Evaluting Domestic Lighting: an Investigation into the Use of Compact Fluorescent Lamps in the Domestic Environment

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1. Introduction

The most popular replacement for GLS lamps appears to be CFLs. This paper will set out to investigate if CFLs are an adequate, suitable and appropriate replacement for GLS lamps in the domestic environment. Initially a literature review will be compiled in an attempt to highlight some of the major issues associated with CFLs. The headings examined are outlined below:

- **2.1** - Efficacy
- **2.2** - Embodied Energy
- **2.3** - Illuminance
- **2.4** - Manufacturer Wattages
- **2.5** - Lamp Life
- **2.6** - Colour Rendering and Colour Temperature
- **2.7** - Total Lumen Output
- **2.8** - Ultraviolet Radiation
- **2.9** - Mercury and Re-Cycling
- **2.10** - Power Factor
- **2.11** - Total Harmonic Distortion
- **2.12** – Pricing and Costs

The literature review conducted indicated a shortage of research findings with respect to power factor, harmonic order currents and levels of total harmonic distortion produced by commercially available CFLs. Experiments were conducted to quantify all three and conclusions were drawn from the results obtained. A set of fifteen CFLs and three GLS lamps were used for all experiments. Accurately measuring the true power factor of any non-linear load requires root mean squared (RMS) measurements. Standard electrical instruments are only capable of quantifying displacement power factor, while true RMS instruments allow for the inclusion of system harmonics and hence, measure true power factor. Incorporating a true RMS Voltmeter, a true RMS Amp meter, a Variac to stabilise the supply Voltage and a Wattmeter, to a circuit containing a lamp holder allowed for accurate measurement of true CFL and GLS power factor. Individual harmonic order currents and THD levels were recorded using a single circuit, with different methods of

measurement. Again true RMS instrumentation is necessary to give accurate results. Four methods were used to try and assess the harmonic patterns produced by the CFLs tested, namely: two power factor meters (one analogue and one digital), an oscilloscope and a Wattmeter plus true RMS Volt and Amp meters. Other research was conducted to investigate CFL warm up time and pricing, but this paper will endeavour to focus on the measured power factor, harmonic order currents, total harmonic distortion and any possible problems or obstacles that they may yield.

2. Literature Review

2.1 Efficacy:

There appears to be a general consensus, that CFLs will provide quite large energy savings over incandescent lamps. Figures around 80% [4] and 75% [5] are often suggested. The adjacent table, from the Lighting Association [24] shows direct comparisons between lamp type/lamp wattage and lumen output. It is clear from this that significant savings, due to improved efficacy, can be made from the use of CFLs. The European Commission, the Energy Savings Trust and manufacturers say CFLs use up to 80% less electricity than traditional bulbs, but Kevan Shaw [7] questions how this figure is calculated? According to a spokeswoman for the European Commission, it is calculated "by comparing the best compact fluorescent lamps Wattage with the Wattage of an equivalent incandescent bulb" [6]. This method results in a 5:1 efficacy ratio between the two types of lamp – a claim the European Commission itself says is an exaggeration when manufacturers use it. It is the "up to" in this 80% claim that is important. The EC spokeswoman says the saving can be as low as 60% [6].

Description	Wattage	Lumen Output (lm)	Efficacy (lm/W)
Incandescent/GLS	25	225	9.0
	40	420	10.5
	60	710	11.8
	75	940	12.5
	100	1360	13.6
	150	2180	14.5
Incandescent - Soft Output	25	200	8.0
	40	370	9.3
	60	630	10.5
	75	840	11.2
	100	1200	12.0
CFL - Stick Shape	5	230	46.0
	8	420	52.5
	11	600	54.5
	14	810	57.9
	18	1100	61.1
CFL - Blub Shape	5	200	40.0
	8	380	47.5
	12	610	50.8
	16	815	50.9
	20	1160	58.0
CFL - Spiral Shape	5	300	60.0
	8	500	62.5
	12	725	60.4
	15	1000	66.7
	20	1350	67.5
	23	1550	67.4

Table 1 - The Lighting Association, Amended to Include Efficacies [24]

2.2 Embodied Energy and Pollutants:

Another issue is the embodied energy needed to create a CFL. Manufacturers claim that the energy input required to construct a CFL is six times that required to produce a GLS lamp [7]. This would of course be offset by the CFLs longer life, i.e. the CFL will last six times longer. Adjacent are figures from VITO [7], an environmental research organisation working for the European Commission, which compare energy used in the manufacture of GLS lamps and CFLs. It is clear from these figures that the energy needed to produce a CFL is up to twelve times that needed to produce a GLS lamp.

