Estimating the Amount and Source of Night-time Light

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Energy Science

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Declaration

'I Anna Horvath declare that this thesis is my own work except where stated through references or in the acknowledgements and that it is 9298 words in length'.

Acknowledgements

First and foremost, I would like to thank my supervisor, Dr Brian Espey, for his continuous guidance and support throughout the project. I would also like to thank Ross Gaynor for providing the pan-sharpened SDGSAT imagery and Ethan Nolan for providing the masks used in this work.

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1 Abstract

The global share of electricity consumption related to lighting reduced to 12% in 2024 from 18% recorded in 2005, but artificial light output increased from 135 petalumen-hours (Plmh) to 240 Plmh between 2005 and 2024. This increase in light output has been investigated using satellite imagery, which captures urban activity from various illumination sources such as street lighting, residential lighting, and commercial lighting, collectively referred to as Artificial Light at Night (ALAN). The growth in ALAN has not been fully understood whether it is due to increased street lighting, or other light sources. However, previous studies lacked investigation of the combined importance of nighttime light sources stemming from street lighting, residential lighting, and commercial lighting together, and were instead focused on only one of them. Here, we show using data from the Sustainable Development Goals Science Satellite 1 (SDGSAT-1) with a spatial resolution of 10 m alongside International Space Station imagery and the Visible Infrared Imaging Radiometer Suite (VIIRS) that there is more than 50 GWh of electricity use in Dublin resulting in 11,500 tonnes of CO_2 emissions annually related to public and private lighting. We show that the largest light contribution comes from residential areas and from areas of high commercial activity, which correlate well with electricity use. Thus, results demonstrate that private lighting is a major contributor to electricity use and to related CO_2 emissions. The main subject of environmental policy has so far been focused on public lighting, which is important but does not address the problem around the high energy demand related to lighting. Hence, environmental policy must also include private lighting measures. The project describes spatial and temporal variation of light output in different land use areas in Dublin to investigate which are the largest contributors that should be considered in energy efficiency policies. Private lighting from commercial and residential areas is characterised by poorly directed and shielded lights. Sharpened SDGSAT imagery shows that such lights tend to emit light upwards and sideways, thereby contributing to energy lost to space and to skyglow above cities. The project also contains recommendations to reduce the energy demand of both private and public lighting.

2 Introduction

Artificial light at night (ALAN) has risen over the past century due to increased population and rising economic activity (Kyba et al., 2017). ALAN sources stem from residential outdoor lighting, street lighting, facade lighting of commercial stores or monuments, floodlights, and light escaping through windows from buildings. Artificial lighting negatively impacts ecosystems, human circadian rhythms and reduces dark sky areas globally (Cabrera-Cruz., 2018, Walker et al., 2019). Furthermore, there is very little public awareness about the large contribution of public lighting to municipal electricity use, which can account for up to 40% of a municipality's budget, overall energy demand and overall CO_2 emission (Codema, 2021). Whilts, the global share of electricity consumption related to lighting dropped from 18% in 2005 to around 12% in 2024, artificial light output increased from 135 petalumen-hours (Plmh) to 240 Plmh between 2005 and 2024 (Bardsley et al., 2024). This discrepancy underscores an improvement in lighting technology due to the widespread retrofitting of older incandescent fixtures with more energy efficient lamps. However, few studies have assessed the impact of illumination sources other than street lighting on artificial light pollution and potential energy savings. While retrofitting public street lighting is highly advantageous and can prevent the emission of substantial amounts of CO_2, this project also considers the importance of commercial and residential lighting as an unexploited area where further energy efficient measures ought to be taken.

2.1 Public lighting

Public lighting plays an important role in reducing crime rates and traffic accidents. In Dublin streetlights consist of older discharge lighting technologies such as low-pressure sodium lamps (SOX), high-pressure sodium lamps (SON), and modern light emitting diode (LED) lanterns. Small fraction of public streetlights is comprised of compact fluorescent (CFL), metal halide, or mercury lamp types. The older SOX and SON lamps are still widely used in urban areas due to their high lumen per watt output and relatively long lifespans, ranging from 12,000 to 30,000 hours (SEAI, 2017). SOX lamps produce a characteristic orange light, while SON lamps emit a yellow-pink glow. As these discharge lights have a restricted range of emission lines, both have low colour rendering indexes (CRI). This is a measure of how colours are represented under a given light source on a scale of 0-100, 100 meaning that colours appear just like under natural light. SON and SOX lamps have a CRI typically between 25 and 85 (SEAI, 2017), which means that colours are poorly represented under their light. Despite these lights have relatively high luminous efficiency, measured as the amount of light produced in the spectral region of the human eye's peak sensitivity, they have lower electrical efficiency when the associated electronics are included. Furthermore, the nature of the tubular or lamp sources creates difficulty in terms of optics (Espey, 2021). As a result, as much as 36% of the light from older SOX units is projected above the horizontal, contributing to the scattered light appearing as skyglow observed over urban areas (Figure 1). Besides this obvious light and energy loss, one further difficulty with older discharge lighting is that it takes time to reach optimum light output. Moreover, they cannot be easily dimmed which restricts their operation to full output throughout the night, including dawn and twilight hours, resulting in further energy waste.

Figure 1. Skyglow above Dublin. Picture taken by Prof. Brian Espey. Source from: https://www.darksky.ie/comet-neowise/

This is the reason why many European countries have decided to act upon the energy waste related to public lighting. In Croatia and Greece laws require lights to be fully shielded which means that no light should be emitted above horizontal (ULOR = 0%) and impose strict correlated colour temperature (CCT) caps between 2200–4000 K depending on area, in order to reduce waste and light pollution (Espey, 2020)

LED lights offer much higher electrical efficiency (around 120-150 lm/W), with lifespans ranging from 25,000 to 75,000 hours and a CRI between 65 and 97 (SEAI, 2017). While retrofitting to LED lighting has a higher initial cost, the energy savings and extended lifespan result in a payback period of 1–7 years, depending on the scale of the retrofit (SEAI, 2017). For instance, in Dublin public lighting accounts for 40% of each council's energy budget (Codema, 2021) and, similarly, around 40% of a councils' CO_2 emissions are attributed to public lighting. As a result, ambitious targets have been set to retrofit older SOX and SON systems with more energy efficient LED lighting.

2.2 Other sources of nighttime light

Commercial lighting refers to lighting used for the illumination of retail services, including façade lighting, outdoor wall lights, decorative lights, self-luminous lights, spotlights, and floodlights (Figure 2). These lights are commonly LED types, although many of them emit light the on a horizontal plane or above, thereby contributing to skyglow and wasting the radiated energy upwards (Figure 2). Commercial lighting is generally designed to attract the attention of customers, yet their continued use late at night may not be justified. For example, after midnight the illumination of stores and festive lighting no longer serves an essential function, unlike street lighting on roads. That's why among the first countries, France in 2018 mandated that interior lights in non-residential buildings, shop windows, and parking area lighting must be switched of by 1 a.m or one hour after closing. Furthermore, all outdoor lighting must be shielded to prevent upward light emissions and energy waste (Ministère de la Transition écologique, 2019).

Finally, residential lighting describes light sources escaping through private windows, garden decorations, wall-mounted lights and decorative lighting. All types of lights mentioned above can be detected by satellites hence, observations from space enable urbanised and industrialised areas to be studied. (Figure 3).

a)

b)

c)

d)

Figure 2. Light sources from different land use types. (a) Clayton Hotel Merrion road highlighting poorly directed wall-mounted lights and decorative upward facing garden lighting. (b) High mast lights on sport field. (c) Picture taken by Brian Espey in Roundwood showing festive lighting, light diffusing through private windows and old poorly directed SON lamp. (d) Picture of Grafton Street in December showing decorative lights and self-luminous lights above retail units.

Figure 3. Pan-sharpened SDGSAT-1 imagery of Dublin at nigh. Work of Ross Gaynor.

2.3 Satellite imagery

Previous research has shown that ALAN can be used as a proxy for tracing population density, human development, electricity use, and even natural disasters and wars (Zhou et al., 2018, Li et al., 2017, Bhattarai et al., 2023). Previous ALAN studies used the US Air Force's Defense Meteorological Program/Operational Line-Scan System (DMSP/OLS) weather satellite data or the dedicated Visible Infrared Imaging Radiometer Suite (VIIRS) data from the National Oceanic & Atmospheric Agency's SUOMI satellite which had 3 km and 750 m spatial resolution, respectively. However, due to their low spatial resolution and wide swath sizes these studies lack finer scale detail and this limits their application in ALAN studies. In 2021 the Chinese Sustainable Development Goals Science Satellite 1 (SDGSAT-1) was successfully launched, and this spacecraft can capture images with a multispectral resolution of 40 m, panchromatic resolution of 10 m, and a swath width of 300 km which allows for the identification of individual buildings while sometimes even headlights from a single car can be identified. This huge improvement in resolution has promoted numerous ALAN studies to better understand the drivers of light pollution and to find ways in which it can be mitigated. In this study the SDGSAT-1 satellite imagery is used alongside with data of similar resolution sourced from the international space station (ISS: EOL, https://eol.jsc.nasa.gov), and also the lower resolution Visible-Infrared Imaging Spectrometer (VIIRS) instrument (NASA Black Marble Product, https://blackmarble.gsfc.nasa.gov/) . Differences in overpass time permits us to capture a snapshot of lighting over Dublin at various points at night. The overpass time of the SDGSAT over Dublin takes place at around 21.35, capturing peak urban activity, while the VIIRS records imagery between 1.30 and 1.40 am, thus documenting late night urban activity. Moreover, as VIIRS data is available from 2015 this allows us to assess how radiance output from Dublin changed throughout the last 10 years. The ISS imagery has an unregular overpass time yet in this project imageries taken between 21.20 and 23.30 were used.

2.4 Drivers of light pollution

As mentioned previously, lighting has an associated electricity demand and CO_2 emission. Therefore, any way in which its efficiency can be improved or its operational time reduced is favourable. To achieve this, one must understand the drivers of light pollution. By combining the data provided in the 2015 CODEMA Energy Demand Analysis (Codema, 2015), with our space measurements, it is possible to compare the relationship between energy use and radiance. Radiance is the standard unit used in ALAN studies expressed in $nW/cm^2/sr$ or $mW/m^2/sr$. In this study radiance is reported in both (i) summed radiance over polygons which gives the total radiant intensity in nW/sr, and (ii) mean area normlaised radiance which is calculated by dividing the radiance by area, expressed in $nW/m^2/sr$. The latter one can provide a measure of average brightness per unit surface area. This report used the CODEMA detailed breakdown of energy use per electoral area and associated population data to enable the calculation of radiance per capita as well.

To support this analysis, the open-source Quantum Geographical Information System software (QGIS) (http://www.qgis.org) was used to process and visualise both vector and raster data. It was used to create and process shapefiles, which are standard GIS data formats that store geometry and attributes of spatial features such as boundaries, roads, or land parcels (Yin et al., 2024). Using vector shapefiles obtained through the open source OpenStreetMap (OSM) (https://osmfoundation.org), different land use types in Dublin could be identified, such as shopping centres, universities, offices, the airport, and Dublin Port. These shapefiles were then used to process related information on electricity use and radiance, thereby allowing to compare summed radiance and electricity use between different land use types.

