ANNEX 1 – TESTING PROCESS

Step 1: The retrofit LED tube is prepared for testing by placing thermocouples at various locations outside the LED tube, especially on designated Tc point(s).

Step 2: Fluorescent lamp ballast is warmed up for 2 hours with original fluorescent lamp. A temperature measurement of ballast internal components is taken to ascertain reference.

Step 3: The pre-warmed ballast is placed in a test box containing the test setup (see pictures in Figure 3).

Step 4: The retrofit LED tube is powered on for 10 minutes with fluorescent lamp ballast in all possible lamp holder wiring combinations. For more information on possible lamp holder wiring combinations, refer below.

Step 5: The test box is a fully automated test setup designed and maintained by Seaborough to prevent human errors which influence electrical parameters directly. The following electrical parameters are measured in the test box:

Fluorescent lamp ballast inputs

a. Input Voltage
b. Input Current
c. Power (or System Power)
d. Power factor

Fluorescent lamp ballast output / retrofit LED tube input

e. Voltage
f. Current
g. Power (or Lamp Power)
h. Power factor
i. Ballast output Frequency

Step 6: Broad thermal stability is seen to be achieved within 10 minutes, however testing is also performed for a duration of 30 minutes inside the test box. All tests are performed in an ambient temperature of 25 ± 2 °C.

Step 7: The retrofit LED tube is changed in orientation, called a tube turn. The electrical and thermal parameters are measured again. This step assures the operation of LED tube in any orientation thereby making the LED tube uniform in its operation and irrespective of the orientation and positioning in an actual luminaire in the field.

Step 8: All measured electrical and thermal results are saved in an easily accessible excel sheet.

Step 9: Step 2 through step 8 are repeated with each and every fluorescent lamp ballast combination with the retrofit LED tube combination.

ANNEX 2 – LUMINAIRE LAMP HOLDER WIRING COMBINATIONS

Figure S1 shows a typical electrical wiring of a single fluorescent lamp electronic ballast. In case of a retrofit LED lamp, the fluorescent lamp is replaced with an LED lamp without changing the wiring or removing the ballast.

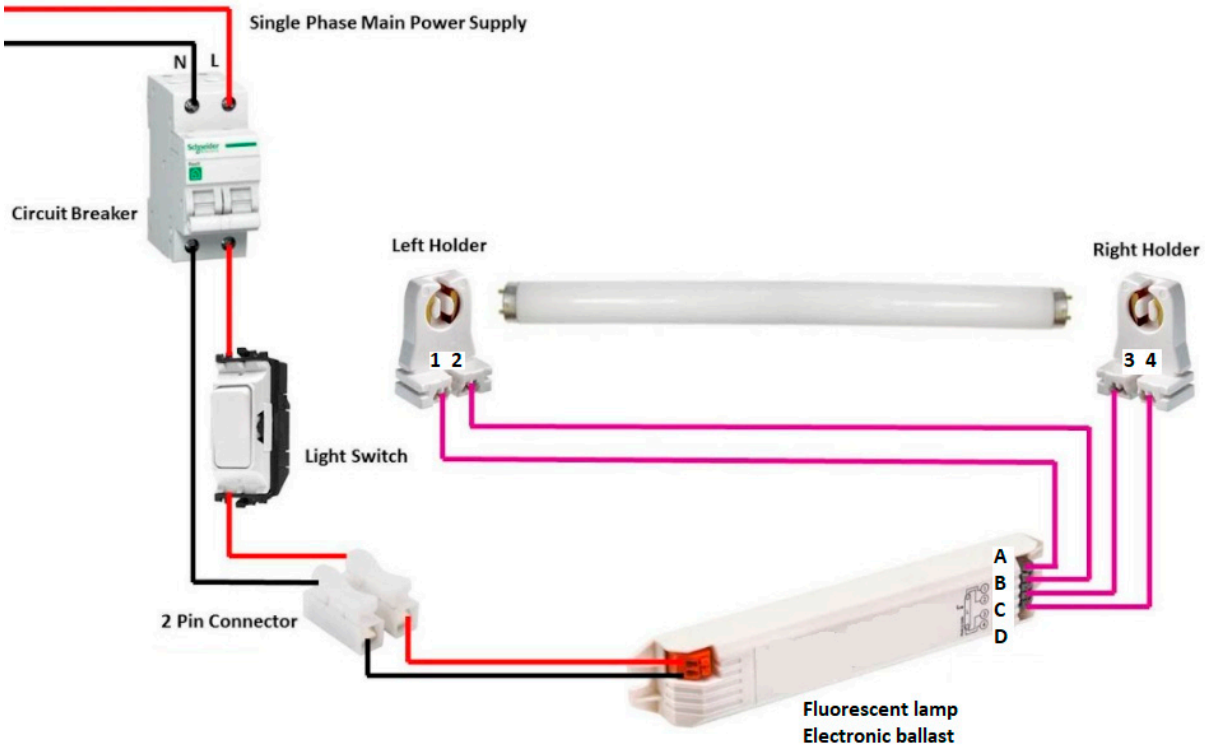


Figure S1 : Typical single fluorescent lamp electronic ballast wiring scheme

The possible combinations of wiring in a luminaire can be the following:

Combination number	Connection between Ballast and Lamp
1	A->1 ; B->2 ; C->3; D->4
2	A->2 ; B->1 ; C->3; D->4
3	A->1 ; B->2 ; C->4; D->3
4	A->2 ; B->1 ; C->4; D->3
5	A->3 ; B->4 ; C->1; D->2
6	A->3 ; B->4 ; C->2; D->1
7	A->4 ; B->3 ; C->1; D->2
8	A->4 ; B->3 ; C->2; D->1

ANNEX 3 – TOTAL COST OF OWNERSHIP (TCO) CALCULATIONS

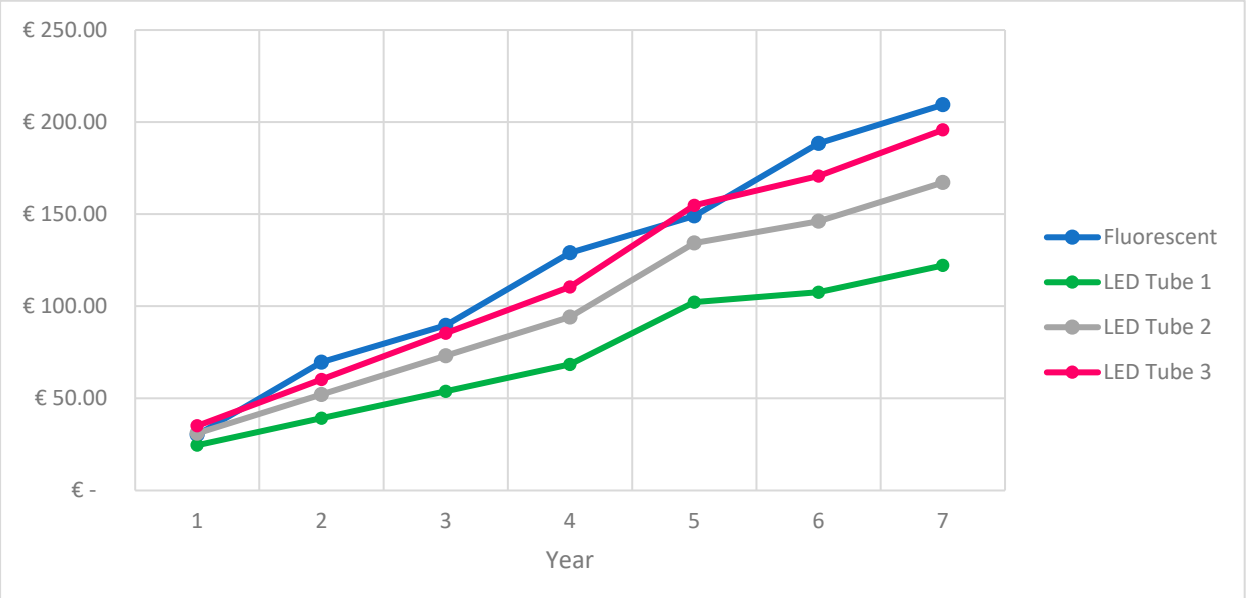
The following assumptions were made in the total-cost of ownership (TCO) calculations discussed in Section 4.1:

Operation:	16	hrs/day
Electricity:	0.1	Eur cent per kWh

		Power (W)	**50**	**25**	**36**	**43**
		Cost	€ 1.00	€ 10.00	€ 10.00	€ 10.00
		Lifetime	10,000	25,000	25,000	25,000
months	yrs	hrs	Fluorescent	LED Tube 1	LED Tube 2	LED Tube 3
12	1	5,840	€ 30.20	€ 24.60	€ 31.02	€ 35.11
24	2.00	11,680	€ 69.60	€ 39.20	€ 52.05	€ 60.22
36	3.00	17,520	€ 89.60	€ 53.80	€ 73.07	€ 85.34
48	4.00	23,360	€ 129.00	€ 68.40	€ 94.10	€ 110.45
60	5.00	29,200	€ 149.00	€ 102.20	€ 134.32	€ 154.76
72	6.00	35,040	€ 188.40	€ 107.60	€ 146.14	€ 170.67
84	7.00	40,880	€ 209.40	€ 122.20	€ 167.17	€ 195.78

Re-lamping costs

1.	Cost of 2 people for 8 hours	€	720
2.	Travelling expenses	€	100
3.	Equipment rent - Lift etc	€	100
	Total	€	920
	Total lamps replaced (5 mins per lamp)		100
	Cost per lamp	€	9.2



ANNEX 4 – LUMEN MEASUREMENTS

In order to substantiate the assumption that lamp measured power is a good proxy for output lumens, full integrating sphere measurements of stabilized lamp flux (at a third-party site) were measured on a selection of lamp/ballast combinations, as follows:

1. All measurements were done inside a 3meter integrating sphere in a draught-free room at a temperature of 25°C with a tolerance of +/-1°C, a relative humidity of 65% maximum and a steady state operation of the LED tube as per IEC 62612 standard.