However, the lifetime embodied energy lost in the manufacture of CFLs (1.5-2kWh max) seems insignificant when one considers that a 100W GLS lamp uses approximately 100kWh per annum and a 20W CFL uses about 20kWh. A saving of 80kWh per annum, or 480kWh over six years.

Energy Used in Manufacture
GLS = 1MJ of 0.28kWh
CFL = 12MJ or 3.33kWh
Pollutants Created in Manufacture
GLS = 5mg - None Hazardous
CFL = 128mg of which 78mg is Hazardous

Table 2 - Embodied Energy

2.3 Illuminance:

A recent undergraduate study carried out at The Dublin Institute of Technology [8] compared illuminances from GLS lamps and "equivalent" Wattage CFLs. Nine lamps were used, three 100W GLS and six 20W CFLs. It was found that the CFLs produced 50 – 60% less light on a surface at a distance of 40cm, than the GLS lamps. The average GLS value was 778 lux, compared to 367 from the "equivalent" Wattage CFLs. However, a more recent undergraduate study at The Dublin Institute of Technology [9] has shown slightly different results. Browne [9] found that illuminance levels were much more comparable (±20%). This may show an improvement in performance in the time between the two studies, or possibly illustrate the variation between individual lamps and manufacturers. Some tests were conducted for this paper, but there accuracy was considered unreliable and excluded for that reason. Overall it appears that CFLs do produce slightly lower illuminance levels than their so claimed "equivalent" GLS lamps.

GLS Lamps	Illuminance (Lux)
Solas	760
General Electric	687
Tesco Generic	887
CFLs	Illuminance (Lux)
Omnicron	490
Philips	435
B&Q	346
General Electric	398
Philips Soft Tone	572
Solas	362

Table 3 - Bernie Illuminance Comparison [8]

2.4 Manufacturer Stated "Equivalent" Wattages:

Some users complain that the light quality emitted from CFLs is poor and not as *bright* as their "equivalent" GLS lamps [4]. This may be due to the method of comparison between the two lamps and wattages. CFLs are compared to "soft output" lamps, which have a lower light output (see Table 1 from The Lighting Association) [7][24]. The initial lumen output of each lamp should also be considered. Shaw [7] claims "manufacturers set the equivalence of output to the worst incandescent lamps, with colour coatings". He backs this up with a simple example:

- A 12W CFLi at 660lm is advertised as the equivalent of a 60W GLS at 710lm.

- A 21W CFLi at 1230lm is advertised as the equivalent of a 100W GLS at 1340lm.

This raises issues, but it would seem that manufacturers are just trying to provide a simple method of comparison that is easily understood by lay people. However, it may suggest that manufacturers claims of 5:1 energy savings are closer to 4:1.

2.5 Lamp Lifespan:

It is claimed by manufacturers that CFLs can "increase lifespan by a factor of 6 to 12 times that of an incandescent lamp" [4]. Lifespan for a lamp is generally stated in hours and for CFLs is usually between 4,000 and 12,000 hours. However, CFLs only manage 85% of their output at 2,000 hours [7]. Hence, what will their lumen output be at 12,000 hours and will this output be sufficient to avoid replacing the lamp? Another complaint is that some CFLs burn out far earlier than their estimated lifespan. A branded bulb from a well-known manufacturer may last the full estimated lifespan, but a budget lamp from the local supermarket may not. Even branded bulbs don't always last as long as expected and this is because the estimated lifespan is an average [7]. During the testing of a batch of bulbs, they are switched on for three hours, then off for twenty minutes and this process is repeated over and over until half the batch has failed. This point is then considered to be the average lifespan [5]. With this in mind, it must be considered that any given bulb could fail at a possible 2,000 hours, when its estimated lifespan is 10,000 hours. However, the Lighting Industry Federation says, "the main manufacturers do their best to make bulbs that cluster around the average life mark" [10]. With the above considered, it is clear that CFLs have an far increased lifespan compared to GLS lamps, but individual CFL lifespan is a variable.

