The extent and variability of upward light from artificial light sources in the Wellington area

Michael Jackett, Jackett Consulting, William Frith, WSP Research and Innovation, Julian Chisnall, NZTA

Abstract

Sky glow modelling has demonstrated that light emitted above the horizontal from a light source is often a critical factor in determining the total sky glow from that light source. To quantify the extent and magnitude of upward light five high Wellington vantage points were chosen as observation sites. Measurements were made of the direct light from visible floodlights, street lights and illuminated signs using multiple exposures with a calibrated DSLR camera.

Floodlights were the strongest single source of upward light producing between 10 and 150 times more upward light than a single 150 watt HPS road light. The average value was 50 times more upward light.

HPS road lighting luminaires produced an average of 130 candelas of upward light but no measurable upward light was detected from LED road lighting luminaires.

1 Background

There has been concern among the dark sky community about the possible impact of street lighting on sky glow. This has led to the NZTA carrying out a project investigate the sources of sky glow in the Wellington CBD. The project showed that static lighting (mainly street and industrial lighting) is the predominant type of outdoor lighting in the small hours of the night when the city is predominantly in sleep mode. It was not possible to further disaggregate the sky glow from static lighting into its components and thus the contribution of road lighting to the static lighting is unknown. These are the most important hours for observing the night sky. Upward light is what produces sky glow. Estimates of upward light from static sources including road lighting will improve our knowledge of how important a source of static sky glow road lighting really is. The aim of this project is to improve that knowledge by investigating upward light from a range of artificial light sources and using the literature to shed light on its impact on sky glow.

2 Method

2.1 Measurement of light by Camera

A calibrated DSLR camera was used to measure the luminous intensity from floodlights, road lighting luminaires, and signs as well as the average luminance of road surfaces. To cover a range of light sources and observation angles five sites in the Wellington area were chosen. All sites were vantage points with good overview positions. In photos taken of cities at night the lights appear simply as white blobs because the pixels are fully saturated. For the camera to be used as a scientific tool, the exposure must be chosen to avoid any pixel saturation. In this study the camera was mounted on a tripod at each observation point and a set of 21 exposures were taken each separated by 1 photographic stop (plus 1 stop provides twice as much light). The analyst then chose the most appropriate exposure level for any particular light source and used multipliers to represent the level at which the measurements were taken. A full set of 21 exposures cover an exposure range of 1 to 2,097,000! For each photo a selection area is created to generously surround the light source. The photographic software identifies the average pixel value and with the help of the calibration equation (section 3-4) an average luminance is derived. The luminous intensity is calculated by multiplying the physical size of the selection area by the luminance. Figures 3-1 to 3-3 illustrate the visual transition between bright conditions and the exposure required for light measurement

Figure 3-1: Photo of the port area at exposure level 18 of 21[1]	*Figure 3-2: The same photo as Figure 3-1 but at exposure level 10.*

In figure 3.2 The exposure is now 1/256 of Fig 3-1. Illuminated surfaces are no longer visible, HPS road lights and car headlights are just visible, but floodlights are still clearly visible and still fully saturated. In figure 3.3 the exposure level is 3. The exposure is now 1/32800 of Fig 3-1. No part of the image is saturated, and the image is correct for measurement.

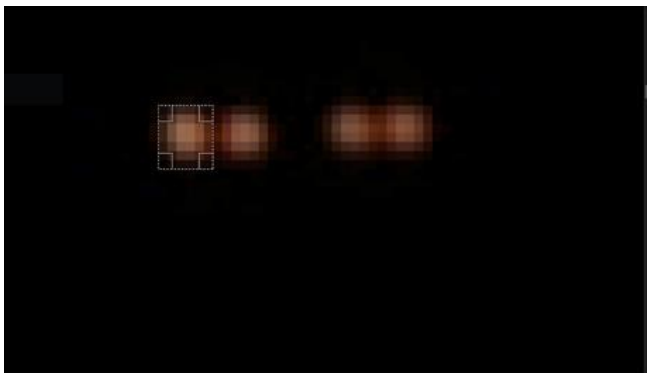

Figure 3-3: The floodlight arrowed in Figures 3-1 and 3-2, zoomed in 20x, and a measurement selection placed around the first floodlight E.

