Power Quality and Energy Efficiency in the Pre-Evaluation of an Outdoor Lighting Renewal with Light-Emitting Diode Technology: Experimental Study and Amortization Analysis

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Article

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Keywords: amortization analysis; break-even point (BEP); LED luminaires; power quality; street lighting; total harmonic distortion (THD)

1. Introduction

The topic of "low-carbon green-growth cities" [1] is rapidly expanding due to environmental and economic concerns, and different energy-saving technologies are being researched and implemented worldwide for this purpose. In terms of lighting, the total global power consumption in this field is roughly 2.100 trillion kWh per year (approximately15% of the global power consumption) which is equivalent to the emission of 1.7 billion tons of carbon oxide [2] and these values are increasing at a rate of 3–6% per year [3].

Any improvement in the development of more efficient lighting technology can have a large influence on energy consumption and local environmental effects as public lighting has key relevance in the economic balance of cities. For example, a study by the Italian research institute ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) has determined that their average total electricity budget for this objective is more than a 12% of their total expenses [4]. Governments worldwide are aware of this situation and the United Nations has declared 2015 to be the "International Year of Light and Light-based Technologies" [5]. In this area, policies pursue two fundamental aims, i.e., to reduce energy use and CO_2 emissions, thereby making lighting practices more sustainable. In this effort, the following measures are proposed:

- Eliminate inefficient lamp technologies. The European Eco-Design Directive (2009/125/EC) has banned mercury vapor lamps [3], promoting more modern devices such as LED luminaires.
- Limit the maximum levels of direct light (illuminance) and light emitted to the upper hemisphere. The standardization boards should specify minimum light levels for basic activities (walking or driving) and conservative top appropriate values for these areas [2]. This is important to avoid rebound effects: to increase illumination levels as lighting becomes "cheaper" [6].
- Enhance intelligent systems to generate light adaptive control to dim the emission flows according to the specific needs of the environment.
- Generate new lighting standards for different road types which are better adapted to real use requirements (UNE 13201:2015).

Since 2006, LED lighting has become one of the most successful innovations to renew lighting installations under the above directive as these devices have achieved efficiency levels, measured in lumens per watt, that surpass that of conventional fluorescent lighting. Moreover, LEDs offer other significant advantages for street lighting compared to conventional bulbs as improved white light quality and color rendering index (CRI), no UV emissions, electrical safety, environmental sustainability, reliability with significantly longer lifetime expectation [7], lower maintenance [6], and they are environmentally friendly, containing no heavy metals such as mercury or lead [8].

Today, LEDs lighting equipment are nearly 70% more energy efficient than any other system thanks largely to their directional light-emission capability measured as "Luminaire Efficacy" [9], which minimizes the large losses generated by the bulb's reflectors. The LED package efficiency is in the range of 140–150 lm/W, but, after losses from thermal, electrical, and optical efficiency, the total system efficacy is typically 25–30% lower than that. Nowadays, the average total luminaire efficiency is within the range of the 100–105 lm/W [10]. Considering all the previous, 450 W HID lamp can be replaced by a 150W LED lamp for a 67% energy reduction as well as substantially lower CO_2 emissions [6,11,12].

Active research and development on LED luminaires and their components is striving to optimize lighting properties, and The Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy (DOE) has estimated that the efficacy of LED technology on the market is projected to reach approximately 220 lm/W by the year 2020 [9]. However, the semiconductor and phosphor layer of the LED component can be produced with different technologies and materials, and this consideration is appropriate for their drivers. Therefore, properties such as efficiency, reliability, and environmental impact differ for each LED luminaire but these features are not easily distinguishable. Such uncertainties make it difficult to identify the best product among LED luminaires [13].

2. Electric Grid, Power Quality, and Light-Emitting Diode Lighting in Sustainable Cities

The primary power grid in many cities are several decades old and are undergoing rising electricity consumption that questions its energy efficiency while ageing assets compromise safety and reliability [14]. The reconciliation of economic growth and environmental values is becoming the new paradigm for the most important cities in the world [15]. A crucial factor to consider in this sense is to guarantee good power quality in these grids [16].

