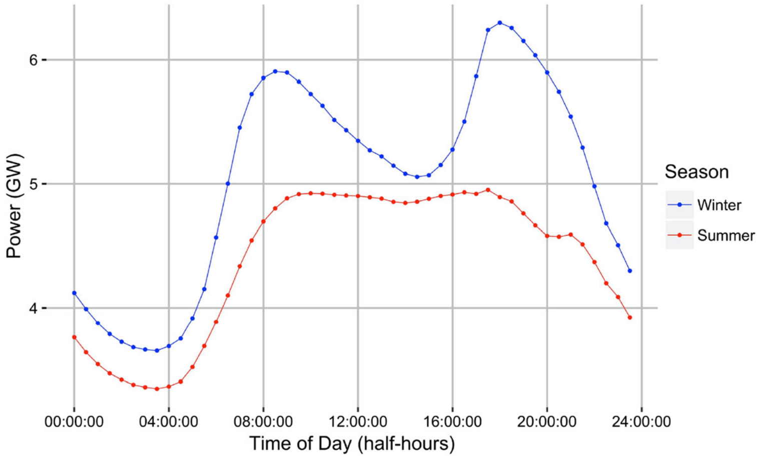


Fig. 1 Mean daily electricity demand (GW per half hour) in summer and winter 2017 (Source: Own calculations using (Electricity Authority 2018))

estimates of the future prevalence of different lighting types and their overall electricity consumption

- National-level New Zealand total energy and electricity consumption data (Energy Efficiency and Conservation Authority 2017a) to provide information on current levels of consumption
- Circuit-level monitoring of lighting electricity demand at one-minute intervals for 21 New Zealand houses over a multi-year period to provide data on the likely temporal profile of lighting demand
- National electricity generation data (Electricity Authority 2018) to provide the context for assessing the significance of the modelled demand reduction due to lighting efficiency gains

We detail how each of these is used below, but in summary, the method involves rescaling the published annual lighting electricity consumption values from the New Zealand efficient lighting uptake scenario (EnergyConsult PTY LTD 2015) to fit national level figures. We then use the seasonal lighting demand profiles derived from the monitored data to proportionately distribute these annual values by season and half-hour. The model therefore comprises a simple technological substitution model with no change in complex and interconnected habits and no rebound effects (Fouquet and Pearson 2012).

Calculating annual electricity consumption for lighting under efficiency uptake

EnergyConsult's Residential Energy Baseline Study (RBS) contains a forecast of lighting stock proportions by technology in the residential sector from 2015 to 2029 in the absence of any government intervention (EnergyConsult PTY LTD 2015).

The RBS model estimated that the number of lights per house increased at a steady rate to 2010 due to increased dwelling size and use of downlights but then increases at a slower rate to 2030 (EnergyConsult 2015, p. 19). Stock numbers were calculated from both historical and projected dwelling numbers and projected annual number of lights per dwelling. This stock was then allocated to the following technologies based on projected proportions:

a. Incandescent lights
b. Halogen lights
c. Electric low voltage halogen lights
d. Linear fluorescent lights
e. Compact fluorescent lights
f. Light-emitting diodes

The RBS assumes that future sales of incandescent lights cease by 2020, and sales of LEDs are assumed to increase leading to a decline in halogen, compact fluorescent, and linear fluorescent lights from 2017. Although some of these assumptions could be critiqued, the RBS is the only publicly documented and apparently plausible future lighting scenario available in New Zealand for the purposes of this study.

The resulting residential lighting stock forecast, which accounts for both uptake and population growth, is shown in Fig. 3. In the baseline year 2015, 46% of residential lighting units were incandescent lights, followed by compact fluorescent lights with a penetration of 32%. Energy-efficient technology such as light emitting diodes comprised a relatively insignificant 2%