2.2 Sites Investigated

To cover a range of light sources and observation angles five sites in the Wellington area were chosen. All sites had good overview positions. The sites selected were:

1. Lookout on the Wainuiomata Hill At 180 metres altitude this provided data on 28 floodlights, 5 HPS road lighting luminaires and 2 street lighting schemes (one LED one HPS) in the Seaview area

2. Onslow Gorge Road: The view point at 70 metres altitude provided data on a LED lighting scheme (Wellington Urban Motorway), 5 floodlights and a number of car headlights.

3. Horokiwi Road: The view point at 30 metres altitude provided data on a HPS lighting scheme (SH2), 7 HPS road lighting luminaires and an illuminated advertising sign.

4. Mt Victoria – Port area: The lookout at 196 metres altitude provided data on 10 floodlights, and 1 internally illuminated sign.

5. Mt Victoria – Kilbirnie: The lookout at 196 metres altitude provided data on 2 parking area floodlights, 1 externally illuminated sign, and 4 sports ground floodlights.

3 Results

3.1 Seaview Site

The lookout at the top of the Wainuiomata Hill road offers an elevated viewpoint looking west towards Seaview and Petone (see Figures 4-1 and 4-2). The area below is predominantly industrial and contains a mix of both road lighting and industrial floodlighting. Most of the

[1] *The arrow shows the floodlight's location.*

road lighting (2019) is high pressure sodium (HPS) lighting although there is a length of LED road lighting on Hutt Park road seen in the foreground of Figure 4-2). The dominant light sources in the area are industrial floodlights using a mixture of Mercury Vapour, Metal Halide, LED and HPS light sources.

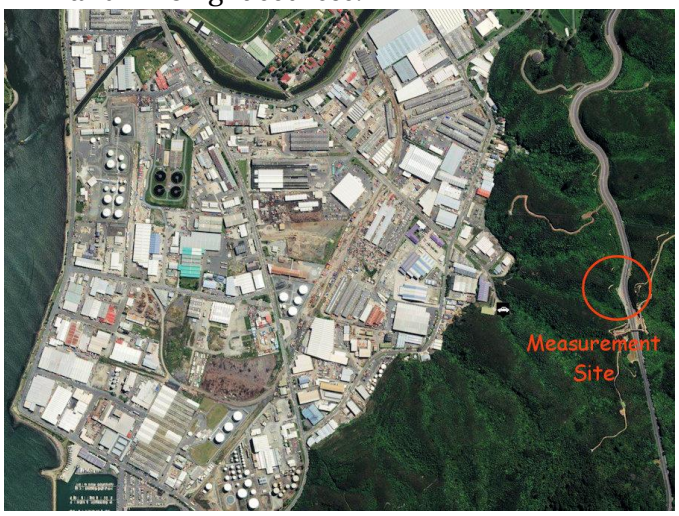

Figure 4-1: Wainuiomata hill road measurement site with the Seaview industrial area below

Figure 4-2: Night time view of Seaview from the Wainuiomata hill road site.

In figure 4.2 Hutt Park road can be seen as a diagonal route across the lower right-hand corner of the photo. The LED luminaires on this road are not visible at night because they emit no upward light.

3.1.1 LED Lighting on Hutt Park Rd

Direct Light from luminaires:

The angle of view down to Hutt Park road varies from 17 °s near the Wainuiomata hill to 8 °s at the Parkside road end. There was no direct light visible from the LED luminaires.

Light reflected from the pavement

The average luminance of Hutt Park road when viewed from the Wainuiomata hill road measurement site was 0.68 cd/m2.

3.1.2 HPS Lighting on Parkside Road

Direct Light: from luminaires

Measurements were taken of the direct light from five, 150-watt HPS luminaires in Parkside road observed an angle 8 °s above the horizontal. Their luminous intensity ranged from 120 to 310 cd with an average of 210 cd.

Light reflected from the pavement

The road surface was visible for one span of lighting near the Parkside road / Seaview road roundabout. The luminance of this single span from the Wainuiomata hill site was 0.35 cd/m².

3.1.3 Floodlights

Unlike the LED street lighting which emitted no direct upward light there were many floodlights in the area that emitted a substantial amount of upward light. Measurements were made of the direct light from some 28 of the stronger floodlights to provide perspective with upward light from road lighting schemes.