2.1. Grid Power Quality

The term "power quality" is applied to a wide set of electromagnetic phenomena that may occur within an electric grid that affect the parameters of its voltage and current: symmetry, frequency, magnitude, and waveform from the ideal sine wave with constant frequency [17]. These deviations from the nominal parameters can be generated by a poor power generation but may also be due to the effect of the loads. Street luminaires are installed in the outdoor conditions and can be operated under various electrical conditions that may not be ideal. To replace conventional luminaires with new LED luminaires means greater use of more sensitive electronic devices than those replaced in old electrical public-lighting installations. However, they are expected to work continuously with a very low failure rate [18].

Poor power quality raises the chance of intermittent shutdowns, while electric and equipment cost overruns may result from poorer performance and premature luminaire malfunction: "Any disturbance manifested in the voltage, current and frequency from the standard rating is treated as a power quality (PQ) problem that results in failure or malfunctioning of electrical/electronic equipment" [19].

Several studies reveal that current harmonics of odd order and peak currents are the main negative effects regarding power quality associated with the electronic sources of LED technology [20,21]. This problem becomes exacerbated as smart digital control and transmission systems are being installed together with LED luminaires to be tele controlled. These systems can be dimmed without significant efficiency losses in the LEDs, but their drivers working below their nominal power may generate more accentuated harmonics, flicker, voltage sag/swell, voltage regulation, load unbalancing, deviations in phase as well as in frequency, "resonance in distribution networks, increased transmission and distribution losses. For the economic consequences there might be potentially higher electricity costs resulting from a power factor charge utility" [22].

Another significant aspect that affects both the LEDs and their driver is their working ambient temperature. This parameter severely alters their electrical performance (harmonic distortion on the current, supply current) [23], their service-life expectancy [24] and their emission spectrum: CRI, correlated color temperature (CCT) and International Commission on Illumination (CIE) chromaticity coordinates "x" and "y" [25].

Therefore, the effect on the grid of any specific LED luminaire needs to be analyzed before any mayor installation renewal evaluating how it affects the power quality of its power line in order to maintain a standard of supply and economic operating conditions. We propose a simple methodology to detect and classify power-signal disturbances of new LED lighting equipment that may be significant to the power quality of the installation according to the requirements of the IEEE standard 1159:1995:

- Transient: cold starts
- Eventual: Sustained under/over voltages
- Steady state: Harmonics, flickers, and frequency variations.

2.2. Power Quality and Light-Emitting Diode Drivers

LED drivers are the most important component of these types of luminaires to improve the above quality concept. Most of the initial LED drivers were based on the switched-mode voltage sources, and it has been necessary to design new suitable circuit topologies that can be used as current sources for LED applications, the most common power methodology [26]. Thus, high-efficiency high-reliability converters optimized for LED-based applications have been proposed in the recent years, including different dimming, power factor correction (PFC), harmonic-reduction units and control techniques.

The efficiency of the latest boost pre-regulator models using electromagnetic ballast chokes has been raised to levels as high as 94.5% for low power (40 W) [27] and about 95% for a total input power was 155.4 W with a power factor as high as 0.99 and a total harmonic distortion (THD) of 10.7% [28]. These values are important to achieve the highest efficiency values in LED luminaires.

With regard to the power factor (PF), several on-grid single-stage active topologies with PFC can be found on the market. These include a rectifier in cascade with a DC-DC converter and a capacitor used to regulate the current through the LEDs. However, this solution generates a significant ripple in the input current of the light emitting semiconductors and two stages are being incorporated to prevent "LED light-flickering problems" [29].

Higher efficiency values and PFC are not the only objectives under investigation. Also, wider ranges in the input voltage of drivers (even greater than the standardized 90–305 V_{AC}) or to eliminate lifetime-limiting components such as electrolytic capacitors, inductors, or transformers [30,31] are sought.