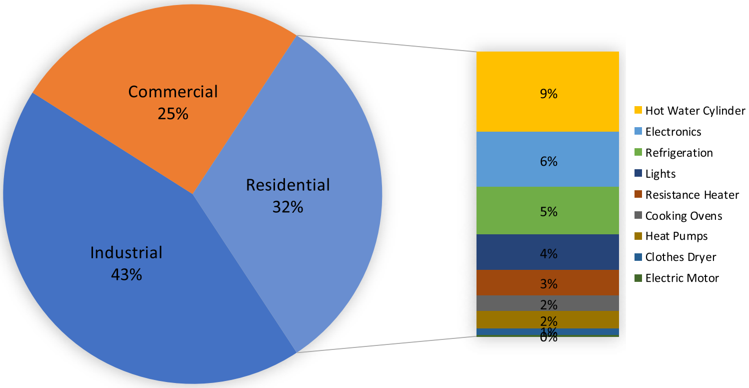


Fig. 2 Electricity consumption in New Zealand by sector and end-use in 2015 (Energy Efficiency and Conservation Authority 2017a)

of the stock. However, over time, a significant decrease of incandescent lights and an increase of light emitting diodes are forecast with the proportion of incandescent lights decreasing to 3% and light emitting diodes increasing to 46% by 2030.

The RBS study then uses these stock projections to estimate the energy demand for each technology and year using the following:

$$E_{jt}^{\mathrm{RBS}} = e_t^{\mathrm{RBS}} \times S_{jt}^{\mathrm{RBS}}, \qquad (1)$$

where E_{jt}^{RBS} is the energy consumption for each year j and technology t, e_t^{RBS} is the energy use per unit for each technology t (which is assumed to not vary by year), and S_{jt}^{RBS} is the average stock for each year j and technology t.

When summed, these energy consumption values give the projected electricity consumption for lighting under this uptake scenario. However, the estimates for 2015 proved to be 27% lower than national level residential lighting electricity demand estimates for 2015 (Energy Efficiency and Conservation Authority 2017a). To account for this, the RBS values were re-weighted as follows:

$$E_{jt} = \left(\frac{E_{2015}^{\mathrm{EECA}}}{E_{2015}^{\mathrm{RBS}}} \times e_t^{\mathrm{RBS}} \right) \times S_{jt}^{\mathrm{RBS}}, \qquad (2)$$

where E_{jt} is the energy consumption for each year j and technology t used for our estimates, E_{2015}^{EECA} is the total lighting energy consumption for 2015 from EECA data, E_{2015}^{RBS} is the total estimated energy consumption for 2015 using the RBS model and S_{jt}^{RBS} is the stock of each technology and year. This ensures that:

$$E_{2015}^{\mathrm{EECA}} = \sum_t E_{2015t}, \qquad (3)$$

We assume that the need for this re-weighting was caused by systematic underestimation in the uptake scenario model, and so, we repeated it in each year with the same upweighting ratio ($E^{\mathrm{EECA}}/E^{\mathrm{RBS}} = 1.37$).

Calculating annual seasonal lighting electricity consumption profiles

In order to estimate the seasonal and temporal profile of lighting demand under the uptake scenario, we need to estimate when lighting is actually used. If we assume that the social practices that drive the temporal pattern of lighting use (Walker 2014) will not change for different technologies (i.e. no time-shifting rebound effect), we can use measured lighting demand profile data for this purpose.

The GREEN Grid household electricity study measured 1-min level electricity power demand data for 21 New Zealand households in Hawke's Bay and Taranaki using commercially available monitors from 2014 to

Table 1 Seasons and mean hours of direct sunshine for Taranaki region (mid-New Zealand, Source: National Institute of Water and Atmospheric Research 2010)

Season	Mean sunshine hours per month
Spring: September, October, November	186
Summer: December, January, February	228
Autumn: March, April, May	178
Winter: June, July, August	139

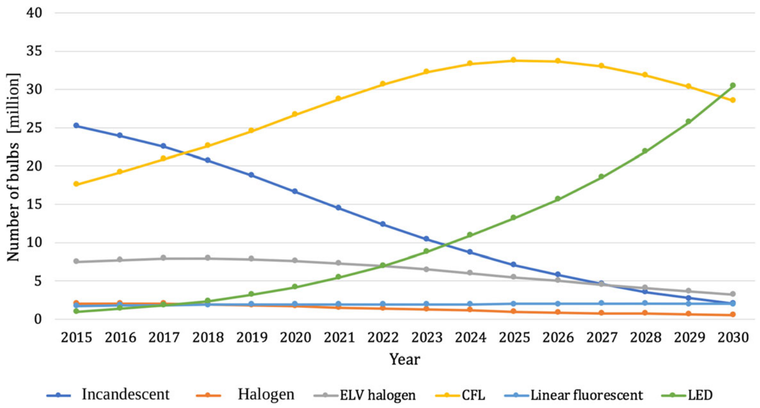


Fig. 3 New Zealand household lighting stock forecast by technology (Source: Own calculations based on EnergyConsult PTY LTD (2015))