The luminous intensities of the flood lights are listed in Table 4-1 (See 4.1.5 Summary) with locations indicated by reference to the letters shown in Figure 4-4. The "Horizontal Distance" provides a measure of distance to the light and "Upward Angle" a measure of the upward angle to the measurement site. "Luminous Intensity" is the calculated measure of the intensity of light emitted by the floodlight towards the measurement site. The luminous intensities of the individual measured floodlights ranged from 1,500 cd to 20,000 cd with an average of 8,500 cd.

3.1.4 Summary

While only a sample of the flood lights were measured it was quite clear that flood lights are the dominant source of sky glow from the Seaview area. The sample total amounted to 238,500 cd which is equivalent to the upward light of 1,255 category V HPS road lights. The actual number of category V street lights in the area would be a small fraction of this.

Figure 4-4: A view of the Seaview site (split into two photos) showing with circles and letters the floodlights measured. The letters link to the "ID Letter" column of Table 4-1.

3.2 Onslow Gorge Road

Onslow Gorge Road is an elevated viewpoint looking south towards Wellington City including part of the Wellington Urban Motorway, the Interislander ferry and rail yards, and Thorndon (figures 4-6 and 4-7). it was possible to measure upward light from the LED lit section of the motorway, the headlights of cars using it and high mast floodlighting in the rail yards

Figure 4-6: Onslow Gorge Road site *Figure 4-7: City view from the Onslow Gorge Road site*

3.2.1 Wellington Urban Motorway

Direct Light from luminaires:

There was no direct light visible from any of the Motorway LED luminaires when viewed from Onslow Gorge Road (Figure 4-8). This applied to both the closest luminaires (20 °s below observation point) and to those on the most distant elevated section of highway some 2.5 kilometres away (1 ° below observation point).

Figure 4-8: Lighting on the WUM showing that no direct light was coming from the LED luminaires. The position of the luminaires is circled in red.

Light reflected from the pavement

The luminance of the road surface seen by motorists is calculated during design and is in the range 0.75 – 1.0 cd/m². From the Onslow Gorge Rd site the luminance is lower at 0.50 cd/m².

3.2.2 Car Headlights

Car headlights represent a small but intense source of upward light that was able to be measured using this method. The average luminous intensity from a single vehicle headlight facing towards the camera but viewed from 3 °s above was 220 cd. There was no way of distinguishing trucks, cars, high beam or low beam but most vehicles would be cars on dipped beam. A typical figure for the direct light from twin headlights from the observation position was 440 cd.

3.2.3 Floodlights

The path of view included five high mast, high pressure sodium (HPS) floodlights used to light the rail yards and the interisland ferry terminal. Each floodlight was located on an aerial map

(Mobile Road) and the direct distance from the observation point measured. The height of the flood light tower or mast was measured from the shadows cast and related to known height objects such as street lighting poles. Google Earth Street View photographs were used to establish the nature of the flood light and confirm its relationship to the photographic image.

Table 4-2: A list of the 5 floodlights visible in the area of the photograph.

ID Letter	Location	Horizontal Distance	Upward Angle (°)	Luminous Intensity	Equivalent HPS Lights
A	Rail yards (x4)	1,810	1.6	18,160	96
B	Rail yards (x3)	1,800	1.6	9,450	50
C	Rail yards (x2)	1,660	1.2	3,940	21
D	Rail yards (x2)	1,910	1.5	6,290	33
E	Rail yards (x1)	1,990	1.3	2,000	11
TOTAL				39,900	210

Floodlight C (2 lights)

Floodlight E (1 light)

Figure 4-9: Three of the 5 floodlights identified in Table 4-2.

There were 5 prominent floodlight clusters in view and their output is shown in Table 4.2. All floodlights used HPS lamps and because of the mast height and distance from the observer they had a relatively small upward angle of between 1.2 and 1.6 °s. Photographs of some floodlights viewed from State Highway 1 are shown in Figure 4-9. The total luminous intensity from the 5 floodlights was 39,900 cd; the equivalent upward light of 210 HPS road lights. Floodlight A [B is very similar]

3.2.4 Summary

- The railway yard floodlights are quite powerful lights and the amount of upward light they create (39,900 cd) seems a little out of proportion to their task.
- Light from the LED road lighting luminaires was conspicuous by its absence. There was no upward light from these fittings even at relatively small upward angles (1°).