2.6 Colour Rendering Index and Colour Temperature:

It is clear that the colour rendering of any CFL is poor compared to a GLS lamp [11]. In a recent study at The Dublin Institute of Technology [8], spectral irradiances in the photopic ranges were investigated. Rather than the CFL spectral curve following a curve similar to a Planckian radiator, as with a GLS lamp, the CFLs showed peaks in spectral irradiance separated by regions of little or no irradiance [8]. Beirnie showed that the CFLs tested had an average CRI of 72.1 [8]. The reason for this is that the CFLs produced an incomplete spectrum, while the GLS lamps produced a complete spectrum (Figure 1) [8]. A more recent study at The Dublin Institute of Technology [9] produced similar results to Beirne. Browne [9] measured the spectral irradiance of fifty CFLs and found an average CRI of 77.4. Values ranged from 58.4 to 83.2, although this average value is below the CRI of 80 required by the EU, for compliance with the EU quality charter of CFLs [9]. The CFL spectrum lacked the higher wavelengths and hence, the colour red, which our eyes detect as being the warmest. This lack of red light in the CFL spectrum goes a long way to helping us understand their colour appearance and cool colour temperature when compared to a GLS lamp.

GLS Lamps	Colour Rendering Index
Solas	99
General Electric	99.5
Tesco Generic	99.5
CFLs	**Colour Rendering Index**
Omnicron	80
Philips	79
B&Q	77
General Electric	45
Philips Soft Tone	79
Solas	78

Table 4 - Beirnie CRI Results [8]

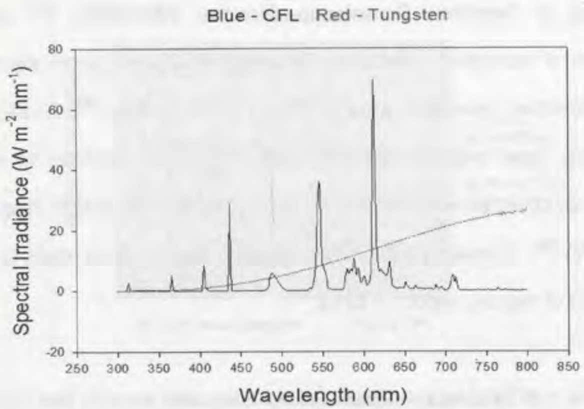

Figure 1 - Spectral Irradiance of CFLs and GLS [8]

2.7 Total Lumen Output:

To measure the luminous flux of any CFL would require an expensive integrating sphere for the spectroradiometric system used in both Browne and Bernies' studies. This could calculate the luminous flux emitted into the entire region (sphere) around the bulb [9], however due to the expense, not many, if any independent studies are publicly available that accurately measure the luminous flux of CFLs. The measurement of illuminance offers a pragmatic validity check for this research.

2.8 Mercury and Re-Cycling:

CFLs use mercury vapour and the question arises of what to do with spent lamps? Mercury is an emotive subject and the general public are a ware that heavy metals are potentially dangerous. Figures for mercury content per CFL range between 1.5mg and 6mg, in gaseous or liquid form [7][12]. However, according to European Commission Directive 2002/95/EC [26] on the restriction of hazardous substances in electrical and electronic equipment (RoHS Directive), mercury content in CFLs is limited to 5mg [26]. An indicative benchmark (best available technology) of 1.23 mg of mercury in energy efficient CFLs is provided in the above mentioned Ecodesign Regulation (Annex IV) [26]. Simpson provides various points that could be made to argue the effects of mercury vapour in CFLs [12]:

- The "pro CFL" lobby claims that the amount of mercury that might get into the environment as a result of CFL use is far less than the quantity of mercury that power stations would put into the atmosphere in order to provide the extra energy needed to power GLS lamps.
- The "anti CFL" lobby claims that an estimated 176 tons of mercury will end up in our landfills annually in Europe as a result of the disposal of CFLs.
- It is stated that elemental mercury, as would be emitted from power stations to the atmosphere, is less harmful than organic mercury compounds that arise from landfill mercury by microbial action.