2016 (Anderson et al. 2018; Stephenson et al. 2018). In this paper, we use data for the year 2015 as it had the maximum number of dwellings reporting data, had the fewest data outages or quality issues and coincides with the first year of the efficient lighting technology uptake model described above. Whilst this sample cannot be considered representative of all New Zealand households due to its recruitment methods and focus on family households (Anderson et al. 2018), it provides the most detailed data available on the temporal pattern of residential lighting demand in New Zealand. For 2015, the sample shows mean lighting consumption of 740 kWh (median = 618 kWh, s.d. = 691 kWh) or 9.6% of mean total household consumption. If we assume that households are responsible for 32% of electricity consumption (c.f. Fig. 2), then our sample suggests that some 3.1% of total electricity consumption in New Zealand is due to household lighting. This is marginally lower than EECA's estimate of 4% (Fig. 2) and suggests that either our sample is not representative, or that the EECA data is an over-estimate, or some combination of the two.

As New Zealand spans 35 to 46.5° in latitude thus producing considerable variation in daylight hours in winter and summer, and the monitored households are at around 39°, we consider them close to the mean daylight length for New Zealand. Given this and our confirmation that the sample's lighting consumption is only marginally lower than EECA's estimate (see above), we assume that the mean demand profiles derived from the sample will be at least indicative of the overall mean New Zealand pattern.

We therefore use this data to calculate the sample mean household electricity demand (in Watts) for lighting for each half hour per season in 2015. These profiles were then used to apportion the total electricity demand (in MW) for lighting derived in the previous section to the 48 (half hours) × 4 (seasons) according to the shape of the measured profiles so that it summed to the total estimated consumption for that year, E_j. In addition, in the absence of a robust alternative, we assume that the efficiency of each specific lighting technology remains constant and thus no additional benefits of efficiency improvement within one lighting technology occur. This is likely to mean that our efficiency savings are underestimates.

Results

Estimated baseline lighting power demand for 2015

Our analysis (Table 2) suggests that residential lighting comprised ~ 12% of national winter evening peak power demand and ~ 10% of winter morning peak power demand. The values are lower for winter daytime as we might expect, but winter off-peak evening lighting power demand is roughly the same as during peak. Note that these results cannot be compared with Fig. 2 which shows *annual electricity consumption* rather than *mean power demand* in a specific period.

To give further detail, Fig. 4 shows the estimated baseline national level lighting demand in MW by season for 2015 calculated using the method described in "Calculating annual seasonal lighting electricity consumption profiles". Unsurprisingly, given the annual variation in daylight hours, electricity demand due to lighting was highest in winter and lowest in summer, with spring and autumn intermediate. The maximum lighting demand for an average winter morning was estimated to be 510 MW, more than double the summer morning peak of 220 MW. Lighting demand on winter evenings was much greater at 750 MW, whilst average summer evening demand was 370 MW.

As Fig. 4 shows, the timing of morning lighting demand varies little from season to season: demand rises from 05:00 onwards, reaches its maximum around 07:00 and falls rapidly over the following hour. In contrast, timing of demand in the evening varies considerably by season. In summer, demand starts to increase at 18:00 and reaches a short-lived maximum at 21:00 before falling rapidly. In autumn and spring, demand starts to increase at 16:00, reaches the maximum between 18:00 and 19:00 and stays close to peak for 2 h (in spring) to 4 h (in autumn). Demand in the winter evening starts to increase from as early as 16:00, reaches a maximum at 18:00 and stays high for several hours.

Figure 5 shows the distribution of estimated mean lighting demand for each season in 2015. Although the plot is limited to 48 half-hour points for each season, it indicates that whilst the majority of values fall below 300 MW, there are some periods, especially in Winter but also in Spring and Autumn when much higher demand levels occur. As a result, the mean-based model used in this paper may underestimate the generation capacity needed to meet such large spikes in demand (Transpower New Zealand Limited 2018).