Since data is only available for public streetlighting energy use and there is a lack of energy utilisation data for private lighting, it is difficult to estimate the overall energy demand related to lighting. Therefore, in this project, a calculation methodology is employed to estimate how much energy was required to produce the detected amount of radiance by the satellite. The quantification of upward flux can then be used to quantify the associated electricity use, CO_2 emissions, thereby providing a useful metric for public municipalities and authorities.

To distinguish between different types of public lamps spectral masks were created in R and applied to satellite imagery to isolate light emitted at specific wavelengths which is characteristic for each type of lamp. For example, LED lights have a driver peak in the blue region at 470 nm, which can be detected by the SDGSAT satellite using RGB information (Figure 4).

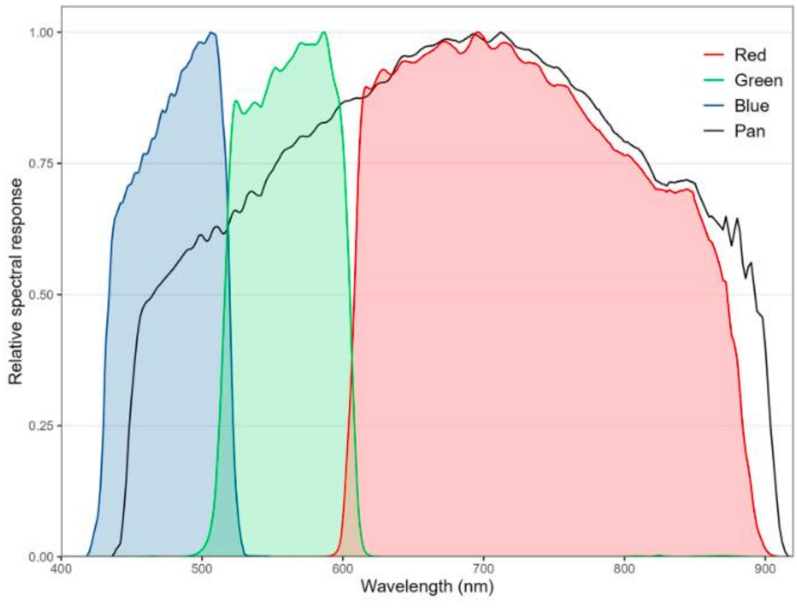

Figure 4. Spectral response of the SDGSAT's GI sensor. Figure adapted from Yin et al., 2024

3 Aims and objectives

The aim of this project is to quantify nighttime light emissions over Dublin using satellite imagery and to relate them to different land use types, electricity utilisation, and lamp types. To achieve this aim, the following questions are aimed to be addressed:

- What type of land uses are the biggest contributors to light emissions?
- What areas are characterised by the highest mean radiance?
- How has radiance changed over time in Dublin?
- Does radiance correlate with electricity use, and are there any distinct spatial patterns in Dublin?
- Is public street lighting the main contributor to electricity demand, CO_2 emissions, and light output?
- Can satellite imagery data be used to give an estimate about the energy requirement of lighting on the ground?
- How can public and private lighting be made more energy-efficient and sustainable in order to reduce energy demand, CO_2 emissions, and light pollution?

4 Methods

4.1 Calibration

The SDGSAT raw satellite imagery was provided to Prof. Brian Espey. The Visible Infrared Imaging Radiometer Suite satellite imagery was produced by the Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines (https://eogdata.mines.edu). These data are provided as digital numbers (DN), which represent the intensity of light recorded in each pixel. However, these are not physical units, so they must be converted into radiance to allow further analysis. The calibration of the SDGSAT imagery was carried out using R language in the Rstudio Environment using gain and bias coefficients specific to the PH (Panchromatic High Gain) band, as provided in the accompanying metadata file (calib.xml) which is available in the download package from the SDGSAT website (sdgsat.ac.cn). The calibration used the following expression (1) which yielded units of ($W/m^2/sr$):

$$L=(DN\times gain+bias)\times\Delta\lambda. \quad (1)$$

Where DN is the raw digital number, gain and bias are the sensor-specific calibration constants, Δλ is spectral bandwidth of the PH band (0.466 μm) (SDGSAT User Handbook, 2022).

The applied constants adopted in this work were:

Gain: 0.0000643698
Bias: 0.0000183897
Bandwidth: 0.466 μm

Table 1. Calibration constants

The raw ISS RGB imagery data is similarly provided in non-physical units of digital numbers (DN). To convert to broadband radiance, the calibrated values are in units of nW/cm^{-2}/ $Å/sr^{-1}$. Next, these values are integrated over each filter's spectral response using the effective bandwidth (**λ** effective) provided in (Table 2), as such the final results are expressed in $nW/cm^2/sr$ for red, green and blue channels which allows for comparison between ISS, SDGSAT and VIIRS data. These images are taken by astronauts using digital SLR cameras such as Nikon D3S from the International Space Station, as documented by NASA's Earth Observations Laboratory (EOL, https://eol.jsc.nasa.gov)

Band	λ effective (nm)	Filter Width (nm)
Red	6090.68	714.13
Green	5359.96	967.33
Blue	4867.20	662.01

Table 2. calibration ISS

The VIIRS Day/Night Band (DNB) Level-1 products are already radiometrically calibrated in units of $nW/cm^2/sr^1$ therefore, no additional calibration is necessary prior to analysis (NASA Black Marble Product, https://blackmarble.gsfc.nasa.gov/).

Once the raw data had been calibrated, the satellite image could be analysed in QGIS and in the Rstudio Environment. The raster image contains recorded measurements for each pixel (in $W/m^2/sr$), which correspond to specific locations. These values can then be linked to land use or energy use data within a given area.

4.2 Land use

First, using QGIS shapefiles were downloaded from OpenStreetMap (OSM) for different land use types (Table 3), making sure they cover a broad range of land uses (Coesfeld et al., 2018). Next, the detected radiance values within each area were summed and each value was multiplied by its pixel area to calculate total radiant intensity (nW/sr) for each polygon. The 'exact_extract' function from the 'exactextractr' package in R was used, which extracts values (radiance) from raster imagery. Finally, mean area normalised radiance was calculated by dividing the total radiance by the polygon feature's area which describes how bright is the source which was expressed in $nW/m^2/sr$. This was important because large areas, like parks, may show high total radiant intensity simply due to their size, yet their area normalised mean radiance is low. We assumed a Lambertian emission therefore for the temporal changes, total radiant intensity values were multiplied by π to remove the steradian term, resulting in radiant flux reported in kW as the total light output.

1. University	9. Greenhouses
2. Shopping centre	10. Dublin port
3. Sport fields (GAA, soccer, hockey, rugby)	11. Residential
4. Data centre	12. Parks
5. Prison	13. Hotel
6. Luas stations	14. Restaurant
7. Office	15. Public buildings
8. Airport	

Table 3. List of investigated land use types

This analysis was repeated for all available SDGSAT image dates to better understand how light output changes over time.

4.3 Codema: energy and population data

We made use of the 2015 Codema Energy Demand Analysis Report (Codema, 2015), which includes a detailed breakdown of energy use data for each electoral area in Dublin. The dataset also contains population data from the 2011 census, which was updated using a more recent version from 2016. The CODEMA data provides information on total energy use, total electricity use, and commercial electricity use, which allows for the estimation of non-commercial electricity consumption.

As the data is available in shapefile format, it includes spatial information and can be analysed alongside radiance data recorded by SDGSAT for different dates in both QGIS and R. This dataset was used to better understand spatial patterns in energy use and the relationship of energy with radiance across Dublin. As the case of the land use type analysis, the exact_extract function from the exactextractr package in R was used to extract radiance values for each electoral area expressed in (W/sr) and mean radiance expressed in $mW/m^2/sr$. These radiance measurements were then compared with the CODEMA electricity use data to assess their relationship for each electoral division. Moreover, by using population data, radiance per capita was obtainable for each area.

To gain a deeper understanding of the relationship between electricity use and radiance, a non-parametric Kendal partial correlation test was carried out using the ppcor package in R, while controlling for population density. This made it possible to isolate the relationship between electricity use and radiance, removing the confounding effect of density which well correlates with radiance (Appendix 10.3). In other words, it helped confirm whether electricity use and radiance are genuinely correlated, or if the correlation is due to the effect of areas with higher population density.

4.4 Public lights and masks

Public lighting data was acquired from data.gov.ie website (Government of Ireland, 2021). The public lighting information is unique to each Council in Dublin, therefore, they had to be downloaded and processed individually. All data originates from 2021 except for that for Fingal Council which dates to 2016 provided to Prof. Espey by the Fingal Council lighting engineer. This is an important note to make as transition to LED lighting under the Public Lighting Energy Efficiency Project (PLEEP) has been ongoing and therefore, numbers might differ as of 2025. Public lighting data includes information on (i) geographic location of lamp posts to the nearest metre, (ii) rated (nominal) and assessed wattage including electrical circuit load, (iii) specific description of lantern type e.g. LED, SON, SOX, or metal halide. This information is used to calculate the energy consumption of lamps within an area to compare the total energy requirement of streetlighting (see next section for more detail). To identify areas dominated by distinct lamp type emission (Figure 5), threshold values were applied to the ISS imagery bands. The Normalized Difference Lamp Index (NDLI) approach was employed (Sánchez et al., 2022) to filter for areas dominated by blue light emission distinct of LED lamps as follows:

$$NDLI = \frac{R-G}{R+G} \tag{2}$$

Where R and G denote red and green bands respectively. To avoid division by zero pixel where $R + G = 0$ were excluded. Before applying the NDLI approach, sample areas around known lamp types using the public streetlighting data were used to extract their RGB values and confirm the spectral differences between LED and non-LED sources.

The threshold condition to create a mask were as follows:

- Pixels with $NDLI < 0$ were assigned a value of 1 (indicative of LED/white light, which has higher blue content).
- Pixels with $NDLI > 0$ were assigned a value of 0 (non-LED)

This selection created a binary mask which was applied to the original ISS image. Thus, the mask retained only pixels classified as LED (value = 1), highlighting areas of dominant blue-rich lighting.