ENERGYSTAR®, a U.S Environmental Protection Agency [25] provides figures on how it believes CFLs will cut down on mercury emissions compared to GLS lamps. It compares a 13W CFL and a 60W GLS lamp.

Light Bulb Type	Watts	Hours of Use	kWh Use	National Average Mercury Emissions (mg/kWh)	Mercury from Electricity Use (mg)	Mercury From Landfilling (mg)	Total Mercury (mg)
CFL	13	8,000	104	0.012	1.2	0.6	1.8
Incandescent	60	8,000	480	0.012	5.8	0	5.8

Table 5 – Energystar Mercury Emission Comparison [25]

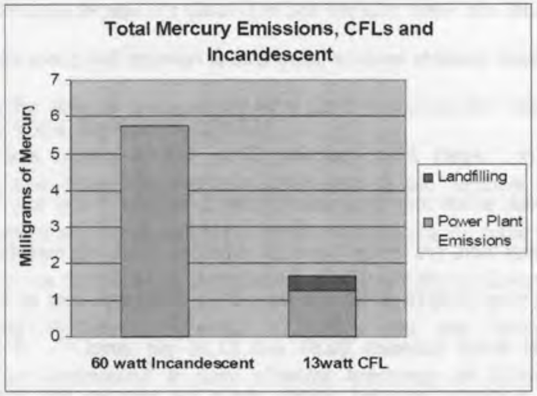

Figure 2 – Energystar Stated Mercury Emission Savings [25]

ENERGYSTAR® states that electricity generation is the single biggest source of mercury emissions in the U.S. [25]. It believes that the 13W CFL above will save 374kWh over its' lifetime, thus avoiding 4.0mg of mercury emissions through generation [25]. This figure will drop if the bulb goes to landfill.

Assuming manufacturers' figures are correct, then to replace the 2.1 billion incandescent lamps sold each year, about 350 million CFLs will have to be sold annually [7]. This means that in a few years, almost 350 million CFLs will reach their end of life cycle. While the methods for recycling of fluorescent lamps have become well established in industry and commerce, the domestic consumer is likely to dispose of CFLs in their non-recyclable refuse bag. This will result in either landfill or incineration for most CFLs. This is possibly the worst way of disposing of mercury. In landfill, certain microbes digest mercury and excrete it as methyl mercury, a compound almost twenty times more toxic than metallic mercury [7]. Methyl mercury is easily soluble and could leak out of the landfill into water courses and eventually the sea, where it may get into fish and could possibly become poisonous to humans that consume these fish [7]. It is also not particularly clear what the recycling process will actually do with CFLs. Apart from mercury, CFLs include plastic and electronic components, which may be uneconomical to recycle in any way [12]. Shaw believes that there are limited paths for recycling and in his experience, many lamp recycling companies will not take CFLs and those that do can charge substantial sums, between £0.50 and £1.00 per lamp [7]. A local lamp recycling company provided details about the process that they use for recycling CFLs. Their method is almost identical to that described by Shaw [7]. The ballast is not separated from the lamp, but rather the entire lamp is crushed and materials then separated. The glass element of the CFL can't be re-used as glass due to the phosphors used to contain ultraviolet radiation, but Shaw [7] states that this can still be used for some construction materials like road paint and wool insulation. The mercury contained within the CFL is

mixed in with the phosphors and glass particles and the local lamp recycling company uses a distillation process to remove it. The control gear and plastic components are then shredded and heated to extract solder and other low melting point metals, as the plastics are largely burned in the process. The remains, with the ferrous metals extracted, are then sent to landfill. Shaw claims that there is probably less than 1gm of fully recyclable material recovered from each lamp that typically weighs around 80gm [7]. The local lamp recycling company were unwilling to disclose exact information on this. It should also be noted that this particular company charges €0.95 per CFL, but IKEA Dublin offer a recycling service free of charge for CFLs that are purchased in their store.

