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An Examination Into the Use of Compact Fluorescent Lamps in the Domestic Environment

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Young Irish Lighter Award winner 2010

An examination into the use of compact fluorescent lamps in the domestic environment

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Abstract

The Irish government, UK government and European Commission have recently passed a ban on the sale of all incandescent/GLS lamps above 100W. This commenced in September 2009, with smaller wattages to be phased out by 2012.

This paper sets out to investigate if compact fluorescent lamps (CFLs) are an adequate, suitable and appropriate replacement for GLS lamps in domestic environments. An overview of CFL performance is undertaken, initially through a literature review and then through laboratory measurements. The findings of this are insightful for all readers using CFLs in their homes.

In-depth research was carried out to examine CFLs, power factor, harmonic distortion and their likely effects on the national grid. The possible risk of an overloaded three-phase neutral conductor are also evaluated, which provides useful information for electrical services design engineers.

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 lampholder 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.

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. Table 1, from the Lighting

Association[24] shows direct comparisons between lamp type/lamp wattage and lumen output.

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 – Bulb 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]

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].

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. Table 2 shows 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 12 times that needed to produce a GLS lamp.

Energy used in manufacture	Pollutants created in manufacture
GLS = 1MJ of 0.28kWh	GLS = 5mg – none hazardous
CFL = 12MJ or 3.33kWh	CFL =128mg of which 78mg is hazardous

Table 2: Embodied energy

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.

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.

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]

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 their 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.

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 a 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 50 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]

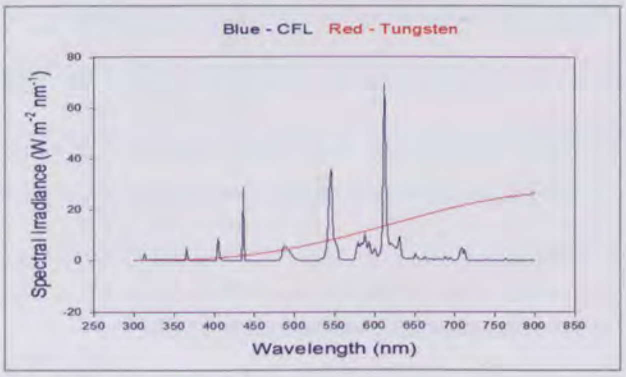

Figure 1: Spectral irradiance of CFLs and GLS[8]

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 aware 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 1.23mg of mercury in energy efficient CFLs is provided in the above mentioned

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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 Land Filling (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]

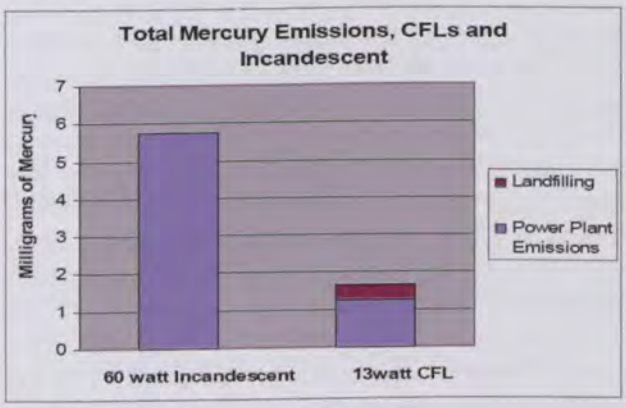


Figure 2: Energystar stated mercury emission savings[25]

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 was unwilling to disclose exact information on this. It should also be noted that this particular company charges €0.95 per CFL, but another major retailer in Dublin offers a recycling service free of charge for CFLs that are purchased in its 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 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.