The SON and SOX masks were created by Ethan Nolan by analysing the distinct spectral signatures of these lamp types. As each lamp type has a characteristic spectral emission curve (Figure 5), ratios of the red to green (R/G) and blue to red (B/R) bands were investigated to distinguish between their emissions.

a)
b)

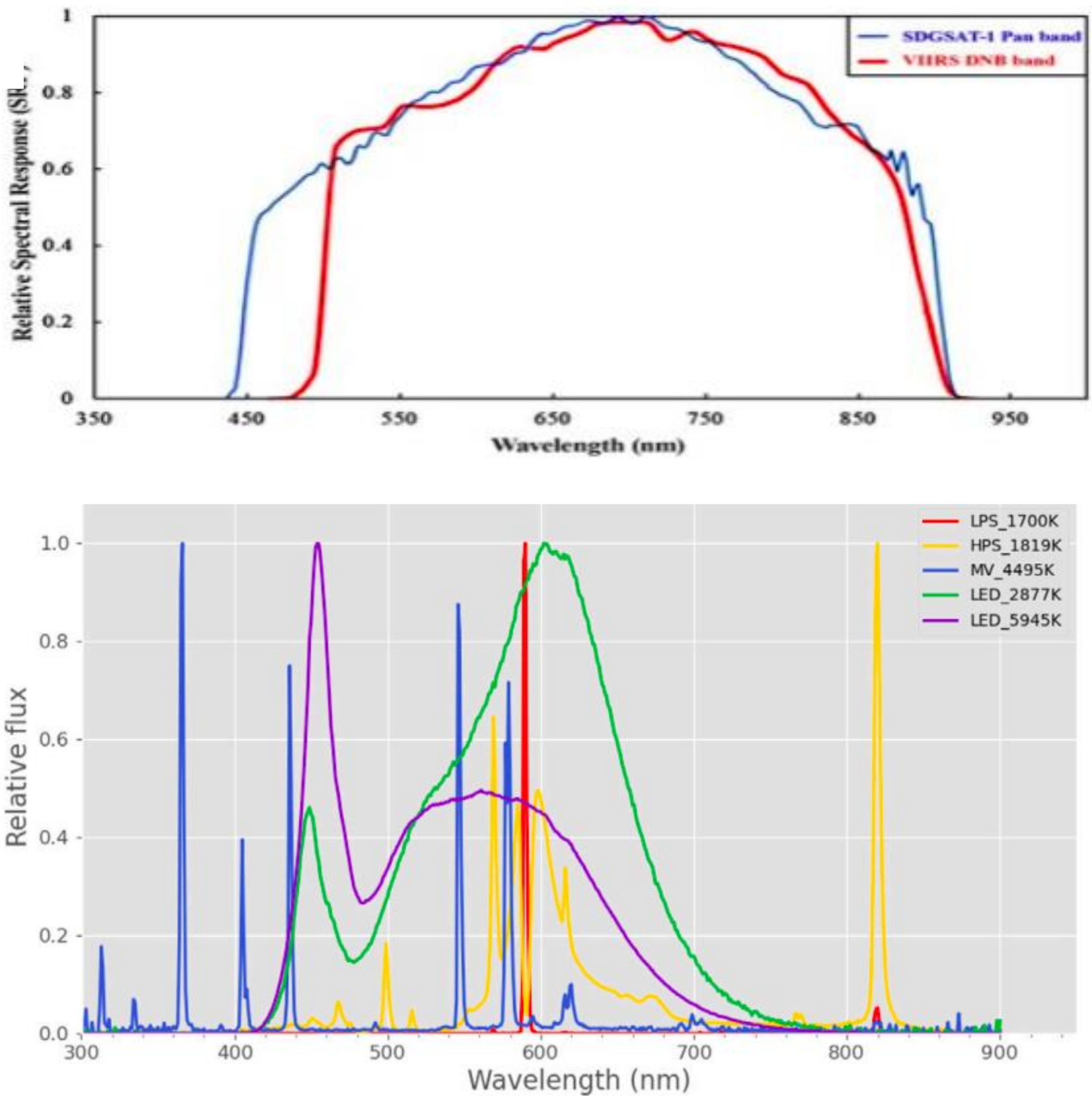

Figure 5. Top image (a) shows the VIIRS DNB and SDGSAT panchromatic passband relative spectral responses. Adapted from the work of Prof. Brian Espey. Image on the bottom (b) shows the radiative flux for different lamp types. Adapted from (Bustamante-Calabria et al., 2024). Note that, unlike the VIIRS DNB band, the SDGSAT instrumentation has the advantage of covering the peak of the blue driver emission characteristic of LEDs at 470nm.

4.5 Energy conversion

After calibration, satellite imagery provides radiance values in W/sr for each pixel, which can be integrated to obtain the overall energy detected in the SDGSAT passband. To relate this radiative energy detected by the satellite instrumentation in the form of photons (W_{photon}) to the electrical energy consumed on the ground ($W_{electrical}$), a conversion methodology is required. This conversion can be very useful as environmental policy and efficiency analysis are expressed in terms of electrical energy, while the satellite records photon energy.

To do this, a number of factors need to be accounted for, and these are discussed in turn below. (i) Atmospheric transmission refers to the proportion of light that passes through the Earth's atmosphere without being scattered or absorbed. As artificial light travels upward from the ground, particles in the atmosphere such as dust, water vapour, aerosols, and clouds can interfere with it. Some of the light is scattered in different directions or absorbed by these particles which means that only a fraction of the original light reaches a satellite sensor in space. A value of 74% is used in this study suggested by the work of Prof. Brian Espey. (ii) The emission towards the zenith (spacecraft) is a portion of the total upwards emission and hence, a correction factor has to be applied to account for the emissions in other directions. The ratio of total to zenithal emission is 10.8 for SOX lamps and 3.7 for other lamp types (Espey, 2023). (iii) The photopic ratio expresses how much of the lamp's emission detected in a broad spectral band by the satellite instrumentation (e.g. 400–900 nm) corresponds to the portion visible to the human eye (photopic vision, ≈ 400–700 nm). The ratio is defined as radiance in detection band divided by the photopic radiance. A ratio greater than one indicates that a lamp emits a large proportion of its light outside the visible range of the human eye. (iv) The luminous efficacy of radiation is accounted for by multiplying the detected radiance by the calculated lm/W value which is unique to each lamp type (Table 4). This expresses how effectively the lamp converts photon energy into visible light (lumens) in the photopic range. This is determined by taking the total luminous flux and divide by spectral power. Therefore, a higher value relates to a more visually useful light per unit of radiant energy in the visible spectrum. (v) Following that, the luminous efficacy of electrical power is accounted for. This aspect describes how many lumens of light are produced per watt of electrical input which is commonly used when evaluating lighting efficiency policies. (vi) Finally, the calculated values are corrected for the transmission losses involved in delivery of the electrical power to each location amounting to 8% (SEAI, 2024).

The calculation uses the Dublin public streetlight dataset with the city divided into road regions and non-road regions (complementary area of roads region), as these have different reflectance properties. The calculation for the roads region includes a 15% reflection factor typical of roads (Gilbert et al., 2017). While, for the non-road regions (industrial estates, sports fields, ports) are assumed to have no surface reflection.

Lamp type	400-900nm/Photopic	VIIRS DNB/ Photopic	lm/W_{photon}	$lm/W_{electrical}$
SOX	1.47	1.25	516.4	200
SON (250/400W)	2.4	1.98	467.94	100
LED 4000K	2.18	1.5	405.61	120

Table 4. Electrical- and luminous efficacy values, photopic ratio used in the energy conversion calculation from W_{photon} to $W_{electrical}$. Values were derived by Prof. Biran Espey.

5 Results

The analysis of the VIIRS data (https://blackmarble.gsfc.nasa.gov/) over time showed that the detected radiance varies over years and between the days of the week. The overpass time of the VIIRS satellite is at 1:30–1:40 am, therefore, this dataset can describe baseline urban activity. The lowest detected radiance of 98 kW was obtained for the data for the 5th of February 2022. However, images reveal that cloud cover may have influenced the imagery of the satellite on that night and, therefore, it was dropped from the temporal comparison. Excluding the 2022 data, the 2015 and 2024 weekday data are the lowest, with 148 kW and 150 kW respectively, while the 2024 weekend data showed the highest detected radiance of 165 kW.

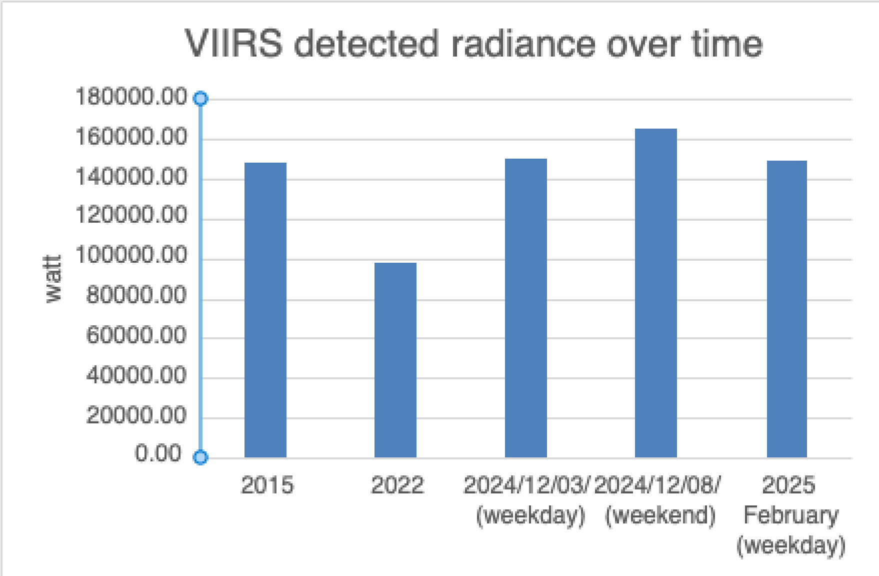

Figure 6. Radiance changes over time using VIIRS data.

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5.1 Inner outer city

Dublin City Council was divided into two areas – an inner and outer part divided by the Royal Canal on the north side and the Grand Canal on the south side and was tested whether the inner city was the dominant contributor to the combined radiant intensities (inner +out city). The inner city part represents 10 % of the total investigated area, while the outer city area represents the remaining 90%. Using the SDGSAT data, the inner-city radiance (in MW/sr) share shows relatively consistent values, suggesting that the inner city is responsible to almost one-third of the radiance recordings. However, the 2022 and the 2025 data have lower contribution of 21 and 22 % respectively. In 2024, even though the two dates originate from the same week, the weekday night has a higher value of more than 2% compared to the weekend value.

	inner city MW/sr	outer city MW/sr	total dublin MW/sr	share of inner city
2022.02.04	13	50	63	21%
2024.12.02	28	68	96	29%
2024.12.07	24	64	88	27%
2025.02.04	20	72	92	22%

Table 5. Comparison of inner and outer city radiances for 4 dates in order to see how the city centre contributes to overall light emission.

5.2 Land use

In this work, 15 different land use categories were analysed (Table 3). Using the SDGSAT data from four dates (Appendix 10.1a), the largest light emission came from residential areas, parks, sports fields, and car parks, measured in nW/sr. Large areas such as Phoenix Park and Bull Island appear to have high total radiant intensity (nW/sr) because they accumulate scattered light from across the city. Their high totals are mainly due to their large size rather than dense network of lighting. However, when their area normalised radiance is considered, these areas apart from sports fields are among the least bright. The highest area normalised radiance was measured for hotels on the weekday of 02/12/2024, with a value of 4 $nW/m^2/sr^1$. Following that, restaurants, offices, Luas stations, public buildings, and shopping centres were identified as the brightest sources. The lowest area normalised mean radiance was measured for parks, with a value of 0.1 $nW/m^2/sr^1$.