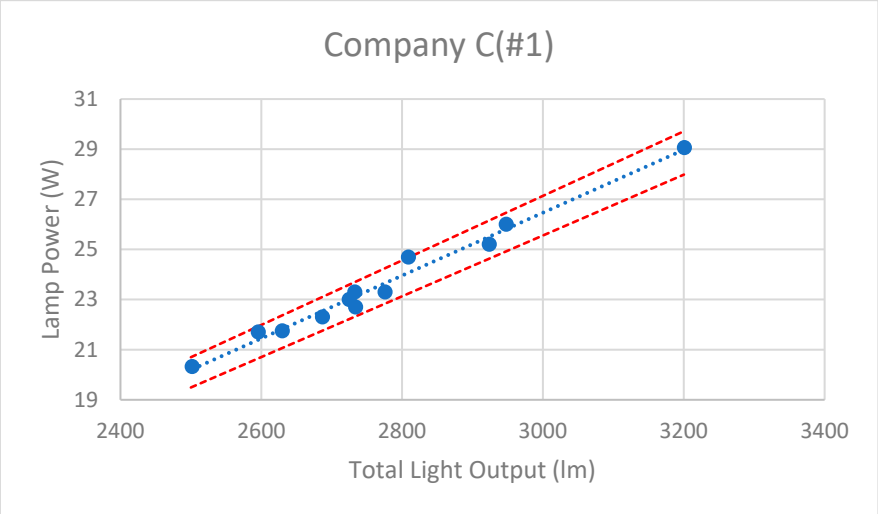
2. The test voltage was stabilized within +/- 0.5% of its rated value.

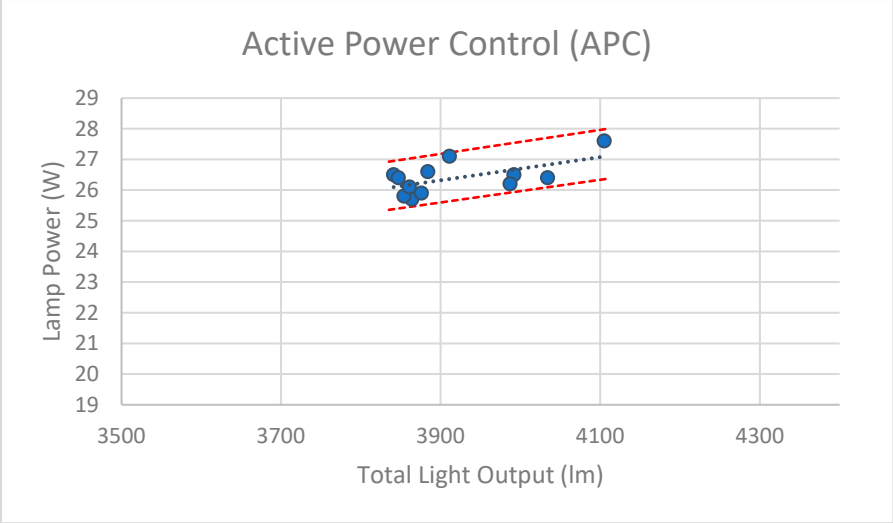
3. The luminous flux and power measurements were made at least at 1-minute intervals to observe the difference between consecutive luminous flux and power readings below 0.5% and 1% respectively. After this the lamp is considered thermally stable.

4. After thermal stability, the lumen measurements and power measurements are recorded.

Measured were a select number of ballasts with both the Active Power Control (APC) prototype tube as well as one of the commercially available tubes (Company C #1). The results are shown in the table and charts below:

	Company C (#1)			APC		
Ballast ID	Lumens	System Power	Lamp Power	Lumens	System Power	Lamp Power
1	2734	26.6	22.7	3841	29.5	26.5
2	3201	33.6	29.06	4105	31.7	27.6
6	2502	25.2	20.32	3992	30	26.5
7	2809	26.6	24.69	3911	28.5	27.1
17	2776	27.3	23.3	3884	30.4	26.6
97	2733	27.2	23.3	3864	30.8	25.7
171	2630	26.7	21.75	3854	29.7	25.8
202	2596	25	21.7	3876	29.1	25.9
272	2687	27.5	22.3	3861	30.8	26.1
296	2948	29	26	3987	30	26.2
401	2725	27.4	23	3847	30.7	26.4
406	2924	28.8	25.2	4034	29.7	26.4





While there are slight variations, the data show the lamp light output is largely proportional to the lamp input power. The tighter spread in lumens for the APC tube is because the lamp input power is being controlled by the driver electronics (the main theme of the paper). The higher light output for the APC tube is simply because high lumen-per-Watt LEDs happened to be used to build the prototype lamp.

These data show that measuring lamp power is a good proxy for total light output, since the small (+/-3%, as indicated by the dashed red lines) spread in light fluctuation with power is insignificant compared to the large lamp power variations (from ~ 33% to 200% of rated power) measured in the various lamp/ballast combinations. Thus, the use of measured lamp power is valid for ascertaining lamp light output and appropriate for our study.