Distance = 20mm	UVC (250-280mm)	UVB (280-315mm)	UVA (315-400mm)	Mean Effective Irradiance
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})

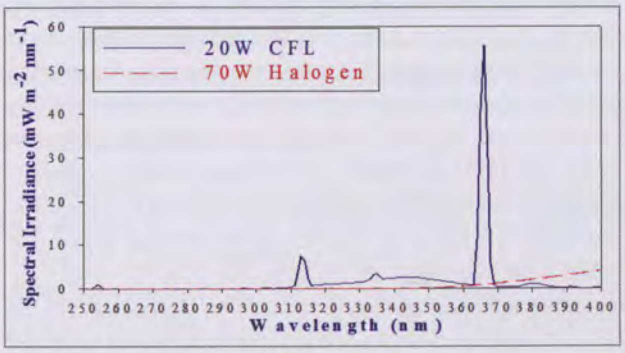


Figure 3: Spectral irradiance of a 20W CFL (blue)

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 photo-sensitive 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.

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 inter-connector 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 they vary in price. 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.

3. The research

A set of 15 CFLs and three GLS lamps are used for all experiments unless stated otherwise.

Research questions

3.1 What is the measured wattage and true power factor for a group of commercially-available CFLs in Ireland?

3.2 What are the levels of THD being produced by the tested CFLs and what effect will this have on the supply utility distribution system?

3.3 What is the actual "warm up time" for most CFLs?

3.4 How much variation, in price, exists between the similar CFLs and different manufactures?

3.5 What are the running costs and true CO2 savings from domestic CFLs?

3.1 Power factor

Power factor is defined as the ratio of the real power (W) flowing to a load, to the apparent power (VA) in the circuit[13][25]. It is a dimensionless number between 0 and 1. Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. This research examines the power factor of a group of 15 CFLs and three GLS lamps.

Methodology

1. Circuit set up as in Figure 4 and Figure 5.
2. Time was allowed for any inrush currents to steady and values were then recorded for wattage, current, voltage and power factor for all fifteen CFLs and each of the three GLS lamps.

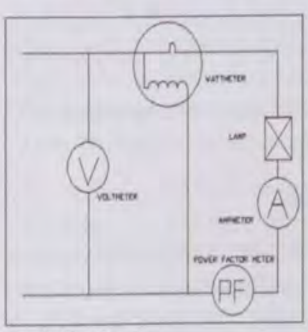


Fig. 4: Circuit set up

Fig. 5: Circuit illustration

Note: It can be seen in Figure 4 that the voltmeter used is not placed directly across the lamp. It is assumed that the volt drop across the meters will be negligible.

Lamp Type	Lamp Ref. No.	Lamp Shape	Manufacturer	Manufacturer Stated Wattage	Measured Power Factor	Calculated Power Factor	Volt-Amps (VA)
CFL	29	Spiral	Philips	20W	0.90	0.55	36.4
CFL	39	Stick	Philips	18W	0.99	0.57	29.9
CFL	38	Spiral	Philips	15W	0.87	0.53	28.3
CFL	26	Bulb	Philips	20W	0.98	0.58	34.5
CFL	68	Stick	Philips	20W	0.99	0.61	30.9
CFL	27	Bulb	Philips	20W	0.99	0.61	34.6
CFL	42	Bulb	Solus	16W	0.99	0.50	32.1
CFL	32	Stick	B & Q	20W	0.99	0.59	32.0
CFL	41	Bulb	Solus	16W	0.99	0.52	30.1
CFL	35	Stick	Tesco	20W	0.98	0.62	35.6
CFL	31	Stick	B&Q	18W	0.99	0.57	31.8
CFL	30	Stick	B&Q	20W	0.99	0.59	33.8
CFL	45	Bulb	GE	15W	0.97	0.57	24.4
CFL	33	Stick	B&Q	20W	0.99	0.58	31.2
CFL	34	Stick	Tesco	15W	0.99	0.62	35.4
				Average =	0.97	0.57	
GLS	1		Eveready	100W	1	1	100.4
GLS	1		Solus	60W	1	1	60.1
GLS	3		Solus	40W	1	1	40

Table 8: Measued wattages and power factor

It should be noted that the power factor meter used in this experiment is an analogue meter and only records displacement power factor. It was included only to indicate the difference between true power factor and displacement power factor. Displacement power factor gives an accurate indication of the power factor in linear circuits only. As the CFLs being used are predominantly non-linear loads (i.e. they draw current in sharp bursts or pulses), the readings from the true RMS volt and amp meters were used, along with the measured wattages, to give values for true power factor (calculated power factor, Table 8).