The extent to which modern road lighting now controls upward light is perhaps best illustrated in the segment of figure 4-9 related to Floodlight C. The road lighting luminaire at the LHS of the photo is mounted with its surface parallel with the road surface so that all its light goes downward. The floodlights are mounted with their main beam aligned close to the horizontal so that a sizable proportion of their light is emitted upwards.

3.3 Horokiwi Road

Horokiwi road rises steeply off SH2 Hutt road near Petone. At a point some 300 metres from the Hutt road it provides an overview of the HPS lighting on the Hutt road and provides a comparison with the Onslow Gorge road overview of LED lighting on the Wellington Urban Motorway (Figure 4-10). It also includes an overview of an illuminated sign on the Hutt road.

Figure 4-10: Horokiwi road site and its view of Hutt road

3.3.1 Direct Light

The upward angle from the luminaires on the Hutt road to the Horokiwi road site varied from 5° to 17°. Unlike the LED lighting on the Wellington Urban Motorway, light from these luminaires was clearly visible over all the upward angles (Figure 4-12). Luminous intensity measurements from each luminaire are shown in Table 6-1 along with the horizontal distance to the luminaire, the upward angle and the light output expressed in cd.

Table 4-3: Upward light output in cd from the 7 foreground HPS luminaires in Figure 4-12.

Luminaire number	Horizontal Distance (m)	Upward Angle (°)	Luminous Intensity (Cd)
1	75	13	50
2	119	9	80
3	165	6	120
4	220	5	160
5	60	17	30
6	114	9	110
7	158	6	130
TOTAL			680
AVERAGE			97

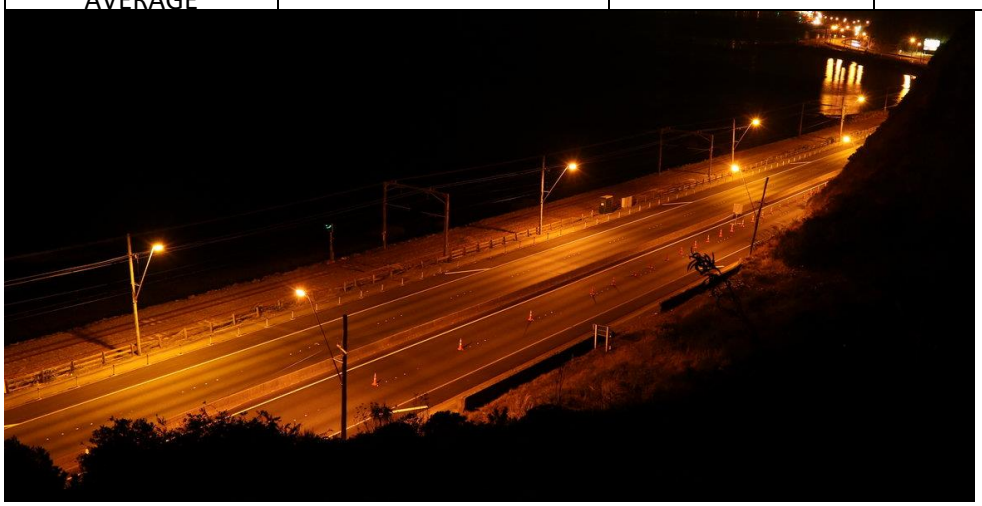

Figure 4-12: Road lighting on the Hutt road showing upward light from each HPS luminaire. This figure can be compared with Figure 4-8 where no upward light from LED luminaires is seen.

The luminous intensities ranged from 50 to 170 cd with an average of 100 cd. In general, the highest luminous intensity luminaires had the lowest upward angle from the viewing site. Luminous intensity is a function of the luminaire itself – its design, tilt, orientation and lamp power. The luminaires are a semi-cutoff type with150 watt HPS lamps. They are one of the most common HPS luminaires found on traffic routes in New Zealand but are now being progressively replaced by LED luminaires. The semi-cutoff design of the GL600 means that upward light is well controlled but not fully prevented. The maximum luminous intensity found from these luminaires was 160 cd. For context the same technique used at the Wainuiomata hill site found individual floodlights had upward luminous intensities over 100 times greater.

3.3.2 Reflected Light:

The luminance of the Hutt road surface viewed from the Horokiwi site measured at 0.25 cd/m^{2}- somewhat less than that measured for the Urban motorway at Onslow gorge road. The average upward angle for this measurement is 15 °s and is markedly offset from the path of the road. A likely range at road level would be 0.75 – 1.0 cd/m^{2}.