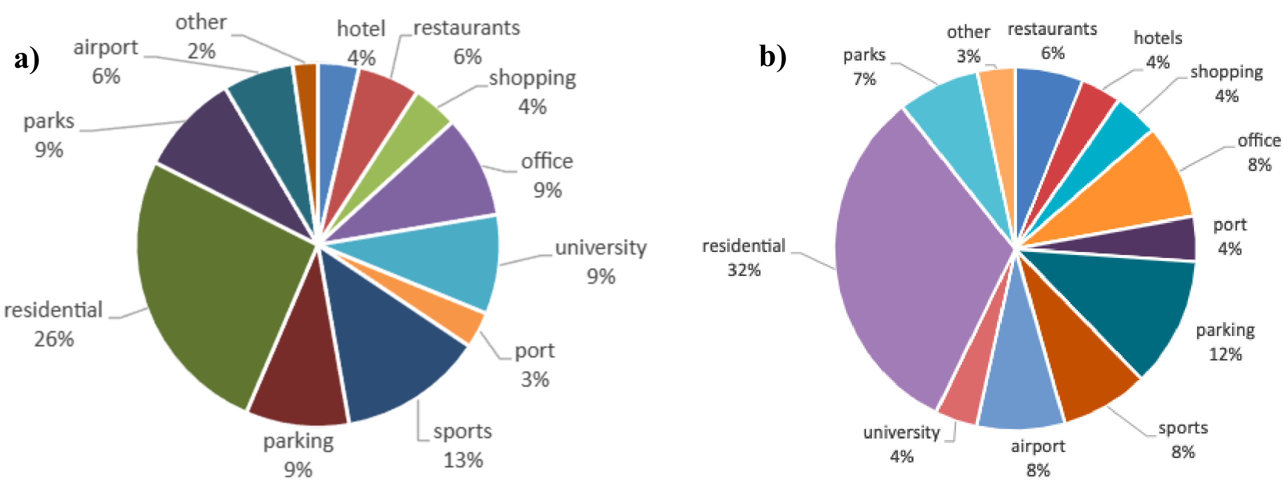

Figure 7. Radiance contributions of land use types using the (a) weekday data of 2nd of December and the (b) weekend data for the 7th of December 2024. "Other" category designate the sum of greenhouses, train stations, data centres, luas stops, public buildings, prison.

As satellite imagery was available for different dates in 2024 covering both weekdays and weekends, it was possible to compare whether the recorded radiances deviated from each other. However, these values do not represent the overall light emission from

Dublin, since not the entire area was classified into land use categories but rather focused on the city centre and surrounding land use activities.

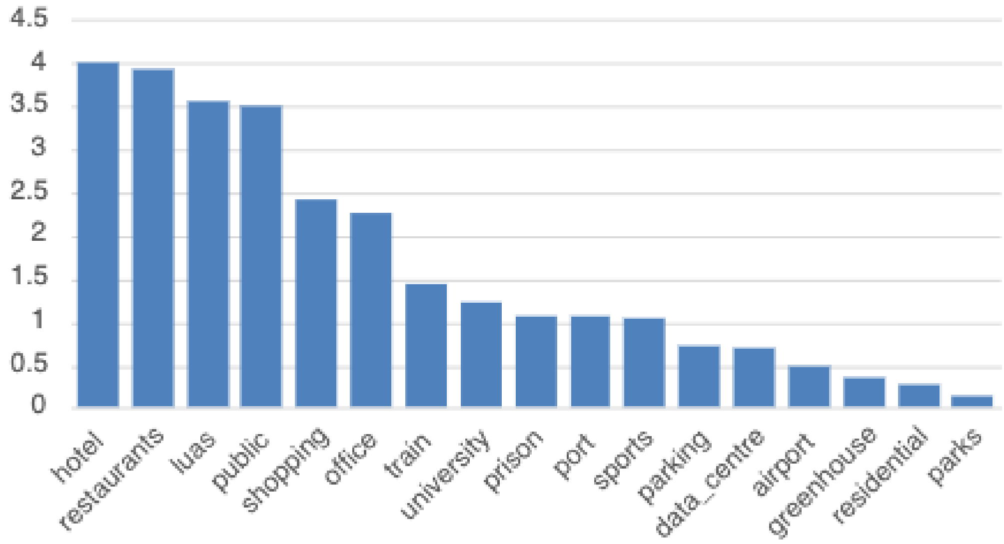

Figure 8. Area normalised mean radiance in nW/m^{-2}/sr^{-1} using 02/12/2024 SDGSAT data

The total radiant intensity in 2022 was 46.5 mW/sr. On the weekday in 2024 it totalled 51.97 mW/sr, which represents an 11.5 % increase compared to 2022, while the weekend of the 7th of December 2024 reached 49.54 mW/sr. Finally, the largest total radiant intensity was obtained for the 2025 data totalling to 65 mW/sr (Appendix 10.2.d). This means the weekend was ~4.68% lower than the weekday within the classification range.

The largest changes were observed in radiance from residential areas, which increased their overall contribution by about 5% at the weekend, which equates to an increase of roughly 2 mW/sr. Parking areas also rose by 0.87 mW/sr, while the airport increased by about 0.5 mW/sr. Conversely, sports areas, universities and parks showed decreases of 3.27, 3.10 and 1.3 mW/sr respectively (Figure 7).

On weekdays, the highest contributions came from residential areas (26%), sports fields (13%) parks (9%) and universities (9%) (Figure 7). The highest mean radiances were recorded for hotels, restaurants, Luas stations and public buildings (Figure 8). Offices, restaurants, greenhouses, public buildings and shopping centres remained relatively constant between weekdays and weekends, with deviations of no more than 10%. Data centres, prisons and greenhouses contributed minimally to the total radiant intensity and remained below mean radiance of 1 nW/m^2/sr.

As of 2025, compared to the 2022 data, radiance from restaurants and hotels increased markedly. Restaurants from 1.8 to 5.1 nW/m^2/sr, and hotels from 1.8 to 3.6 nW/m^2/sr

5.3 Relationship between radiance electricity use and, population Codema

After investigating the effect of land use on radiance, the relationship between electricity use and radiance was explored using the SDGSAT data from 2nd of December 2024. As shown on the map below (Figure 9) a general trend can be observed that mean radiance is the highest in the city centre and gradually decrease toward the edge of Dublin city council (DCC) boundary. Large green areas such as Bull Island and Phoenix Park show the lowest mean radiance with 0.04 mW/m^2/sr. The brightest sources were recorded in College street, Pearse street and Thomas street and amounted up to 55 mW/m^2/sr. The average radiance per person amounted to 116.25 nW/cm^2/sr/person. Similarly to the mean radiance, the largest values were found in Dublin city centre, reaching up to 6857 nW/cm^2/sr/person in areas such as North Dock, Mansion House, and Pembroke West. The lowest radiance per person came from Finglas, Ballymun, and Kilmainham, with values as low as 2.29 nW/cm^2/sr/person.

Non-commercial electricity and radiance showed no correlation, evidenced by a an R^2 value of 0.002 (Table 6) which expresses the proportion of variance explained. The R^2 value for radiance and total electricity use was 0.35, while for commercial electricity it was slightly higher at 0.36 (Figure 10.a).

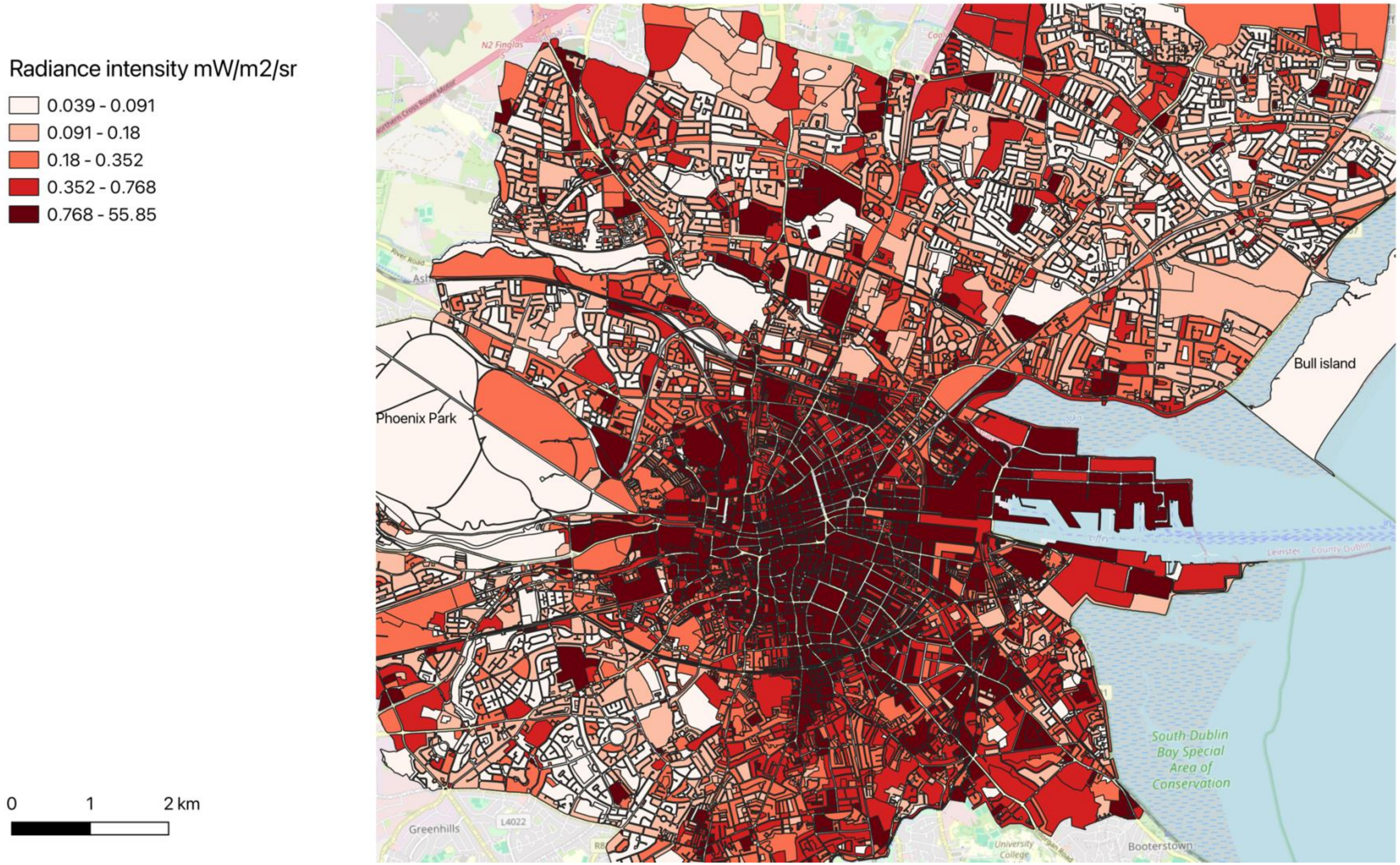

Figure 9. Map of radiance intensities over Dublin on the night of 02/12/2024.

Commercial electricity showed the strongest relationship, with a partial correlation r value of 0.283 meaning, radiance explains 7–8% of the variation in commercial electricity after controlling for population density. Total electricity showed a slightly weaker relationship, with a partial correlation r value of 0.27, explaining 4–7% of the variance. By contrast, non-commercial electricity showed no meaningful relationship to radiance, with a partial correlation r value of 0.033.