Discussion, finding and analysis

The manufacturer-stated wattages for most of the CFLs were very accurate when compared with those wattages recorded. The largest deviation was just 2W, which only occurred twice from the 15 tested lamps. These deviations do not suggest anything unusual and provide no real insight to suggest manufacturers may be stating incorrect wattages. The reason for the high VA (apparent power) of all the CFLs is the poor power factor associated with them. The average power factor from the group of 15 CFLs was 0.57, with the best being 0.62 and the worst being 0.52. When this is compared to the GLS lamps, they have a far higher power factor of almost unity. The average VA for the group of CFLs was almost double the measured wattage (18.47W compared to 32.13VA). With the GLS lamps, the VA and wattage were almost identical. Many people appear to have mistaken how poor power factor will affect power consumption and CO2 savings from a given CFL. To illustrate this with an example: Using a typical 12W CFL and a current of 110mA, would give an apparent power of 25.3VA. This will have significant implications for the supply system, but not the actual power used. What also must be remembered is that this increased stress on the electrical utilities has to be balanced against the reduced power usage from replacing GLS lamps with CFLs.

3.2 Total harmonic distortion (THD)

CFLs are fed by power supply units, which conduct current only during a very small part of the 50Hz period so that the current taken from the AC supply has the shape of a short pulse[21]. This leaves the remaining, distorted, sine wave to be returned to the national grid, producing distortion to the voltage and current waveforms of the supply system.

Methodology

1. Circuit set up as shown in Figure 6 and Figure 7.
2. CFL numbers 38, 42, 45, 39, 26 and 35 were used.
3. The six CFLs were placed into the lamp holders and switched on two at a time, and all available readings were recorded when new lamps were added to the circuit.

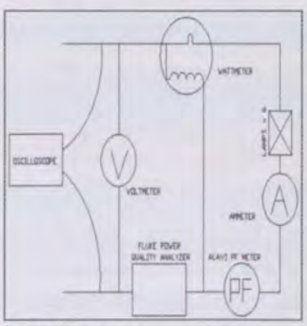


Fig. 6: Circuit set up

Fig. 7: Circuit illustration

Results:

Of the four measurement methods used, the Fluke Power Quality Analyser (digital TPF meter) results proved to be most useful when compared with the true RMS volt and Amp meters:

Fluke power quality analyser:

Lamp Type	V	A	W	VA	VAR	PF	DPF	THD(%)
38,42	236.2	0.23	30	58	50	0.51	0.87	81.3
38,42,45,39	236.2	0.454	61	108	90	0.56	0.89	79
38,42,45,39,26,35	235.4	0.756	101	175	143	0.58	0.89	76
2x40W Philips GLS	235	0.344	81	81	7	1	1	1.6

Table 9: Total harmonic distortion

Figure 9 shows the high levels of THD, up to 81.3%, produced by the group of CFLs, compared to the negligible levels of THD produced by the GLS lamps.

Figure 10 shows the levels of current experienced on each individual harmonic frequency. The levels of current on the 3rd harmonic are of particular interest.

Oscilloscope – two GLS lamps in parallel

It can be seen from the Figures 8 and 9 that the GLS lamps produced virtually no harmonic currents on higher order frequencies and caused almost no distortion to the oscilloscope voltage or current waveforms.

Frequency	38,42	38,42,45,39	38,42,45,39,26,35
Fundamental	0.147	0.289	0.474
3rd	0.122	0.235	0.383
5th	0.091	0.17	0.278
7th	0.073	0.135	0.219
9th	0.062	0.113	0.174
11th	0.049	0.076	0.101
13th	0.032	0.033	0.026
17th	0.015	0.018	0.024
21st	0.018	0.021	0.009
25th	0.017	0.012	0.006

Table 10: Harmonic order currents

Figures 8 and 9: two GLS lamps in parallel

Note: It can be seen that the top of the voltage and Current waveforms are flattened slightly. These small distortions were present before any lamps were added to the circuit and are caused by harmonics already existing in the electrical supply.