3.3.3 lluminated Sign

At the edge of the view from the viewing site is an illuminated sign lit by four sign mounted spotlights (Figure 4-13) 670 metres in a direct line from the viewing site. The sign faces south bound traffic on the Hutt road. The upward angle from sign centre to the site is 1.8 °.

Figure 4-13: Illuminated sign. The measured sign face may differ from that depicted here.

The following results were obtained using the measurement techniques discussed earlier.

Upward angle to measurement site	1.8 °s
Average luminance of the sign	21 cd/m^{2}
Luminous Intensity of the sign	1,100 cd

These values relate to the viewing angles from the Horokiwi road site and apply to the light intensities and sign content that applied on the night.

3.4 Mt Victoria -City view

3.4.1 Introduction

The Mount Victoria lookout is located on a hill of 196 m altitude to the east of Wellington CBD and is a popular tourist viewpoint both day and night. The site has an overview of the CBD and the port area. The port area (figure 4-14) was of particular interest as it was identified in the 2018 sky glow study as a brightly lit area where the lighting did not vary throughout the night. The night photos were taken at 7.50 pm on Tuesday 9th April 2019 and the day photo on

Wednesday 10th April 2019. To be seen on Mt Victoria, light from the port area must be emitted at between 3° and 6° above the horizontal.

3.4.2 Results

Luminous intensity measurements were made of 8 port floodlights, 2 rail yard floodlights and the "Westpac STADIUM" lights sign. The results are shown in Table 4-4 with Figure 4-14 indicating which lights were measured.

Table 4-4: Measurements of upward Luminous intensity made at the Mount Victoria lookout.

ID Letter	Location	Horizontal Distance (m)	Upward Angle (°)	Luminous Intensity (Cd)	Equivalent HPS Lights (No.)
A	Port area	1,978	5.1	40	0
B	Port area	1,769	5.7	60	0
C	Port area	1,848	5.5	1,110	6
D	Port area	2,028	5.0	820	4
E	Port area	2,137	4.7	900	5
F	Port area	2,307	4.4	32,100	169
G	Port area	2,177	4.6	29,800	157
H	Port area	2,207	4.6	1,240	7
I	Rail yards	2,656	3.7	6,480	34
J	Rail yards	3,125	3.2	23,700	125
K	Stadium sign	2,546	3.8	7,260	38
TOTAL				103,510	545

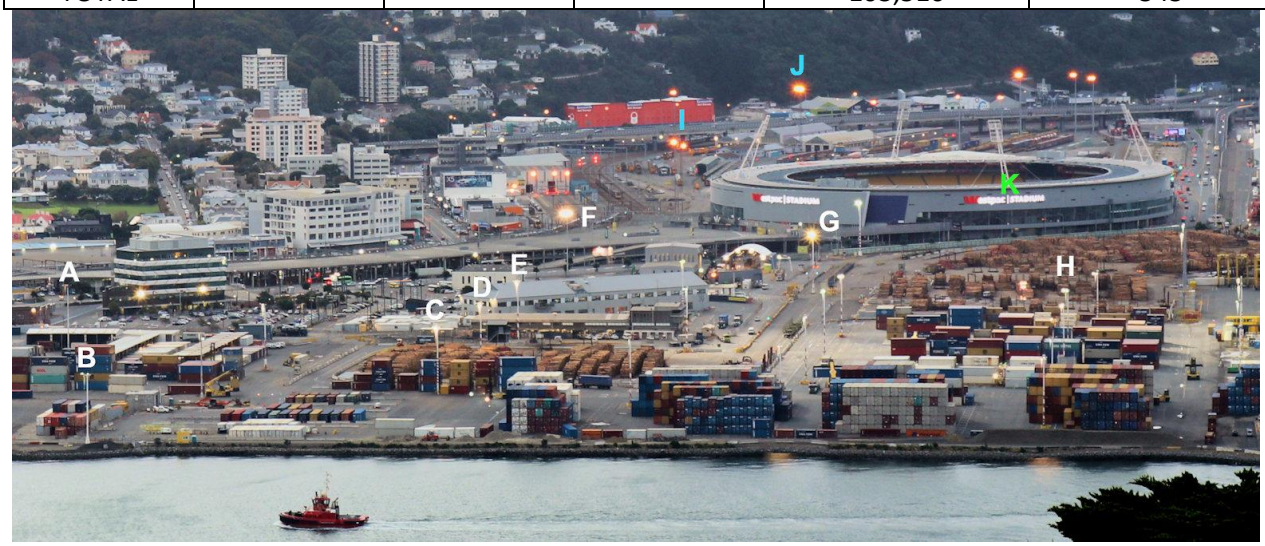

Figure 4-14: Photograph of the port area as viewed from Mount Victoria annotated with lettering. White letters show port floodlights, blue letters rail floodlights and green the "Westpac STADIUM" sign. This photograph merges two images, one day and one night so that the strength of each light can be seen.