3. Methodology

3.1. Case of Study

This study was undertaken in the context of a large outdoor-lighting renovation project by the city of Fuengirola (Spain), which will replace a large number of conventional lighting technology projectors used to cover the 2-km-long urban seaside beach and boardwalk [32].

In this case, 63 MH 1 kW bulb projectors installed in the same number of poles are to be replaced by 189 new LED projectors (three units for each MH device). We tested sample units by six different manufacturers to analyze the electrical performance and power quality of the electric grid of this renewed facility, considering that it is meant to change only the projectors without changing the present 6 mm^2 cross-sectional area cooper cable installation or the 6 electric panels that power all of them.

The six chosen projectors are available on the general market with power consumptions ranging between 180 and 200 W and with similar light output diagrams. In Table 1, we show the rated power and efficiency (lm/w) declared by the manufacturer for each device as well as the results of a basic lighting simulation performed with the DIALUX software and using their published plug-ins. The simulation converts the basic real parameters of the installation: 12-m-high poles with three spotlights spaced an average of 35 m apart to illuminate a 50-m wide section of beach. Specifically, this location used to develop the methodology is not a functional lighting installation as it has an ornamental function with touristic porpoise and the illuminance levels required by the city council were higher than the specifications of the EN 12464-2.

Table 1. Power, luminous efficacy, and DIALUX simulation results for the six projectors tested. *Em*: mean/average illuminance; *Emin*: minimum illuminance. Uniformity: $U_0 = Emin/Em$.

Projector ID	Power (W)	Luminous Efficacy (Lumen/W)	DIALUX Software *Em* (lux)	DIALUX Software $U_0 = Emin/Em$
1	200	94	7.6	0.29
2	190	101	10.1	0.34
3	200	102	6.5	0.18
4	180	83	6.9	0.20
5	200	101	8.3	0.32
6	190	80	7.1	0.19

The electrical and photometric experimental tests were made by situating the LED projectors on the same pole where they would eventually be installed. Only a behavioral test of the luminaires performed with different ambient temperatures have been made within a climatic chamber in a laboratory. Figure 1 shows an overview of the location of the lighting installation and two different LED luminaires positioned in a test pole.

This test pole is used to eliminate the external influence factor of other equipment or the energy-generation system; we have isolated each of the sample projectors in an average length one-luminaire single-phase circuit with a 230 V_{AC} stabilized voltage power input. The electrical parameters were measured using:

- A high-precision clamp ammeters (model: K2413R, manufacturer: KYORITSU, Tokyo, Japan) with a very wide measurement range (5 mA–1000 A) and a sample rate of three values per sec. This equipment is not specifically designed to capture peaks of very short duration and thus does not provide an accurate quantitative value of inrush currents. However, taking a sequence of

10 measurements and recording the highest value, we can make a meaningful comparison of the performance of the different projectors being tested.

- A high-frequency network analyzer (model: AR6, manufacturer: CIRCUITOR, Barcelona, Spain) capable of measuring stationary values of voltage, current, power, waveform, phase, and harmonics. Researchers such as Bergen et al. [33] state that "many SSL devices produce highly distorted current waveforms and harmonic content well into the hundreds of kilohertz" and "additional distortion of the waveform can also be introduced when dimming the SSL device". Consequently, power analyzers with low bandwidth, non-continuous or an inadequately sampled current waveform will have difficulty in accurately profiling the current waveform when measuring SSL devices.

Figure 1. Overview of the study lighting installation area and evidence and detail of two models of LED projector mounted on our test pole.

3.2. Experimental Procedure

Through this work, we intend to introduce several simple test to verify in field luminaires performance rather than using software simulations and technical data sheet. The process designed in thought to be executed in two different stages (outdoors and in a thermal chamber) as follows:

First, a single-pole power line was isolated in the testing field to power and measure independently each single LED projector with an average cable length toward its electrical panel in the outdoor installation. We temporarily created a 230 V_{AC} single-phase circuit network with a head stabilizer-phase inverter voltage equipment based on a toroidal rheostat (Model: EA 600; maximum power: 600 VA, manufacturer: POLYLUX, Barcelona, Spain).