Comparison	Partial r	R^2
radiance ~ non-commercial electricity	0.033	0.002
radiance ~ total electricity	0.27	0.35
radiance ~ commercial electricity	0.283	0.36

Table 6. Results of statistical tests for the partial correlation test, and r^2values between radiance and electricity

The outliers above the regression line on Figure 8 such as Finglas North C, Ushers F represent areas where commercial electricity use is disproportionately high compared to their radiance. This suggests that high commercial electricity from non-lighting source loads such as HVAC, refrigeration, kitchens, data centres, industrial processes. Outliers below the line (e.g., Rathfarnham, Finglas North B) show relatively high radiance but lower reported commercial electricity use. This may arise due to poorly shielded outdoor lighting, floodlighting in residential areas which are underrepresented in commercial electricity statistics.

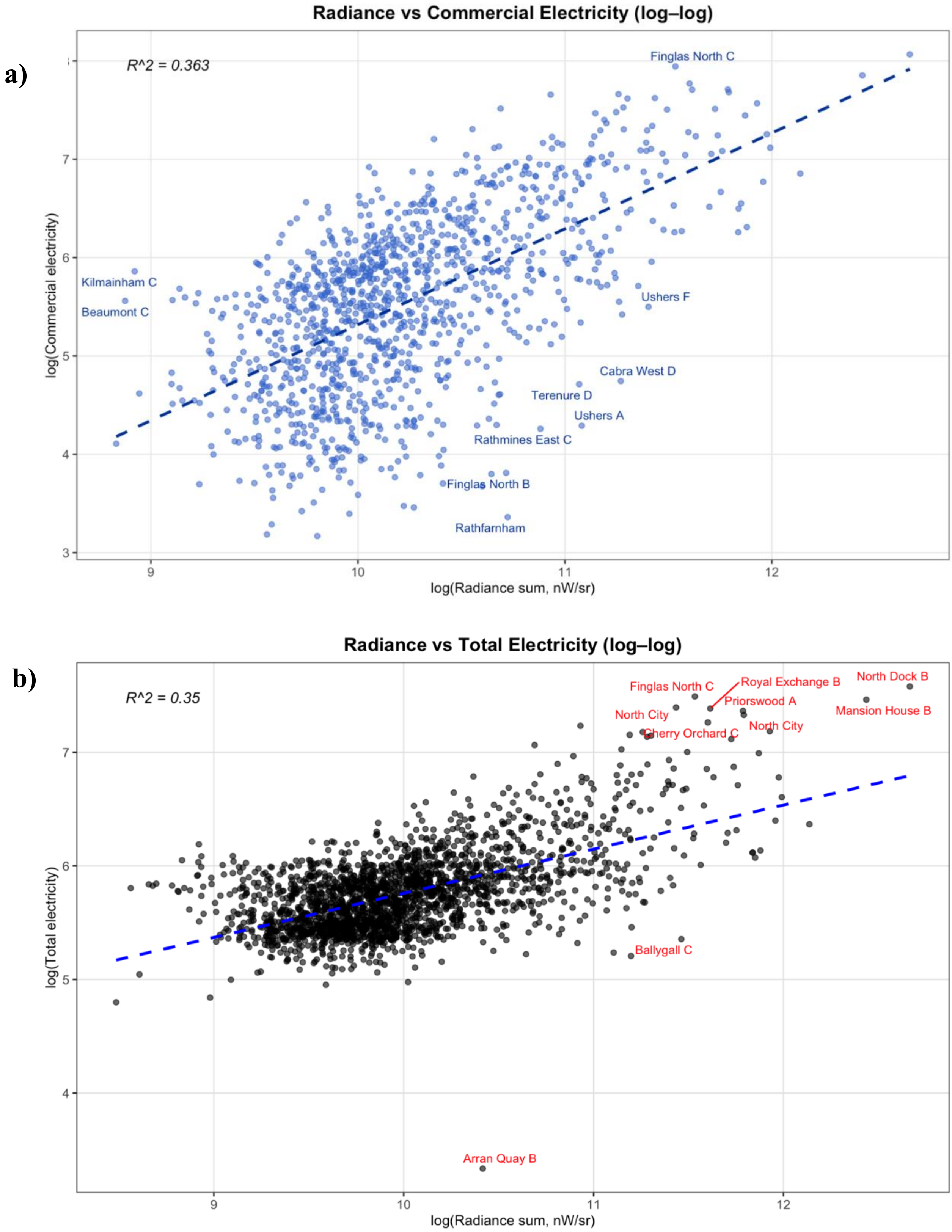

Figure 10. Correlation between (a) commercial electricity use and radiance (b) total electricity use and radiance. Least squared regression lines are shown on both plots marked by dashed blue lines.

Furthermore, ISS imagery from 2015 was used to assess how electricity use relates to different spectral bands. The 2015 ISS imagery was used as it was captured in the same year as the electricity data reported in the Codema Energy Demand Analysis. The blue band can serve as a proxy to detect commercial activity stemming from LED lamps which commonly arise from façade lighting, self-luminous lighting, advertising, and decorative lights. These lamps have a distinct peak in the blue region at 470mm (Figure 5). Whilst the red spectral band was hypnotised to be related to the presence of older, less efficient lights such as SOX which is characteristic of residential areas. These lights tend to have higher emission at longer wavelengths between ~500 and 650nm (Figure 5). The correlation was moderate for commercial electricity and blue light emission with r^2 value of 0.449 whereas, between non-commercial electricity and red-light emission the correlation was negligible (r^2=0.009).

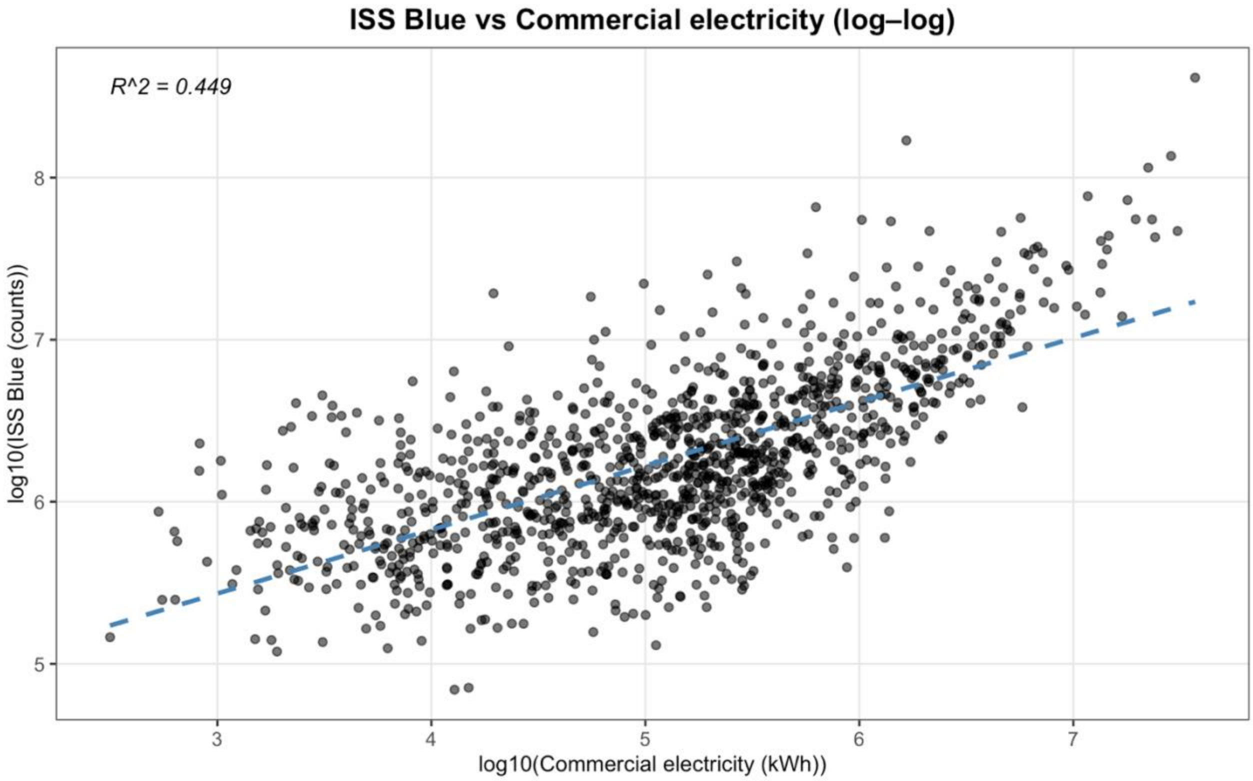

Figure 11. Relationship between the ISS Blue spectral band and commercial electricity

5.4 Public lights

Results show that in Dublin 28 % of lights are LED, 36 % and 30 % are coming from low pressure (SOX) and high-pressure sodium lamps (SON) respectively (Figure 12.b). Metal halides and Compact fluorescent lamps contribute by 2.5 % and 1.3% respectively. Other lamp types include old incandescent lamps, ceramic metal halide. These numbers describe city-wide results, yet LED proportions highly vary among different councils. The spatial distribution of public lights is depicted on Figure 13. For example, above 60% of the streetlights in SDCC and DLR councils are LEDs whilst this proportion in DCC and Fingal council remains below 4 %.

Using the CO_2 emission factor for the Irish electrical production mix provided by the SEAI (SEAI, 2023) it was possible to determine the electricity and CO_2 savings upon conversion of 100% LED public street lighting. For electricity generation a factor of 226.3 gCO_2/kWh was used and a luminous efficacy of 150 lm/ W for LED lighting (SEAI, 2017). The results show that the retrofit would save 18 GWh electricity annually and prevent the emission of 4,000 tonnes of CO_2 per year. This is equal to the annual CO_2 emission from the M50 lighting inventory (Brennan, 2018).

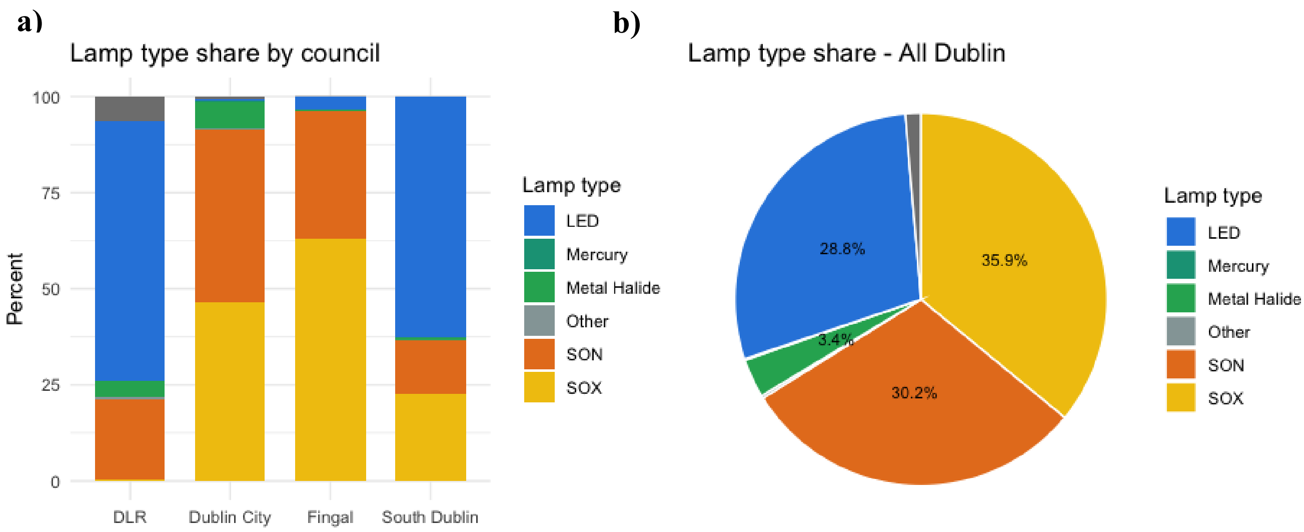

Figure 12. Lamp type share by councils in dublin highlighting variable proportions of LED street lighting. (b) Overall lamp type share in Dublin including all councils.