Port Area:

The luminous intensity of upward light from measured floodlights ranged from 40 cd to 33,800 cd. While the luminous flux of the lights is not known, a large part of the wide variation appears related to their orientation or tilt. Figures 4-15 and 4-16 show 2 sets of LED floodlights close up. One is orientated with near zero tilt and the other at near 45°s tilt. The zero tilt lights produced 40 cd while the 45 ° tilt lights produced 32,600 cd of upward light: different by a factor of 800.

Figure 4-15: Light A with zero °s tilt. It produced uplight of 40 cd- less than a single HPS luminaire.

Figure 4-16: Light F with lilt near 45 °s. It produced uplight of 32,100 cd, equivalent to 170 HPS luminiares.

Railway Yards:
Floodlights in the rail yard and interisland ferry area were measured in the Onslow Gorge Road study. Two further floodlights were measured in this study. The floodlights I and J (Table 7-1 & Figure 7-1) were measured as producing upward light at 6,480 and 23,700 cds respectively.

Westpac Stadium Sign:
A measurement was made of the large "Westpac Stadium" sign (Figure 4-14, "K") a sign composed of many small individual lights. Viewed from the Mt Victoria lookout it produced 7,260 cd of upward light or about the same as 38 HPS luminaires.

3.5 Mt Victoria – Kilbirnie view

3.5.1 Introduction

The observation site was at the Mt Victoria lookout about 10 m to the south of the city viewpoint and facing south towards the airport and Kilbirnie. Figure 4-17 shows the centre of Kilbirnie as a night photo superimposed with the day photo to show the location of lights. Of note in this photo is the near total absence of light from any street lights. The lights visible are floodlights, car lights, domestic and commercial lights, interior lighting and illuminated signs. The area has been retrofitted with LED road lighting luminaires.

3.5.2 Results

Measurements were made of the floodlights at the Kilbirnie Pak n Save supermarket car park, the illuminated "Pak n Save" sign, sports lighting at Kilbirnie Park and sports lighting at the Newtown Athletics Stadium.

Figure 4-17: View of Kilbirnie from the Mt Victoria lookout. A day time photo superimposed with a night time photo. The letters refer to measured lights and signs.

Pak n Save:

Two modern LED floodlights (A and B) were illuminating the car park, the Pak n Save building and sign (C) (Figure 4-18). The upward light from each of the floodlights was around 4,000 cd. The "PAK n SAVE" sign itself recorded 2,200 cd. Including the whole north face of the building increased this value to 5,000 cd.

Figure 4-18: The Pak n Save floodlights A (left) and B (right) and behind the "PAK n SAVE" illuminated sign (C).

Kilbirnie Park: and Newtown Athletics Stadium

Two Kilbirnie Park sports light fittings (D and E, Figure 4-19) produced upward light of around 5,000 cd each. These lights would have been put out later in the evening once practice finished. The strongest single upward light source in the Newtown / Kilbirnie area came the Newtown Athletics stadium (off to the right of the Kilbirnie view of figure 4-17). Two individual lights (F & G) recorded 23,700 and 16,400 cd. However, the stadium is itself in an elevated position so that the upward angle to Mt Victoria is relatively small - a little over 1 °. That aside the floodlights have an almost horizontal tilt as can be seen from Figure 4-20.

Figure 4-19: Kilbirnie Park sports lighting (D&E) Figure 4-20: Newtown Athletics Stadium floodlight (F & G)

Table 4.5: Upward light measured from Mt Victoria of lights in the Kilbirnie – Newtown area.