Oscilloscope – two CFLs in parallel

Figures 10 and 11: two CFLs in parallel

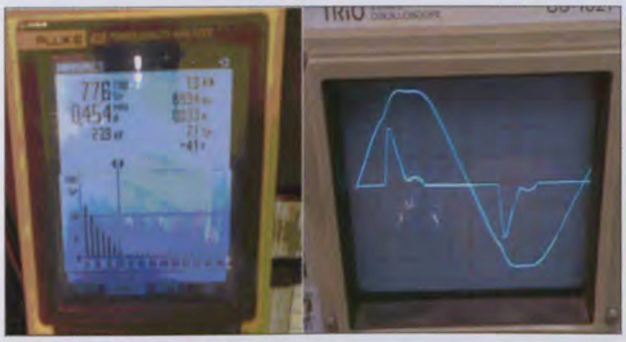
The GLS lamps were removed and two CFLs added to the circuit. Figure 10 shows the harmonic currents produced on lower order frequencies when the non-linear CFLs are introduced, while Figure 11 shows the harmonic distortion produced on the Voltage and current waveforms.

Oscilloscope – four CFLs in parallel

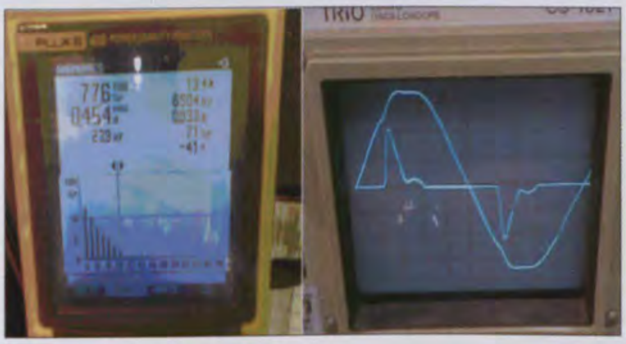
From Figure 12, when two extra CFLs are added to the circuit, a slight increase in harmonic currents on the lower order frequencies is experienced, but a reduction in higher order currents. Figure 13 also shows how the harmonic distortion on the voltage and current waveform is amplified.

Oscilloscope – six CFLs in parallel

Figure 14 shows that higher order harmonic currents have again



Figures 12 and 13: four CFLs in parallel



Figures 14 and 15: six CFLs in parallel

decreased, when two extra CFLs are added. Lower order currents have increased. The distortion to the voltage and current waveforms has been noticeably amplified.

From Figure 14, the total current of 728mA for six CFLs in a circuit should be noted.

Discussion, findings and analysis

The objective of this experiment was to quantify the levels of total harmonic distortion caused to the supply current waveform by CFLs. This could then be compared to GLS lamps. In domestic dwellings, CFLs would be paralleled, usually with six to 10 lamps per circuit. Six CFLs were used in parallel for this experiment. The GLS lamps produced virtually no total harmonic distortion (less than 2%) on the current waveform, where the CFLs produced an average of 79% THD. It can be seen that this large distortion of the current waveform has a noticeable effect on the levels of THD in the voltage waveform. The levels of total harmonic distortion experienced on the current waveform get slightly larger as more CFLs are added to the circuit.

"The biggest problem when installing non-linear loads is the risk of overloading the neutral conductor"[21].

The neutral conductor of most three-phase supply systems experiences very low current levels and is usually not protected by fuses or circuit breakers. The CFLs tested produced significant levels of third order harmonic currents. With this in mind, it is conceivable to think that with large-scale usage, they may provide problems for power quality and distribution systems. Many researchers state high harmonic distortion is the main drawback of CFLs. It is true that for the CFLs tested, the relative current distortion expressed as a percent of the fundamental exceeded 80%. However, since the current on the fundamental frequency is very low (120mA per CFL approx), the values of harmonic currents are very low too. This large harmonic distortion will comprise of only a small percentage of the overall load.