The inrush currents of the LED luminaires were measured at cold start and after a 20, 40, and 300 sec of delay from a power reset. These measurements were taken using the clamp ammeters and the system explained in the previous section.

Voltage, current, power consumption, and current harmonics were measured with the network analyzer described. For all the luminaires, these measures were taken after a 30-min power-on period so that their working temperatures were stabilized according to their heat-sink power-dissipation capacity (this is the minimum time indicated by CIE 198 standard to consider electric and photometric stabilization for a device under test) [34]. This test and the above one were performed for all the luminaires with an ambient temperature within the range of 20–25 °C.

Secondly, the luminaires were re-installed in a 1 m^3 climatic chamber (manufacturer: HERAES-VÖTSH, Grand Rapids, MI, USA) to measure again their stationary electrical parameters with our network analyzer at different ambient temperatures to observe how their drivers perform within all the different working situations they might be subjected to.

We have studied all the measurements made to assess the real consumption values of the equipment tested and to compare the results related to power quality: inrush or peaks of currents and waveforms and harmonic distortion generated in the network compared to their theoretical values given by the manufacturer.

4. Results

4.1. Field Test Set

Table 2 details the voltage and electric-current measurements taken powering the six sample projectors P1-P6 in the field-test set: average values, frequency, and odd-order current harmonics percentage (%OTHD). It also includes the current peaks (inrush currents) measured on cold starts (CP cold start), and restarted after a 20 (CP 20 s), 40 (CP 40 s) and 300 (CP 300 s) seconds delay from a previous shutdown.

Table 2. Electrical measurements of the LED projectors in the field test set.

Projector ID	Current (A)	Voltage (V)	Frequency (Hz)	OTHD (%)	CP Cold Start (A)	CP 20 s (A)	CP 40 s (A)	CP 300 s (A)
P1	0.93	231.1	50.03	6.1	5.93	2.50	3.20	4.71
P2	0.88	230.5	49.99	13.5	8.18	3.85	6.03	7.71
P3	0.91	230.2	49.97	10.2	5.83	2.48	2.52	4.05
P4	0.81	230.4	50.00	6.3	5.04	1.21	1.27	3.66
P5	0.89	230.0	49.99	7.3	8.30	3.08	3.49	7.52
P6	0.91	230.1	50.00	18.3	0.80	0.77	0.77	0.77

Figure 2 details all the current harmonics that appear in the networks with each luminaire. Although these are adequate under standard regulation, are significant and has a significant relevance on the power quality of their grid. Figure 3 shows the power triangles of the luminaires with the power factor measured and the exact values of electric consumption of each luminaire and the reactive proportion generated. All the PF are close to the unit value with a leading nature. No significant values of capacitive currents will be generated and installations are expected to improve in this parameter in all cases.

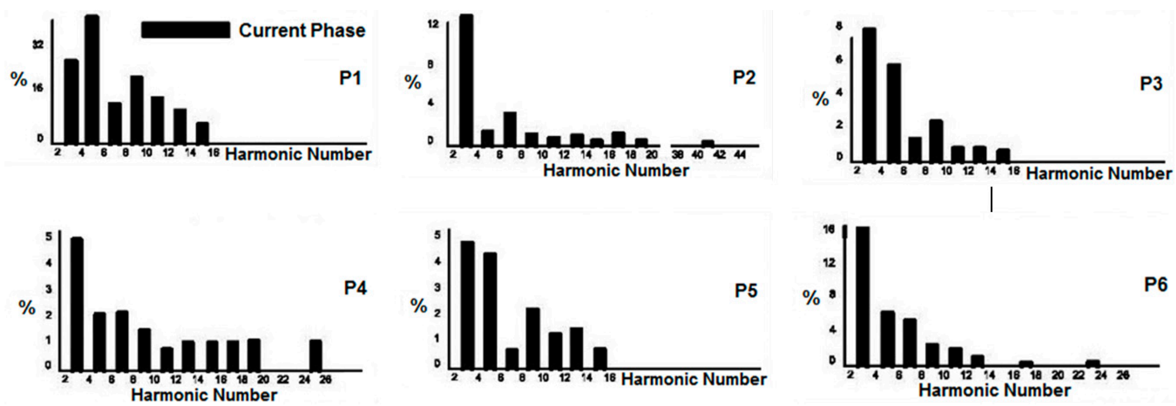

Figure 2. Current harmonics generated by the different LED projectors in the field-test set (Projectors numbers P1 to P6).