ID Letter	Location	Horizontal Distance (m)	Upward Angle (°)	Luminous Intensity (Cd)	Equivalent HPS Lights (No.)
A	Pak n Save	2,536	3.9	3,620	19
B	Pak n Save	2,526	3.9	4,160	22
C	Pak n Save sign	2,546	3.9	2,230	12
D	Kilbirnie Park	2,107	4.7	5,390	28
E	Kilbirnie Park	2,117	4.7	4,960	26
F	Newtown stadium	2,981	1.3	23,700	125
G	Newtown stadium	2,981	1.3	16,400	86
TOTAL				60,460	318

4 Results

The results from each of the five sites have been combined in Table 6-1 to present performance data on Floodlights, HPS road lights and Illuminated signs.

Item	Floodlights	HPS Road lights	Illuminated signs
Sample size	49	12	3
Average upward viewing angle (°)	6.7	8.7	3.2
Maximum upward viewing angle (°)	14.7	16.7	3.9
Minimum upward viewing angle (°)	1.2	4.7	1.8
Total luminous intensity (Cd)	432,800	1,600	10,540
Average luminous intensity (Cd)	8,830	133	3,510
Maximum luminous intensity (Cd)	32,100	277	7,260
Minimum luminous intensity (Cd)	40	35	1,050
Total HPS lights equivalent	2,280	9	56
Average HPS lights equivalent	47	0.8	19
Maximum HPS lights equivalent	169	1	38
Minimum HPS lights equivalent	0	0	6

Table 6-1 Summary of study results by type of light.

The 49 floodlights produced a total of 432,800 cd upwards – the equivalent of 2,280 HPS category V road lights. The values ranged from 32,100 cd down to 40 cd. The average value per floodlight was 8,830 cd or the equivalent of 47 road lights.

Of the 100 LED road lighting luminaires none had any measurable upward light. Depending on the design and precision of the installation it is possible to have LED street lights emitting a small amount of upward light, but none were detected in this study.

The 12 HPS (150 w) road lighting luminaires produced a total of 1,600 cd ranging from 277 cd to 35 cd.

The three illuminated signs were all somewhat different in nature. Their combined output was 10,540 cd or the equivalent of 56 HPS road lighting luminaires. They ranged from 3,510 cd down to 1050 cd.

Car headlights: From a very limited sample (4), twin car headlights were found to average around 440 cd when viewed front on at 3 °s above the horizontal.

5 Impact of upward light on sky glow

The next challenge is to connect this uplight (Kinzey, Bruce, 2017) and the light emitted by reflection from the road surface to the actual quantum of sky glow. Kinzey, Bruce ,2017 used the "*Sky Glow Simulator",* (Kocifaj and Kundracik, 2016) to model some 200,000 sky glow scenarios on a super computer. More recently they compiled these scenarios into spreadsheet form called "Sky glow comparison tool v1.0" [Kinzey, Bruce, 2018] so that it is now possible to isolate some of the effects of these variables modelling. Using this tool, the impacts of different values of "% uplight" (also known as the Upward Waste Light Ratio (UWLR) were tested. The results are shown in Tables 7-1 and 7-2. They account for both sky glow from upward light from luminaires and light reflected from the road. When there is no uplight, all the sky glow impacts are from reflected light from the road surface. At 2%, 5%, 10% an increasing proportion of the sky glow will be due to direct light from the luminaire.

Table 5.1: Relative sky glow by luminaire type and %uplight.

	% uplight			
Light source	0%	2%	5%	10%
HPS	1.00	1.27	1.58	1.95
LED (2719K)	1.00	1.27	1.58	1.94
LED (4075K)	1.00	1.25	1.55	1.89

Sky glow is measured for the "near" condition (within the city), "unweighted" (photopic sensitivity) and clear low particulate skies.
It can be seen from Table 5-1 that:

- Sky glow is very sensitive to even small percentages of uplight. Just 2% uplight from a luminaire was predicted to create a 27% increase in sky glow compared to no uplight.
- The proportional increase in sky glow as the uplight percentage increases is very similar across all light sources so in Table 5-2 only one source (HPS) is tested.

Table 5.2: Relative sky glow for a HPS luminaire where sky glow is measured both "near" and "distant" and with scotopic or photopic sensitivity.