2.9 Ultraviolet Radiation (UVR):

For some time there has been an awareness of the negative effects of ultraviolet radiation on human health. Most notorious are the acute erythemal effects, such as sunburn and skin cancer. The International Commission for Non-Ionising Radiation Protection (ICNIRP) and the World Health Organisation recommend a daily effective irradiance of $30Jm^{-2}$ in the ultraviolet radiation range [14]. Recent research at The Dublin Institute of Technology [15] and by The UK Health Protection Agency [16] have analysed the spectral irradiance of a group of commercially available CFLs. Both studies found similar and interesting results. Because of their mercury content, the CFLs emitted significant quantities of UVA, epically at 365nm. Many of the CFLs had sizeable outputs at 313nm (UVB) and in some cases, at 254nm (UVC). The ultraviolet radiation emitted from the double envelope

CFLs was much reduced when compared with that emitted from the single envelope CFLs [15][16][9]. Table 6 and Figure 2 below are taken from Cantwells' [15] study and give further details indicating exact quantities, in mWm^{-2}, of ultraviolet radiation emitted at specific wavelengths and the Mean Spectral Irradiance.

	UVC (250-280nm)	UVB (280-315nm)	UVA (315-400nm)	Mean Effective Irradiance
Distance = 20mm				
Single Envelope	0.52	570	7900	13
Double Envelope	0.37	20	2100	0.46
Distance = 200mm				
Single Envelope	0.49	15	170	0.43
Double Envelope	0.36	0.87	66	0.09

Table 6 - Mean Total Irradiance (mWm^{-2})

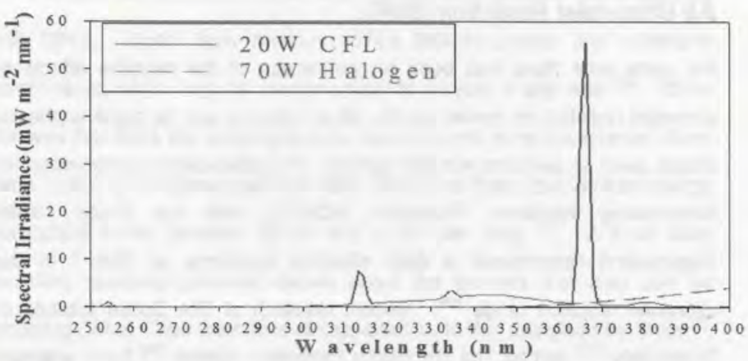

Figure 3 - Spectral Irradiance of a 20W CFL (Blue)

Distance from long axis of CFL = 200mm	< 8 hours	8-10 hours	> 10 hours
% Single Envelopes	9.4	5.6	85
% Double Envelopes	0.0	0.0	100

Table 7 - Time to exceed the ICNIRP Exposure Limit value of $30Jm^{-2}$ at 200mm

In Cantwells' study, the biologically effective exposure from each lamp was assessed using the ICNIRP weighting function [14] and compared to Exposure Limit values to evaluate potentially hazardous exposures. No double envelope CFL exceeded the limit value of $30Jm^{-2}$ at 200mm from the lamp within eight hours [15][16][9]. However, 9.4% of the single envelope CFLs exceeded the ICNIRP limit value in less than eight hours (Table 7) [15]. Similar results were found in other studies [15][9]. This may be due to incorrect or incomplete application of the phosphors coating to the CFL envelope. The Artificial Optical Radiation Directive [20] has become law throughout the European Union as of the 27 April 2010. The Directive requires businesses, including those based in the home, to limit the exposure of workers to optical radiation, including exposure to ultraviolet radiation hazards from general lighting. Since the exposure limits are based on the ICNIRP values, this research may be of significance in this regard. Long term eye exposure at 200mm from a lamp, or in a close proximity to the source, is unlikely due to the eyes' aversion response to a bright source. However, unintentional long-term skin exposure is foreseeable at close distances from the CFLs, e.g. hands under a desk lamp or short-term activity near the source. It should also be noted that exposure levels may be substantially increased by reflection from a lamp shade or a luminaire reflector [16]. The above considered, The UK