Estimated energy consumption and demand reductions over time

Table 3 shows the estimated total lighting electricity consumption for each year of the forecast uptake of energy-efficient lighting (Fig. 3) per household and nationally. These estimates show that residential lighting electricity consumption would fall by ~ 60% between 2015 and 2029 so that, despite expected population growth trends, approximately 1 TWh less generation (3% of total energy consumption in 2015) would be required due to the wider utilisation of energy-efficient residential lighting.

Whilst the reduction in overall consumption is substantial, the reduction in peak demand is even more important for the reasons described above. Figure 6 shows the estimated national residential lighting demand (MW) profile for each year converted from the consumption estimates and illustrates the impact on peak demand by season.

Figure 6 shows that increased energy-efficient lighting could reduce mean peak demand in the morning by up to 100 MW (summer) and 200 MW (winter) by 2029. The impact is particularly visible in the evenings where evening peak demand is forecast to decrease to 200 MW (spring), 170 MW (summer), 200 MW (autumn) and 280 MW (winter). This represents a decrease in national peak demand of up to 500 MW by 2029 as Fig. 7 shows.

Furthermore, we estimated that energy-efficient lighting would reduce winter daily mean electricity consumption by 2.34 GWh in winter by 2029. As Fig. 8 shows, compared to 2015, when mean daily winter residential lighting demand was ~ 6 GWh (12% of total generation), this reduces to ~ 2 GWh (5% of total generation) if no other demand changes are assumed. On a seasonal basis, this means that overall electricity consumption for lighting in winter would be 325 GWh (60%) lower than it was in 2015.

Consequences for national generation capacity requirements

These results suggest that a higher penetration of energy-efficient lighting could *permanently* reduce national electricity demand, and thus required generation, especially in winter peak periods. Figure 9 shows the impact on national demand for summer and winter compared to the 2015 baseline reported in Fig. 1. Increasing energy efficiency associated with residential lighting, according to our estimates, could reduce the highest winter evening peaks (at 17:00; see Fig. 9) by at least 500 MW (9%) by 2029 so that they fall to roughly the same level as the morning peaks. Smaller but potentially valuable reductions in peak demand can be obtained in winter mornings and also in the evenings of all seasons.

Discussion and conclusions

By distributing baseline national lighting electricity consumption from a published lighting efficiency uptake model according to the half-hourly demand profiles of a sample of measured residential households, we estimate that 12% of New Zealand's winter evening peak period electricity demand in 2015 was due to residential lighting even though it only made up 4% of national annual electricity consumption. Whilst this estimate is limited by the small dataset of 21 lighting circuits from two

Table 2 Comparison of winter peak/off peak results for 2015 with national generation (i.e. demand) data for the same period (Source: own calculations and Electricity Authority (2018))

Season	Period	Mean national GW generation	Mean lighting GW demand	Mean lighting contribution to period in %	Max lighting contribution to period in %
Winter	Evening peak	5.98	0.66	11.07	12.35
Winter	Morning peak	5.66	0.36	6.48	9.95
Winter	Off peak (day)	5.30	0.14	2.58	5.46
Winter	Off peak (night)	4.28	0.16	3.56	9.26

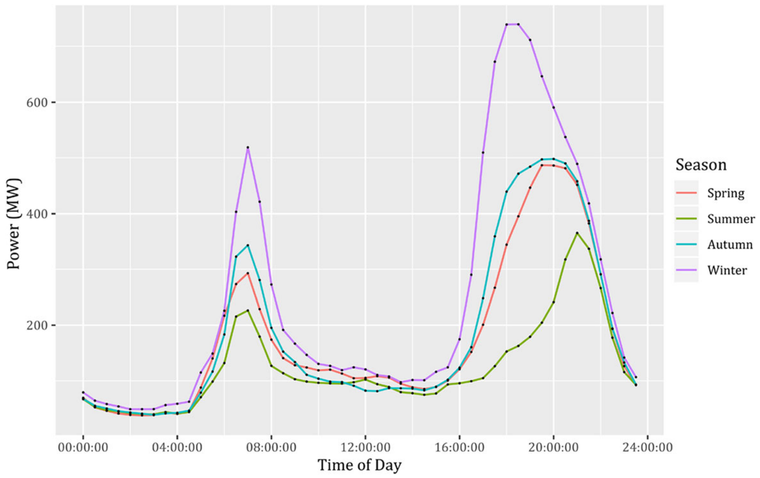
regions in New Zealand, these findings indicate the relative contribution of lighting to peak electricity demand.