It is important to note that using CFLs reduces the total current in the distribution system and provides released capacity for energy suppliers!

3.3 Time to reach full Lumen output

A common complaint among CFL users is the time that lamps take to reach their full brightness. This short piece of research sets out to investigate the actual warm up time of the group of tested CFLs.

Methodology

1. The time taken for each lamp to reach its full lumen output was recorded using an amp meter and an illuminance meter.
2. The time was not stopped until the value shown on the illuminance meter had steadied for more than 10 seconds, this 10 seconds was then subtracted from the time on the stop-watch, to give as accurate as possible a time at which the lamp reached full lumen output.
3. This was done seven times per lamp and an average value recorded.

Results:

Lamp Type	Lamp Ref. No.	Lamp Shape	Manufacturer	Manufacturer Stated Wattage	Average Time to Reach Full Output (Sec)
CFL	29	Spiral	Philips	20W	53
CFL	39	Stick	Philips	18W	70
CFL	38	Spiral	Philips	15W	57
CFL	26	Bulb	Philips	20W	126
CFL	68	Stick	Philips	20W	55
CFL	27	Bulb	Philips	20W	105
CFL	42	Bulb	Solus	16W	75
CFL	32	Stick	B&Q	20W	91
CFL	41	Bulb	Solus	16W	74
CFL	35	Stick	Tesco	20W	62
CFL	31	Stick	B&Q	18W	85
CFL	30	Stick	B&Q	20W	76
CFL	45	Bulb	GE	15W	221
CFL	33	Stick	B&Q	20W	84
CFL	34	Stick	Tesco	15W	55
				Average =	85.90
GLS	1		Eveready	100W	2
GLS	2		Solus	60W	2
GLS	3		Solus	40W	2

Table 11: Time to reach full lumen output

Discussion, findings and analysis

A common consumer complaint with CFLs is the time the lamps take to reach its full brightness. The reason for this "warm up time" is the time needed to excite the mercury vapour within the fluorescent lamp to the levels needed to provide full lumen output. This small experiment was set up to investigate the associated warm-up time with the group of CFLs. It is clear that the associated warm-up time does exist and is quite noticeable when compared to a GLS lamp, which has almost instantaneous full lumen output. It is clear that some CFLs perform better in this area than others. The spiral and stick type lamps proved to be far quicker to reach full output than bulb types. This might suggest that bulb types may be generally more suited for a room where the lights may be on for long periods of time, e.g. television rooms, lounge rooms, etc and the spiral and stick types may be better for use in situations where the lights will be frequently switched and quick full lumen output is needed, e.g. bathrooms, closets, garages, stairwells, etc.

	Spiral	Bulb	Stick
Average (sec)	55	120.2	72.25

Table 12: Warm up time with tube shape

Another important issue to draw from this is the health and safety concerns if CFLs are located on stairs and landings and particularly in the homes of elderly people or those with impaired eyesight.

3.4 Costs in Ireland

From the literature review conducted, it was presumed that the cost of CFLs would vary. With this in mind, investigation into the price of the fifteen CFLs used in this research was conducted.

CFL Price Vs Performance

The price for each of the lamps was investigated to see if there is any correlation between the purchase price of a lamp and the performance it will provide. The price list can be seen in Table 13. All prices were sourced from local DIY shops and supermarkets. Where this was not possible, online catalogues were used and prices converted to Euro.

The variation in the price of the CFLs can be seen to be quite significant, with the cheapest CFL being one-fifth the cost of the most expensive, despite both being the same wattage. Comparisons are possible between any of the tested lamps, but for this section a sample comparison between the most expensive and the cheapest lamp will be conducted using the price, lumen output (manufacturer stated), average illuminance (research not included in this paper) and the measured VA. It can be seen from Table 14, that despite the price difference of over 500%, the two lamps perform almost equally well under the compared headings. Similar results are obtained when comparing prices and performance of other CFLs. This would lead to questions about the mark-up price of CFLs and whether or not some manufacturers are trying to exploit the ban of the GLS lamp.