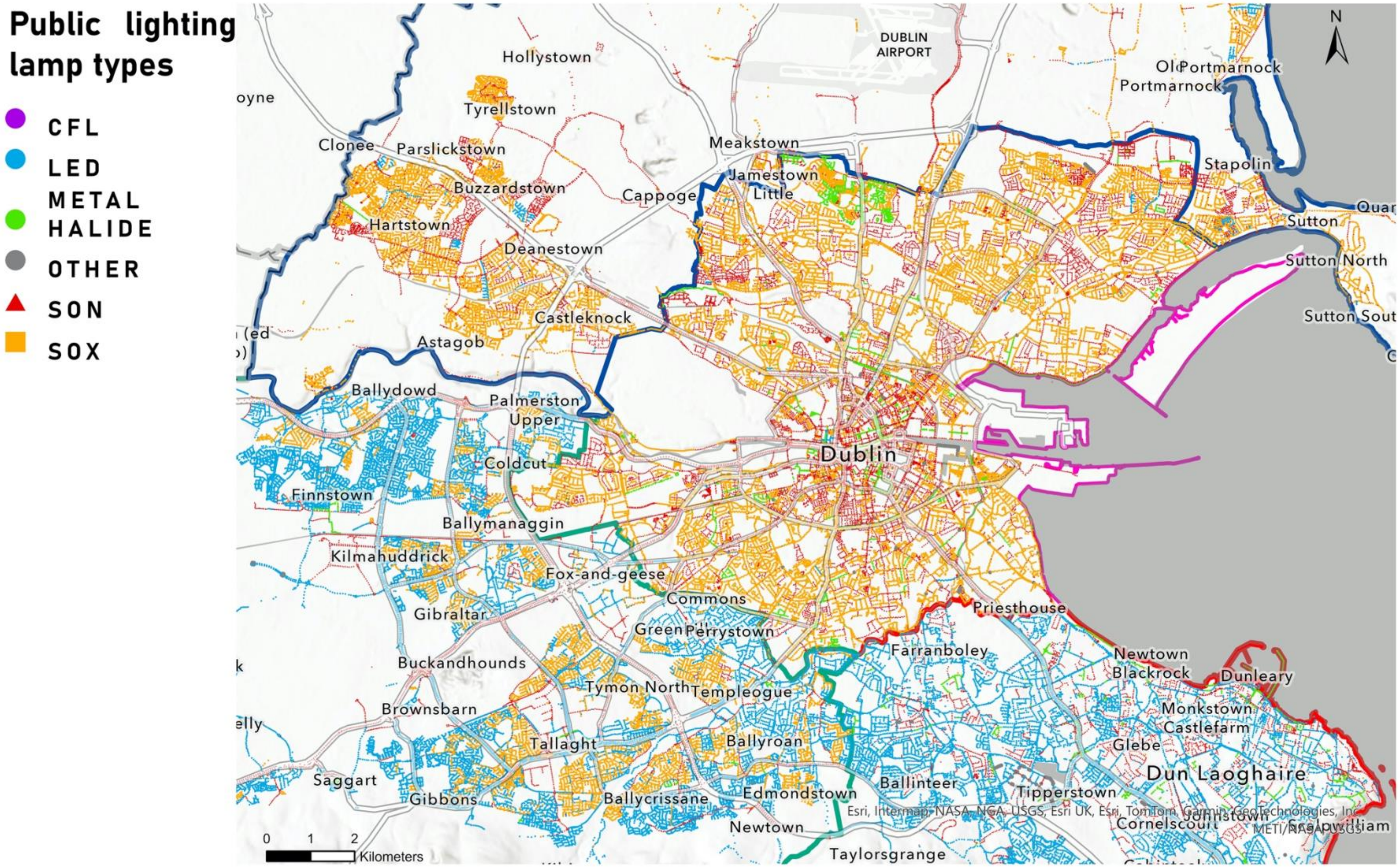

Figure 13. Map of the spatial distribution of different lamp types in Dublin. Compact fluorescent (CFL), Light emitting diode (LED), High pressure sodium lamps (SON), Low pressure sodium lamps (SOX). Pink line marks DCC boundary. Red line marks DLR boundary. Green line marks SDCC boundary. Blue line denotes Fingal council boundary.

5.5 Masks

To better understand the effect of LED public lighting on blue light pollution the unique LED light footprint was separated from the rest of the radiances. Then 20 m buffer areas were created around public LED lamp posts to capture blue light footprint within the M50 ring area, and to see whether streetlighting significantly contributes to blue light emission in Dublin. The results are shown in Table 7, indicating only higher contributions of 7–11% for Dún Laoghaire–Rathdown (DLR) and South Dublin city Council (SDCC) councils, while Dublin City Council (DCC) and Fingal councils remained below 1%.

Council	No. of LED Lamps	Blue radiance from public LEDs (nW/sr)	Total council blue radiance (nW/sr)	Public LED share (%)
DLR	9,787	126,207	1,075,687	11.70%
Dublin City	188	1,730	4,489,017	0.04%
Fingal	71	0	258,932	0.00%
South Dublin	4,471	16,545	228,434	7.20%

Table 7. Blue light at lamps

Following that an analysis was done to investigate the relationship of residential areas and light emissions from SON and SOX lamps using a buffer zone around these lamp posts of 20 m. Within the M50 ring, 55.8% of the SON footprint fell inside the 20 m residential buffer (the buffer covers 32.95% of area), which equates to an enrichment ratio = 1.69. For SOX, 32.5% lies in the buffer area thereby, matching area share (enrichment ≈ 0.99). The enrichment ratio was calculated as follows;

$$Enrichment \ = \frac{footprint\ area\ insideresidential\ buffer}{total\ area\ of M50} / \frac{residential\ buffer\ area}{total\ area\ of M50} \qquad (3)$$

5.6 Photon watts to electrical watts

The result of the calculation is outlined in Table 8. The results describe the amount of energy that was required to detect the radiance by the SDGSAT satellite. These areas require a total of 219 kW of energy, which assuming 4,167 operating hours per year (typical to Irish councils) equates to about 912 MWh. Whereas, the non-roads region corresponds to 12 MW of electrical energy, which would consume 50GWh of electricity for 4,167 operating hours per year. Using the SEAI conversion factor of 226.3 gCO_2/kWh (SEAI, 2023), this represents 207 t CO_2 emission associated with the roads region and 11,000 tCO_2 for the non-roads region. The non-roads detected energy is almost 55 times higher, as this area spans a larger region and covers a wide range of land use types and related activity.

Table 8 represents the energy attributed to specific lamp types which was derived by applying spectral masks which can distinguish regions dominated by each lighting technology footprint. For the roads region, the lamp type that represents the highest energy utilisation is SOX, followed by SON, which are present along the M50 motorway. LEDs make up the smallest portion. In contrast, using the buffered OSM mask for the non-roads region shows a different lamp type contribution to the detected energy use, where SON and LED lamps dominate.

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Roads region		Non-roads region	
Lamp type	Detected Watt electrical	Lamp type	Detected MWelectrical
LED	56,794	LED	4.04
SON	62,211	SON	4.41
SOX	100,093	SOX	3.6
total	219 kW	total	12.05

Table 8. Result of energy conversion calculation $W_{electrical}$ to W_{photon} for roads region on the left and non-roads region on the right

6 Discussion

6.1 Changes over time

The radiance changes spanning from 2015 to 2025 offered an opportunity to investigate temporal changes in artificial light output over Dublin. As mentioned previously, the 2025 December weekend data showed the highest radiant intensity, while 2022 VIIRS data showed substantially lower values which could not be attributed to actual changes in light output but rather to atmospheric clarity over the South Dublin City Council region that distorted the data. As such, the 2022 VIIRS data is treated as an outlier. The difference between the 2015 data and the post-2020 data provides a good representation of how light output has increased due to rising economic activity in Dublin. Furthermore, the comparison of February data with December data highlights the widespread use of festive and decorative lighting around the city. These types of lights are often floodlights, façade lighting, or strings hanging over streets and markets, which emit light upwards and sideways (Figure 2).

Overall, residential areas, parks, and airports showed very consistent values over the years, reflecting the stable and continuous nature of lighting in these land use types. However, parks do not have a network of streetlighting and they simply reflect the mean of the neighbouring light. Conversely, offices, restaurants, hotels, and shopping centres doubled their mean radiance between 2022 and 2025, highlighting that they are disproportionately bright compared to their size. Luas and train stations showed smaller increases in their mean radiance, while universities and sports fields fluctuated across years and days, thus reflecting their activity dependent lighting practices. Greenhouses, prisons, and data centres consistently exhibited modest or negligible radiant intensities across all years.

Interestingly, offices maintained a similar proportional contribution to overall radiant intensity of 9–10%. Despite the fact that these buildings are expected to have minimal activity at weekends, the analysis shows the persistence of lighting independent of occupancy or operational hours. The detected radiance is likely linked to decorative facade lighting, security illumination, and inefficient after-hours lighting practices, as well as light diffusing through windows which is characteristic of typical modern offices (Figure 14.).