Further, by using the same method to temporally distribute projected energy-efficient lighting uptake, we have estimated that more efficient residential lighting could reduce New Zealand's total annual demand by 1 TWh and reduce the highest winter evening peaks (at 17:00) by up to ~ 500 MW (9%) by 2029. To put this in perspective, the winter evening demand reduction by 2029 would be roughly equivalent to avoiding the need for additional generation capacity of the scale of New Zealand's Huntly Power Stations 1–4 (coal/gas) plus the Stratford peaker plant (gas open-cycle) (700 MW).

Even though the paper reports an extremely simple technology substitution model with no assumptions of behavioural change or rebound effects, it provides an indication of the potential value of promoting particular energy efficiency measures in the residential household sector as a viable option to capital intensive peaker plant or energy storage investment.

As an example, efficient lighting can provide a number of benefits at several scales of the electricity network. Firstly, the significant lowering of the annual peak (winter) demand offers an inexpensive way to help national aspirations for higher levels of renewable generation. It reduces the need for either fossil-fuelled peaking plants or significant over-building of renewable generation and/or storage which would only be used during periods of highest demand. This is particularly relevant to nations that are seeking to reach 100% renewable electricity supply, as demand peaks are typically met by fossil fuelled peaking plants generation (Pereira et al. 2016). Interestingly, this may have a limited impact on reducing GHG emissions in New Zealand as hydro lakes can be used to meet winter peaks in demand (Khan et al. 2018). However, with government aspirations of electrifying transport and industrial

Fig. 4 Estimated mean half-hourly residential lighting demand (power in MW) by season in 2015 for New Zealand (Source: own calculations)



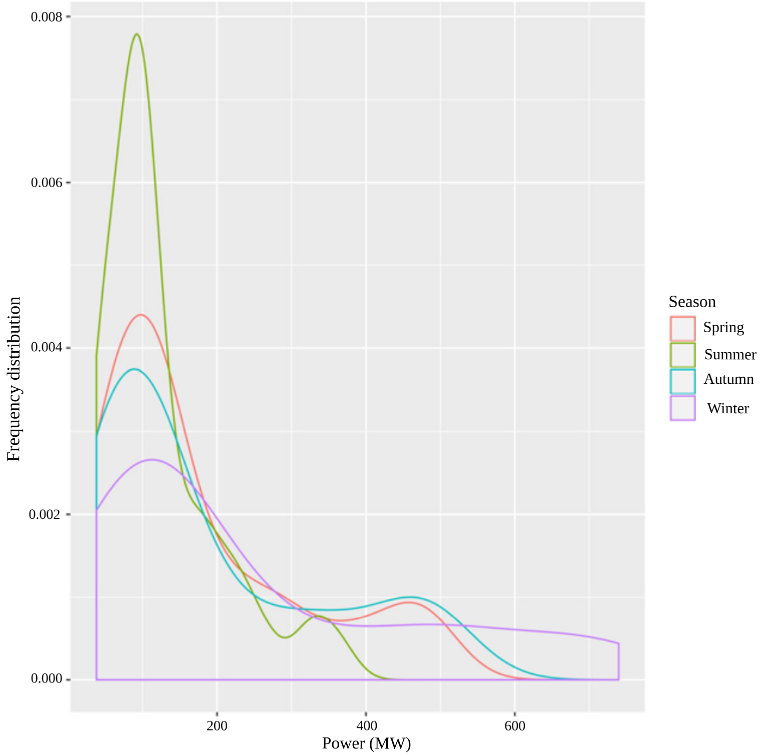


Fig. 5 Density plot to show distribution of residential lighting demand (mean power per half-hour) by season for 2015 (Source: own calculations)

heating to help meet its target of net-zero greenhouse gas emissions by 2050, and little ability to expand hydro generation, this advantage could be lost and winter peaks instead met by peaker plants. Our results indicate that increasing lighting efficiency can help avoid the need for additional fossil fuelled generation to meet winter peaks, especially as electricity demand grows.