Lamp Type Stated Wattage	Philips – Ref 39 18W	B&Q Ref 31 18W
Price	€11.02	€1.95
Lumens	1100 lm	1200 lm
Average Illuminance	300.4 lux	354.4 lux
Volt Amps	29.9 VA	31.7 VA

Table 14: Comparison – cheapest vs most expensive

Lamp Type	Lamp No.	Manufacturer	Manufacturer Stated Wattage	Price – €
CFL	29	Philips	20W	9.50
CFL	39	Philips	18W	11.02
CFL	38	Philips	15W	7.87
CFL	26	Philips	20W	10.99
CFL	68	Philips	20W	8.55
CFL	27	Philips	20W	10.99
CFL	42	Solus	16W	4.35
CFL	32	B&Q	20W	2.20
CFL	41	Solus	16W	4.35
CFL	35	Tesco	20W	3.25
CFL	31	B&Q	18W	1.95
CFL	30	B&Q	20W	2.20
CFL	45	GE	15W	4.37
CFL	33	B&Q	20W	2.20
CFL	34	Tesco	20W	3.25
GLS	1	Eveready	100W	0.99
GLS	1	Solus	60W	0.85
GLS	3	Solus	40W	0.85

Table 13: CFL price comparison

3.5 At-a-glance calculations – running costs and carbon emissions:

Running costs

The running costs of CFLs are easily calculated using the kWh price from an electricity supplier and the estimated hourly usage per day, week, month or year. The calculations below assume 1000 hour usage per annum, roughly 2.7 hours per day and use Electricity Supply Board Ireland kWh prices[22].

Philips 20W CFL – Ref No. 29

20W x 1,000hr/yr = 20kWh/yr x €0.1506 = €3.01 per annum.

Assume ten lamps per household – €3·01 x 10 = €30·10 per annum running costs.

Eveready 100W GLS – Ref No.1

100W x 1,000hr/yr = 100kWh/yr x €0.1506 = €15.06 per annum.

Assume ten lamps per household – €15.06 x 10 = €150.6 per annum running costs.

Savings per annum – €120.50

Note: In Ireland, domestic tariffs do not penalise for poor power factor. Should this be implemented in the future, the potential monetary savings from CFLs may be reduced.

CO2 Emissions

Again the predicted kWh usage for the year can be used to estimate the potential CO2 savings possible from switching to CFLs. The Carbon Trust provides a conversion figure of 0. 544kg/CO2 per kWh for grid electricity[23] and this will be used for the purposes of calculations.

Philips 20W CFL – Ref No.29

20W x 1,000hr/yr = 20kWh/yr x 0·544kg/CO2 = 10·88 kg/CO2 per annum.

https://arrow.tudublin.ie/sdar/vol1/iss1/7
DOI: https://doi.org/10.21427/D7DN0G

Assume ten lamps per household – 10.88 kg/CO2 x 10 = 108.8kg/CO2 per annum.

Eveready 100W GLS – Ref No.1

100W x 1,000hr/yr = 100kWh/yr x 0.544kg/CO2 = 54•4kg/CO2 per annum.

Assume ten lamps per household – 54.4kg/CO2 x 10 = 544kg/CO2 per annum.

Savings per annum, per household – 435.2kg/CO2

Lamp Type	Lamp Cost	Lamp Life	Lifetime Cost (12 Years)	CO2 Emissions (12 Years)
200W CFL	€9.50	12,000	€45.62	130.6kg
100W GLS	€0.99	1,000	€192.60	652.8kg