		% uplight			
Condition	**Sensitivity**	0%	2%	5%	10%
Near (city limits),	Photopic	1.0	1.27	1.58	1.95

	Scotopic	1.0	1.25	1.54	1.88
Distant (40km),	Photopic	1.0	20.7	43.7	70.9
	Scotopic	1.0	21.2	44.8	72.9

It can be seen from Table 5-2 that:

- While luminaire %uplight had a strong effect on sky glow in the Near (city limits) condition, for the Distant (40 km) condition it was dominant
- Photopic and scotopic sensitivity[2] behaved similarly when distance from the city was varied.
- if just 2% of the light from a typical luminaire is directed above the horizontal its overall contribution to sky glow is will increase by 27% in the urban area and by 20.7 times in areas 40 kilometres distant (e.g. for Wellington to the Wairarapa).

Therefore, upward light direct from the luminaire has a disproportionately strong effect on sky glow. These calculations also provide some information on the likely effect that light reflected from the road surface has on sky glow. Taking the urban situation when 2% of the light from the luminaire is directed upward it causes 27% of the sky glow so the corollary is that the other 98% of the light (downward) would cause 73% of the sky glow. As downward light results in road surface reflection this provides a guide on the role lit road surfaces have in sky glow. These figures suggest that per lumen of light emitted, light directed in an upwards direction has some 14.5 times more impact on local sky glow than light emitted below horizontal. If a distant measure of sky glow is the concern (40 kilometres away) then reflection of light from the road surface has little impact and the DoE results suggest that upward light has some 990 times more impact than downward light. Mathematically:

If U and D represent the upward and downward sensitivity of a given flux (fu, fd) to cause sky glow (SG) then SG= fu U + fd D
Normalise by setting the condition of no uplight as producing sky glow of 1 (i.e. fu = 0, fd = 1, D = 1 and SG = 1) then for the "near" condition of 2% uplight causing 1.27 times more sky glow: 0.02 U + 0.98 = 1.27, which simplifies to U=14.5 meaning uplight causes 14.5 times more sky glow per unit of flux as down light.

Applying the same logic to the "distant" condition gives U = 990. That is for the "distant" condition uplight causes nearly 1000 times more sky glow per unit flux than down light.

Van Bommel (2014) describes the concept of a large imaginary box encompassing the luminaire and the entire surface that is intended to be illuminated. Van Bommel specifies that no more than 15% of total outward flux (from both luminaire and reflected light) should pass through the upper or side walls of the construction. That is, with good lighting, 85% of the light generated in the box remains in the box--a simple concept that places controls to reduce both sky glow and spill light. NZ category V lighting standards allow a maximum of 3% uplight from HPS luminaires. Of the 97% downward light, approximately 1/14th (7%) would eventually be reflected back upwards. That puts the sum of all upward light at around 10%. Van Bommel specifies a maximum of 15% figure to cover both spill light and upward light, so the two approaches are not inconsistent.

[2] Photopic vision uses the eye's cone cells and has good performance in well-lit environments, but performance degrades as the light dims. Scotopic vision uses the eyes' rod cells only, foregoing colour sensitivity but allowing for contrast perception at low light levels.

6 Discussion

These results put floodlights into a group of their own at the top of the list when it comes to upward light. For a local authority concerned about sky glow this is an obvious area where improvements could be made. Often a reorientation of the floodlight so that the light is directed closer to vertically downwards would bring substantial improvements. Modern LED fittings like those in Figure 4-15 offer light control that results in very little upward light.

The road lighting industry has maintained contact with astronomy interests through standards groups and, over many years, has progressively reduced the amount of upward waste light that road lighting luminaires are permitted to produce. The advent of LED lighting has allowed further improvements and from this limited study it appears that modern LED road lighting fixtures are achieving something close to zero direct upward light.

Wherever they were measured LED street lights produced little or no upward light, with the main upward light being that reflected from the road surface.

The Sky glow simulator (Kinzey, 2017) suggests that sky glow creation is between 14 (for near viewers) to 1000 (for distant viewers) times more sensitive to direct upward light than it is to downward light.

7 Conclusions

- Direct upward light be it from luminaires or floodlights had a much more powerful effect on sky glow than light which had initially been directed downward. Results from the sky glow simulator suggest the sky glow from upward light is stronger by a ratio of 14:1 for near (10km) observers and 1000:1
- Floodlights in the study were the strongest single source of upward light producing between 10 and 150 times more upward light than a single 150 watt HPS road light. The average value was 50 times more upward light.
- HPS road lighting luminaires in this study produced an average of 130 cds of upward light but no measurable upward light was detected from the LED road lighting.

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