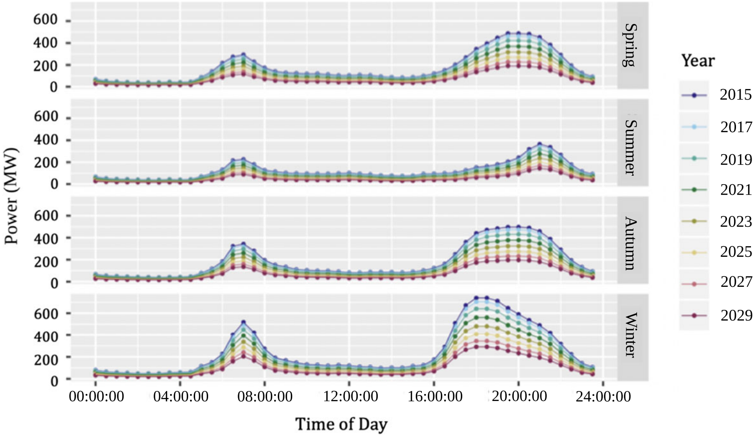
Secondly, it offers potential value to electricity distribution networks since permanently reducing winter evening peak demand may enable offsetting of costly reinforcement of constrained lines, particularly where such investment would be greater than the decrease in revenue due to lower demand from more efficient technologies. In New Zealand, distribution network congestion periods are largely in the winter morning and evening peaks so our estimate that energy-efficient lighting could offer savings to the generation system by reducing total demand by up to 500 MW implies less need for costly investment in underutilised distribution capacity.

These benefits arise from the less generally considered reduction in peak demand rather than the more often discussed overall reduction in electricity consumption

Table 3 Annual lighting consumption energy forecast under efficiency uptake

Year	Number of households	Lighting kWh per year (per household)	Lighting GWh per year (total NZ)
2015	1,796,331	878	1577
2017	1,833,349	818	1501
2019	1,868,507	731	1366
2021	1,903,664	628	1196
2023	1,935,926	530	1026
2025	1,968,188	442	871
2027	1,998,382	367	734
2029	2,026,508	307	622

Fig. 6 Mean half-hourly lighting electricity demand profiles by year and season (Source: own calculations)



(Attari et al. 2010). However, these scenarios also offer savings to household electricity bills: a reduction of more than 500 kWh by 2029 represents a saving of ~ $100 per annum per household at 2019 prices and in a smart-metered future with the potential for peak demand pricing this could be considerably higher.

The findings suggest that active intervention to support households to take up efficient lighting could be justified by the benefits of reductions in peak demand in addition to reductions in overall energy consumption. This is especially relevant for countries like New Zealand that currently do not have subsidies for energy-efficient lighting uptake. Whilst the forecast model used in this paper estimates that energy-efficient lighting would be taken up over 14 years through market forces alone, this process could be accelerated through policy measures by government or pricing (or even installation (Rushby et al. 2018)) interventions by electricity sector businesses if it was recognised as a cost-effective way to avoid generation and distribution infrastructure and reduce future greenhouse gas emissions. In New Zealand, there are some existing policy measures such as minimum energy performance standards and energy labelling for electrical appliances (Energy Efficiency and Conservation Authority 2017b) and these could be further strengthened to support reductions in overall electricity demand. In addition, replacing inefficient lighting technologies with more efficient versions could be seen as a relatively 'easy' least-regret energy efficiency transition since little disruption to infrastructure or to household habits is likely to occur. This study only estimates the technical potential for residential lighting to reduce peak demand and does consider neither the necessary policy, media or commercial interventions nor any consumer behavioural change that may be needed to realise this potential. Further work should therefore analyse the likely costs as well as benefits of accelerating the uptake model under a variety of scenarios.

Inevitably, the results are limited by the assumptions made in the prediction of lighting unit uptake and

Fig. 7 Trends in peak period maximum lighting demand by year and season (Source: own calculations)