Table 15: Running costs and CO2 emissions comparison for "equivalent" lamps

4. Conclusions

It can be seen that manufacturer-stated CFL wattages were accurate, but an average true power factor of 0.57 has a significant effect on the apparent power. It leads to an apparent power that is on average, almost 60% greater than the manufacturer-stated wattage. Some of the problems that this may cause for electrical utilities are increased volt drops or a need to increase the rating of all system components, such as generators, conductors, transformers, switchgear, etc. Many researchers suggest that high harmonic distortion is the main drawback of CFLs. It is true that for the CFLs tested, the relative current distortion expressed as a percentage of the fundamental exceeded 80%. However, since the current on the fundamental frequency is very low, the values of harmonic currents returned to the distribution system are very low too, compared with GLS lamps. This minimises risks of distribution equipment overheating, transformer secondary voltage distortion and possible overload three-phase neutral conductors. The associated "warm up time" with CFLs does exist and is quite noticeable when compared to a GLS lamp, which has almost instantaneous full lumen output. Some CFLs appear to perform better in this area than others. The spiral and stick type lamps proved to be far quicker to reach full output than bulb types. Care should be taken when using CFLs in the homes of elderly people and those with impaired eyesight. The variation in the price of the CFLs is quite significant, with the cheapest CFL being almost one-fifth the price of the most expensive, even though they are the same wattage. From the comparison in Table 14, it can be seen that despite the obvious difference in price, there is little difference in the performance (under the headings examined) of the two CFLs. The financial and environmental benefits of using CFLs in domestic lighting are clearly visible from the calculations in section 3.5.

It is clear that CFLs have a far greater efficacy (lumen/watt) than their GLS equivalent. Using their manufacturer-stated lumen output, the CFLs used in this research had an average efficacy of 58.41 lumens/watt, compared to 13.3 lumens/watt from a GLS lamp. It would appear that CFLs contain a far greater embodied energy, but this is not significant enough to offset the potential savings they provide compared to GLS lamps. At present, it seems that CFLs produce slightly less illuminance than their GLS "equivalents". When manufacturers are stating equivalent wattages, there is some discrepancy between the methods of comparison. However, it appears that this is merely an effort to provide an easily understood method of comparison for the general public. CFL lamp life is hard to analyse critically. CFL lamp life is stated as being six to 12 times that of a GLS lamp, but questions are raised about what CFL lumen output will be towards the end of their lifespan and if this will be sufficient to avoid replacing the lamp. It is understood that stated lifespan is an average. CFLs produce an incomplete electromagnetic spectrum. They lack higher wavelengths, which contain the colour red. It is for this reason that they produce a cool colour temperature. This seems to be a significant factor for most users, but the use of lampshades may offset this somewhat. The spectral irradiance of CFLs does not follow that of a Planckian radiator, as with a GLS lamp. It instead shows peaks in spectral irradiance, separated by regions of little or no irradiance. It is for this reason that the colour rendering index of CFLs is lower than that of a GLS lamp. In the studies reviewed, the average CRI for CFLs was approximately 78. Very few independent studies exist that accurately measure the total lumen output of CFLs, but this research suggests a comparative ratio of 4.5:1, not the 5:1 stated by manufacturers may be more accurate. There are two sides to the debate on mercury content within CFLs. Some argue that more mercury will be released through the generation of electricity for GLS lamps than could possibly be released by incorrect disposal of CFLs. Others argue that the smaller quantities of mercury and mercury compounds (e.g. methyl mercury) that end up in landfills will do far more damage than the larger quantities released directly into our atmosphere. This paper suggests that only a very small fraction of each CFL will actually be recyclable. It is clear that some CFLs emit ultraviolet radiation. The reasoning behind this seems to be incomplete, inadequate or incorrect application of the phosphors coating to lamp envelopes. Cantwells' study found that 9.4% of single envelope CFLs exceed the ICNIRP recommended limit value of 30Jm-2 within eight hours at a distance of 200mm. No double envelope CFLs exceed this value. As of 27 April 2010, this limit cannot be exceeded in places of work, under EU law. The UK EPA recommends a distance of >30cm from CFLs for area and task lighting. The effects of CFLs and their emission of ultra-violet radiation must be taken very seriously where persons with photosensitive skin conditions are concerned.

While we must recognise and acknowledge the shortcomings of CFLs, the potential savings in energy, running costs and CO2 emissions provide a powerful argument that CFLs are an improved alternative to GLS lamps.

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