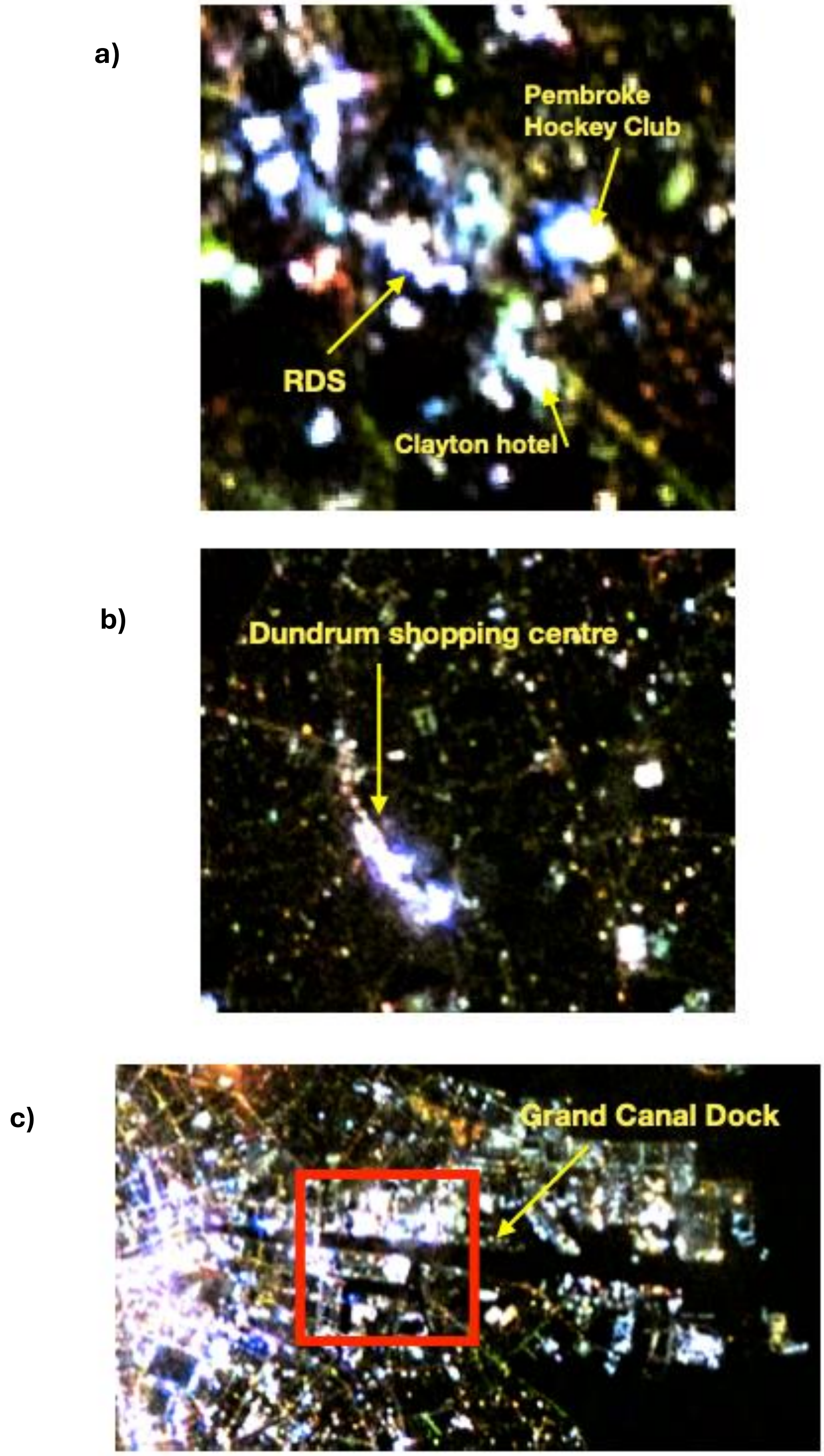

Figure 14. Pan-sharpened SDGSAT imagery by Ross Gaynor shows bright illumination sources caused by over-illumination, poorly directed lights in sport fields, RDS. Christmas festive lighting in the Dundrum Shopping Centre causes the blue spark. The Grand Canal Dock area is also clearly visible, characterised by office buildings with large glass windows and hosting the Bord Gáis Energy Theatre.

The SDGSAT data from 2024 and 2025 also reflect the rise in commercial activity. After the COVID years, hospitality services had dropped, but by 2024 they were fully operational again. This is supported both by the rising radiant intensities detected and by the increased mean radiances from restaurants, hotels, shopping centres, and public buildings.

Furthermore, the increased radiant intensity detected over the weekend in December 2024 compared to the weekday also points to increased commercial activity such as concerts, sports events, markets, etc. Commercial areas are characterised by decorative LED lighting and facade lighting to make buildings more appealing. On the weekday (2nd December) and in the 2022 February satellite imagery, the Aviva Stadium was clearly not illuminated, which indicates that no event took place, amounting to a very low observed mean radiance of 0.3 nW/cm^2/sr. In contrast, over the weekend (7th December) the stadium was visibly lit, recording a mean radiance of 25 nW/cm^2/sr for the area, which suggests it was possibly in use for a public event. This huge difference signifies the importance of single-event-led light pollution. Sports areas just like the Aviva stadium, showed outstandingly high radiant intensity on the city's scale, even though most of them can be regarded as green areas yet due to the presence of high mast lights, these areas are a large source of upward emitted light in Dublin.

Airports, Luas stations, and train stations are characterised by floodlights which similarly emit light upwards and sideways. The high light output from Luas stations can be attributed to the presence of floodlights on the platforms and waiting areas, which similarly emit light sideways and upwards.

Residential areas are generally characterised by indoor lighting which can diffuse through windows, contributing to light escaping upwards (Bará et al., 2019). There is minimal outdoor lighting in these areas compared to other commercial and retail land-use types. However, a study conducted in Germany showed that more light sources stay lit overnight for decorative and advertising purposes than for street lighting (Kyba et al., 2025). The study highlighted that the most common source of light came from private and commercial windows. Moreover, the study considered illumination sources such as billboards, floodlights, illuminated signs, self-luminous signs, doorbells, light strings, and garden decoration. These light types might seem negligible, but as reported in the results, the largest radiance source can be related to residential lighting. They reported that 70% of the light sources were unshielded, especially lights mounted on buildings and floodlights. This means that light can easily escape upwards and could be reduced simply by shielding them, which is regarded as the most effective way to prevent upward light emission. For example, in residential houses it would simply mean closing the curtains at night. Thus, this highlights the importance of private lighting and suggests that environmental policy, which has so far largely focused on municipal street lighting improvements, should also address private lighting impact on energy efficiency and light pollution.

6.2 Electricity

Many studies have shown that urban activity and population density can be traced by nighttime satellite imagery (Falchetta et al., 2019, Zhou et al., 2018, Li et al., 2017). The results have presented a moderate relationship between population density and radiance in Dublin city. Since population density and electricity use also show a strong to modest correlation, one might assume that the interdependence of radiance and electricity use might solely be due to the effect of population density. The partial correlation test underscores the positive correlation between commercial electricity and radiance, which is independent of population density. As described earlier, the best correlation was found between commercial electricity use and radiance, confirmed by both the SDGSAT data and the ISS dataset. The blue light correlation with commercial electricity use highlights the widespread use of LED lighting as decorative elements and self-luminous signs in stores, shops, and hospitality services. Similarly to decorative festive lighting, these types of lights emit light sideways and upward, causing most of the light to escape into space. Generally, households use 3% of their electricity for lighting (Codema.2018). Conversely, this can reach 40% for public buildings and retail services (Codema, 2018). For this reason, the results for commercial electricity reveal a stronger relationship compared to total electricity use.

It is also important to note that the largest light emitters and electricity users were identified within the city centre area of Dublin, where large areas are covered by commercial stores, retail services, restaurants, and pubs, including Grafton Street and Temple Bar. This area is also associated with the highest radiance per person values. Therefore, the city centre is the hotspot for the most luminous and energy-intensive part of the city, thus contributing significantly to energy demand and CO_2 emissions.

Conversely, the non-commercial (or residential) electricity correlation showed a very weak relationship both for the SDGSAT data and for the ISS red light analysis. The use of SON and SOX masks indicated that SON emissions are more concentrated along residential streets, whereas SOX shows no special association with residential areas. In these areas, lighting is indoors and generally well shielded, allowing only diffuse light to escape through the windows. Mean radiance in these areas remain low yet because of their large area cover, they significantly contribute to the city's total radiance (>30%) (Figure 7).

6.3 Public lighting

The result of the categorisation of public lamp types in Dublin shows that only around one-third of the public lighting consist of efficient LED lighting which are concentrated in the DLR council and SDCC council areas. This highlights the importance of the National Public Lighting Energy Efficiency Project (PLEEP) which has been ongoing since 2022 aiming to replace 205,000 non-LED lights (Public Lighting Energy Efficiency Project, 2022). While the results in Dublin might not seem very promising, in Galway over 95 % of the Steet lighting can be attributed to LED lighting systems (Galway City Council Annual Report 2022). In Cork this proportion reaches 75 % (Cork city Council, 2022).

As the result of the 100 % LED retrofit calculation shows, 18 GWh electricity would be saved which translates to 4000 tonnes of CO_2 savings. This is equal to the annual CO_2 emission sourcing from the M50 lighting inventory (Brennan, 2018).

A 10-year experiment in France between 2014 and 2024 mapped changes in street lighting practices across 19,262 municipalities (Cerema, 2025) that participated either by implementing (i) total nighttime light extinction or (ii) partial extinction/major street light renovation. The study concluded that the nationwide experiment resulted in a 3.2 % reduction in electricity consumption and measured a 34.2 % reduction in electricity demand during nighttime hours. This highlights the beneficial impact of nighttime light management strategies on electricity reduction without interfering with safety or well-being and suggests that similar measures could be scaled to other European cities, including Dublin to achieve further energy and CO_2 savings.

There have been concerns about the impact of blue light emission from LED street lighting on skyglow and sleep disturbance. This project highlights that, in fact, most of the blue light emission can be sourced from retail services and commercial activities. As described in (*Sections 5.2-5.6*), the blue light emission from streetlights only makes up 12% of the total LED (blue) light emission in the DLR council area, which represents the highest value due to the highest LED presence in the area. The low numbers highlight that LED streetlights are generally well directed and better shielded to prevent light escaping upwards. Other studies that have investigated the contribution of public lighting to skyglow through a dimming experiment reported that street lighting accounts for only 13% of the total radiance (Kyba et al., 2020). This result clearly underpins the importance of other sources of artificial lighting in terms of light pollution, urging net zero emission initiatives to consider electricity and CO_2 savings related to private lighting as well.

6.4 Energy conversion

The non-roads region represents around 55 times more energy detected than the roads region. This occurs due to covering a larger area of land. Furthermore, the lamp type contribution shows that white/blue light emission from LED and SON lighting is more prevalent in this region, thereby highlighting residential, commercial, and industrial activity compared to the confined roads areas.

The satellite detected energy differs across lamp types. For example, SOX lamps have a relatively low photopic ratio, but a high luminous efficacy (lm/W) compared to SON lamps due to the emission lying close to the eye's peak photopic (colour) sensitivity peak at 555nm. This indicates that most of the SOX lamp emission falls within the photopic sensitivity range of the human eye. As a result, SOX lamps are the most photopically efficient for a given electrical input, requiring less power to produce the same perceived brightness. Downsides of this form of light, however, are the electrical losses of discharge tubes, their limited ability to be dimmed, and the presence of mercury required to strike the initial arc. On the other hand, high electrical efficiency and long lifetime of LEDs make them a favourable choice for sustainable lighting retrofit programmes.

The comparison of the presented energy conversion (W_{photon} to $W_{electrical}$) through satellite imagery calculation shows a total of 12.27 MW of energy detected across Dublin. Using the Dublin lamp inventory dataset (Government of Ireland, 2021) it totals to 11.6 MW (ground-based estimation), which shows fairly good agreement. However, disparity between the two results can arise due to misinterpreting the spectral emission when using masks. For example, other lamp types which have distinct spectral emission such as Mercury lamps, Metal Halide, and CFL were not included in the calculation as they have minor contributions to the streetlighting yet can tweak results. Furthermore, for the non-roads region a direct emission was assumed, and reflectance was not incorporated into the calculation. However, this does not hold true for the entire non-roads region, as areas such as car parks, the airport, and Dublin Port do have higher reflectance. Finally, the public lighting inventory dataset originates from different year compared to the SDGSAT data, which may not describe newly and or retrofitted lamps.