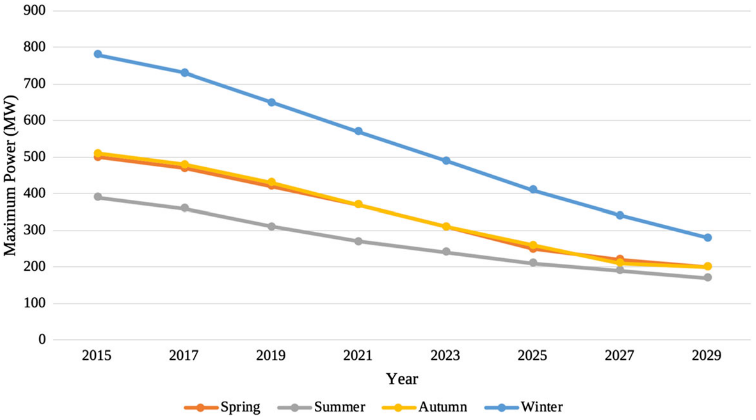
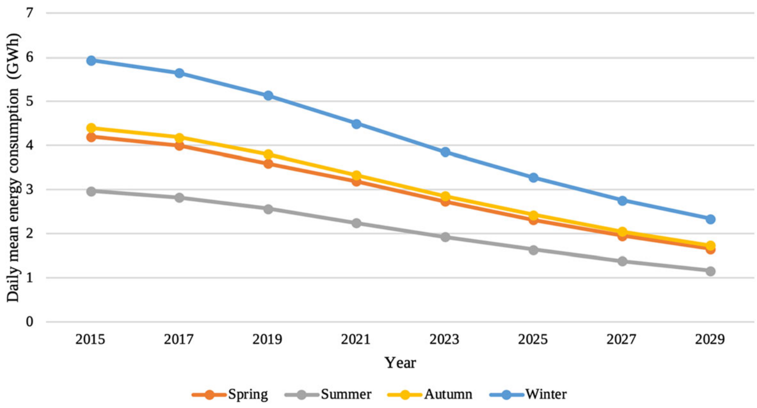


Fig. 8 Projected trends in mean daily lighting electricity consumption for by year and season



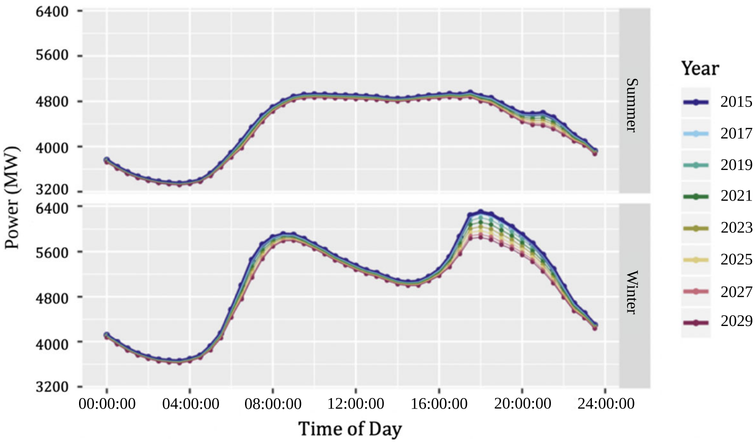
estimates of population growth and, further, are restricted to the residential sector alone. The forecast of efficient lighting uptake that we used had a variety of different technologies with a range of efficiencies, but a more widespread use of LEDs, for example, would result in even lower demand. Additional demand reductions are likely if the commercial and industrial sectors also implemented energy-efficient lighting and if lighting technologies how incremental efficiency improvements over time in contrast to our assumption that this is not the case. Further work could seek to quantify these effects as they are likely to result in even larger overall national reductions than estimated in our model.

In addition, the accurate allocation of consumption to half-hours depends on the extent to which the sample of 21 households' lighting usage reflects NZ households as a whole. Further research should urgently re-implement the models using a suitable nationally representative household electricity demand dataset to understand variations in results by household type and region.

Finally, the use of mean electricity demand profiles masks potential co-incident peaks in demand. In particular, during winter peaks, the scaled modal demand is approximately 100 MW (Fig. 5), but the estimated maximum is over 700 MW. Although this ignores the role of diversity in smoothing aggregated demand, this suggests that a mean-based model may significantly underestimate the size of demand peaks (Strbac 2008) and may also, therefore, substantially underestimate the reduction that could be obtained due to energy-efficient lighting. Future work should therefore explore alternative metrics that can provide improved estimates of the capacity needed to meet co-incident peaks and to account more appropriately for the true heterogeneity in the network.

In conclusion, as the world moves towards decarbonisation of electricity systems, it will be increasingly important to limit or control demand peaks. A critical first step will be to quantify the potential peak load reduction available from the adoption of efficient appliances

Fig. 9 Impact of increasing lighting efficiency scenario on required electricity generation for summer and winter (Source: own calculations)



whose usage has a strong coincidence with annual peaks in demand. The quantification approach used in this research is readily applicable to other nations and other appliances.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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