Health Protection Agency recommends a distance of >30cm from CFLs for area and task lighting [16].

2.9.1 Persons With Photosensitive Disorders:

Ultraviolet radiation is particularly hazardous to those with photosensitive skin disorders, such as lupus erythematosus, xeroderma pigmentosum and skin cancer [27][28]. Although exposure limits have been established for people with normal skin, they have not been determined for those with photosensitive disorders [27][28]. Sayre [28] states "UV exposure in doses similar to those emitted from CFLs have been shown to induce DNA damage, tumour formation and erythemal. Additional studies must be done to determine the lowest dose capable of causing damage in photosensitive patients". Until these studies are conducted, it is widely recommended that patients with photosensitive disorders use bulbs that emit the lowest levels of ultraviolet radiation with a glass envelope or filter [27][28][29]. CFLs will obviously not fall into this category. GLS lamps are recommended where possible [27][28][29]. Failing this, Sayre recommends that Halogen lamps should be "doped or covered with glass prior to use" [27].

2.10 Power Factor:

It is claimed that GLS lamps have a power factor of unity, or close to unity [4][5][7]. There is concern that CFLs have a poor power factor [4][5][7]. As power factor reduces, apparent power increases and all components in a distribution system, such as generators, conductors, transformers and switchgear need to

be increased in size. The literature review conducted indicated a shortage in publicly available results for the direct measurement of CFL power factor. It is for this reason that this research addresses the measurement of power factor in detail.

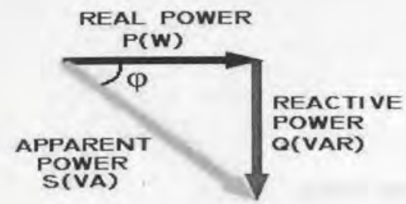

Figure 4 - – Power Triangle

2.11 Total Harmonic Distortion (THD):

Many loads connected to the national grid require a continuous sinusoidal power supply and if the power quality of the grid is allowed to deteriorate, it could have significant costs associated with it. The current waveform drawn from the supply by a CFL is not even close to sinusoidal (as the electronic CFL draws current in bursts) and if used in large numbers, could be constantly returning dirty power to the national grid. An independent study in New Zealand proved that on a 300kVA supply, a total of 33.4kVA (18.4kW) of CFLs produced 5% total harmonic distortion (THD), which exceeded the national limit on THD [19]. The European standards are more lenient for low order harmonics and THD than in New Zealand [19]. New Zealand has a large HVDC interconnector between its' North and South islands and it is for this reason that their harmonic limits are so stringent. Watson believes that widespread use of CFLs will cause significant deterioration in the quality of power supplied by utility companies [19]. It would seem obvious that prevention is far more costly than finding a solution for the problem. This research performs harmonic measurement and analysis to assess the possible impact CFLs will have on power quality before they come into widespread use.

2.12 Pricing and Costs:

There are many varieties of CFLs on the market at the moment and these appear to vary in price from £0.99 to £4.98 for the equivalent of a 60W incandescent lamp [7]. Prices in Ireland, appear to be as low as €0.99 and as high as €8.95. From this it seems that the market price may not be determined by the cost of the product, but in turn by the retailers and manufacturers profit margins. It appears that the typical mark up in the UK is 500% [7]. With such a high mark up, one must wonder about the quality of product being purchased by the retailer and sold to the consumer. Running costs for CFLs must also be questioned. If the true Wattage of CFLs is not as stated by manufacturers, then the running costs will be altered accordingly.