7 Conclusions

In this project the SDGSAT satellite imagery with a spatial resolution of 10 m alongside with lower resolution satellite imagery such as the VIIRS and ISS was used to estimate the amount and the source of nighttime light across Dublin. The analysis was carried out in RStudio and QGIS to assess how radiance changes over time and what land use types and lamp types can be related to highest light output and how it relates to electricity use. The results suggest the following conclusions:

1. **Residential and commercial lighting drives nighttime urban light**. The results of the land use type analysis, considering both the radiant intensity and mean radiance, showed that residential areas were the biggest contributors to urban ALAN, while areas related to hospitality services such as hotels and restaurants were the brightest sources. The relationship between commercial electricity and radiance was evidenced by the ISS RGB data correlation analysis and the partial correlation test analysis. Furthermore, the radiance chages between weekdays

and weekend, Christmas period and non-festive period, highlighted the activity driven nature of light emission and related energy demand. Residential lighting remained the largest radiance contributor to ALAN for all investigated dates, which signifies the importance of various light sources present in these areas, such as light diffusing through windows, decorative lighting, and wall-mounted outdoor lighting. The common thing about lights used in retail and hospitality services and residential lighting is that these lights are mainly poorly shielded and poorly directed, thereby emitting light upwards, sideways, or on a horizontal plane, such as self-luminous lights at stores and shops.

2. **Public street lighting cannot solve the energy demand of lighting.** The results of the energy conversion from photon watts to electrical watts showed that the main energy usage occurs in the non-road regions where residential, commercial, and industrial areas are located. Furthermore, public street lighting for LED only represented 12% of the emissions, which was the highest in Dún Laoghaire-Rathdown council, but remained below 1% in areas with low LED presence. As discussed in point 1, private lighting, including residential and commercial lighting, is characterised by sources which contribute to light waste and therefore electricity waste. Hence, the results demonstrate that LED street lighting represents only a small portion of ALAN, highlighting the significance of private lighting in urban light emissions, and urging policymakers to consider this in environmental policy in order to reduce the energy demand of lighting and light emissions.
3. **Satellite-based energy conversion is a useful method for monitoring energy use and emissions at city scale.** This project demonstrated that satellite imagery can be used to estimate energy usage on the ground. This is a powerful method, as data on how much energy goes into lighting only exists for streetlighting, which represents only a fraction of urban light. As such, this allows for the estimation of energy usage from all types of light. Using the Dublin public street lighting database, assuming all lights run on full power has showed that the difference between the two approaches was roughly 0.5 MW, which is due to potential misinterpretations of spectral profiles of different lamp types.

Therefore, this method is useful to give a rough estimate of the energy demand of lighting.

8 Recommendations

To mitigate unnecessary light emissions and related electricity demand and CO_2 emission, the following measures are recommended to be implemented:

- Introduce regulatory controls for offices and public buildings, requiring lights to be switched off after operational hours to prevent unnecessary electricity use and light escaping through windows.
- Similarly, establish polices which target advertising lights, commercial lights and decorative lights to be switched off during periods when pedestrian activity is minimal.
- Upon LED retrofitting, implement dimming schedules for street lighting to 40-60% of full output during lull hours to conserve energy while maintaining road safety.
- Install shielding on outdoor lighting fixtures to prevent light escaping upwards thereby, improving lighting efficiency.
- Encourage residential areas to close curtains at night to limit the amount of light escaping through windows.
- Promote public education on sustainable, energy-efficient lighting practices to enhance social responsibility.

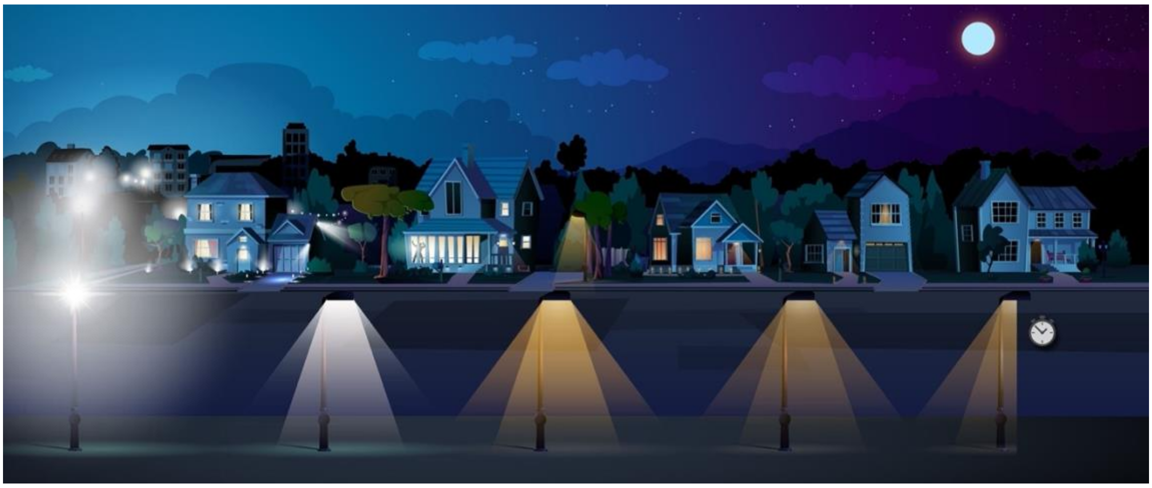

Figure 15. Dark sky friendly lighting practices highlighting the importance of shielding, dimming. Source from University of Texas, McDonald Observatory : https://mcdonaldobservatory.org/darkskies

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10 Appendix

10.1 . Satellite data: dates of image capture

a) Dates of the SDGSAT satellite imagery observations:

04/02/2022
02/12/2024
07/12/2024
04/02/2025

b) Dates of VIIRS satellite imagery observations:

04/12/2015
05/02/2022
03/12/2024
08/12/2024
05/02/2025

c) ISS imagery:

03/12/2015
24/01/2017
19/09/2021

10.2 Land use contributions to radiance

a) 04/02/2022

category	summed_radiance_nW_sr	area_m2	Area_normalised_nW_sr_m2	contribution
shopping	1079811	971275.1726	1.111745703	2.32%
data_centre	463158.0313	467022.3368	0.991725652	1.00%
university	2122849.5	4166417.662	0.509514329	4.56%
parking	4257332	7421496.73	0.573648707	9.15%
sports	4618029	7106151.709	0.649863553	9.93%
office	2,520,491	2,325,785	1.084	5.42%
airport	3643842.75	7272077.629	0.501073137	7.83%
greenhouse	3537.968262	13124.26394	0.269574604	0.01%
prison	213868.8906	220234.9235	0.971094353	0.46%
public	151436.2656	83418.04143	1.815389849	0.33%
port	1447279.125	1728311.157	0.837395002	3.11%
residential	17256812	56663487.52	0.304549062	37.10%
parks	9169204	37064068.39	0.247387953	19.71%
restaurants	1482901.875	812356.7885	1.825431751	3.19%
hotel	970,065	530,634	1.828	2.09%
train	75054.26563	55571.60575	1.350586592	0.16%
luas	178161.8438	96225.18514	1.851509493	0.38%
Total	46509320	121535997.2		1

b) 02/12/2024

category	**summed_radiance_nW_sr**	**area_m2**	**Area_normalised_nW_sr_m2**	**percent_contribution**
hotel	2,124,828.44	530,634.13	4	4.09%
restaurants	3197177.5	812356.7885	3.935681397	6.15%
luas	341701.125	96225.18514	3.55105708	0.66%
public	292095.1563	83418.04143	3.501582526	0.56%
shopping	2346342.5	971275.1726	2.415734043	4.51%
office	5,277,202.69	2,325,784.66	2.27	10.15%
train	79609.75781	55571.60575	1.432561768	0.15%
university	5108516	4166417.662	1.226117114	9.83%
prison	238077.7969	220234.9235	1.081017457	0.46%
port	1865950.125	1728311.157	1.07963784	3.59%
sports	7439302	7106151.709	1.046881956	14.31%
parking	5318525.5	7421496.73	0.716637855	10.23%
data_centre	328705.8125	467022.3368	0.703833172	0.63%
airport	3629862.25	7272077.629	0.499150647	6.98%
greenhouse	4688.352051	13124.26394	0.357227809	0.01%
residential	15084418	56663487.52	0.266210547	29.03%
parks	5240467.5	37064068.39	0.14138943	10.08%
Polygon total	51969936	121535997.2		100

c) 07/12/2024

category	summed_radiance_nW_sr	area_m2	Area_normalised_nW_sr_m2	contribution
restaurants	3243563	812356.7885	3.99	6.55%
hotels	1,914,367.88	530,634.13	3.61	3.86%
public	269360.4688	83418.04143	3.22	0.54%
luas	280055.125	96225.18514	2.91	0.57%
shopping	2115139.5	971275.1726	2.17	4.27%
office	4,495,183.69	2,325,784.66	1.93	9.07%
train	102436.3281	55571.60575	1.84	0.21%
data_centre	812270.6875	467022.3368	1.7	1.64%
prison	330255.0625	220234.9235	1.5	0.67%
port	2129525.25	1728311.157	1.23	4.30%
parking	6185784.5	7421496.73	0.83	12.49%
sports	4170685.75	7106151.709	0.58	8.42%
airport	4190086.25	7272077.629	0.57	8.46%
university	2006377.875	4166417.662	0.48	4.05%
greenhouse	4840.528809	13124.26394	0.36	0.01%
residential	17072858	56663487.52	0.30	34.47%
parks	3899251.5	37064068.39	0.105	7.87%
Polygon total	49535640	121535997.2		1

d) 04/02/2025

category	summed_radiance_nW_sr	area_m2	Area_normalised_nW_sr_m2	contribution
hotel	2,710,829.50	530,634.10	5.11	4.12%
restaurants	2938721	812356.8	3.617524	4.47%
public	281002.7	83418.04	3.368608	0.43%
luas	261118.6	96225.19	2.71362	0.40%
sports	15467346	7106152	2.176614	23.53%
train	120232.7	55571.61	2.163564	0.18%
office	5,014,643	2,325,784.20	2.16	7.63%
port	3265039	1728311	1.88915	4.97%
shopping	1741278	971275.2	1.792775	2.65%
university	5889421	4166418	1.413545	8.96%
data_centre	573941.8	467022.3	1.228939	0.87%
prison	211245.2	220234.9	0.959181	0.32%
parking	5801629	7421497	0.781733	8.83%
airport	5335850	7272078	0.733745	8.12%
residential	16419519	56663488	0.289772	24.98%
parks	7353577	37064068	0.198402	11.19%
greenhouse	1286.709	13124.26	0.09804	0.00%
Polygon total	65723632	1.22E+08		1

10.3 Radiance and population correlation

a) Relationship between 2016 population data and radiance data from SDGSAT for the 2nd of December 2024.