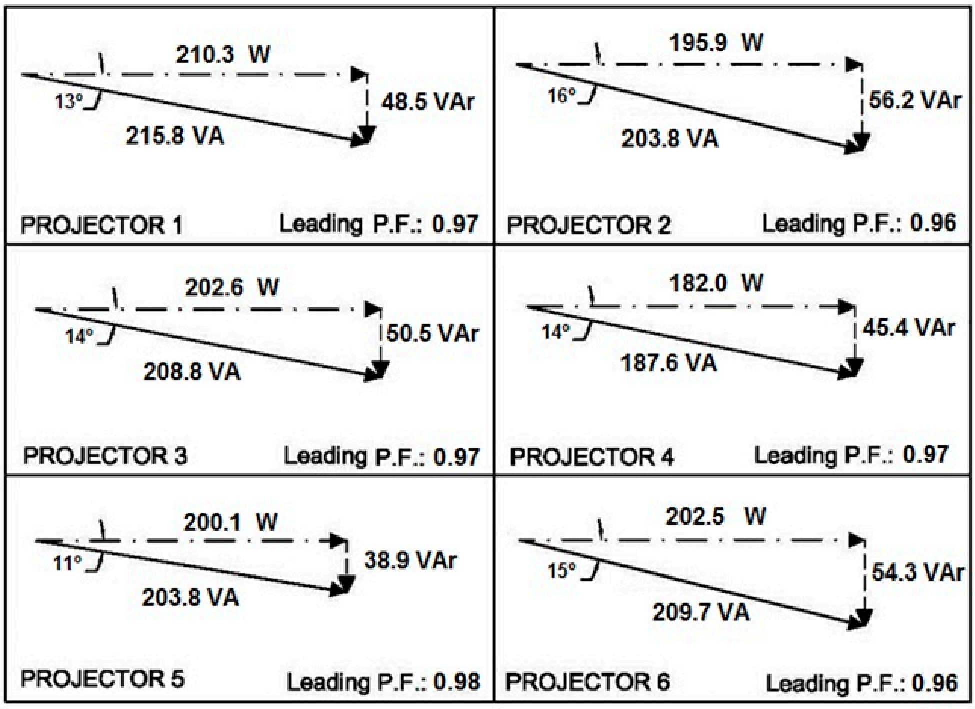

Figure 3. Power consumption triangles (Horizontal: active power (W). Vertical: reactive/inductive power (VAr). Diagonal: total/apparent power (VA)) measured with the 6 LED projectors used in this field-test.

4.2. Thermal Analysis

Generally, any rise in the ambient temperature directly affects to the emission efficacy of LEDs and consequently of its luminaire [35]. This may also limit the lifetime of the projectors as higher temperatures of the semiconductor junction can reduce their light output and shorten the functional life of the luminaire: 70% or 80% of it initial brightness (L70 or L80). However, with this experiment, we verified that the energy quality of the luminaire grid is also affected, by a rise in working temperatures. In all the cases, we observed that higher temperatures increase, at different levels, the average power consumption and the current harmonics with a greater sine waveform deformation.

These increases are small values (<5%) in most of the equipment measured at a maximum test temperature of 35 °C. However, in P5, this working temperature had a highly significant impact on the values measured. Figure 4 shows the current and voltage waveforms of the voltage of its grid at 30 °C and 35 °C ambient temperature and the current harmonics measured for the highest value. In this latter case, it bears highlighting that the percentage of harmonics increased up to the 70% (TDH-A%) and has a maximum power consumption with maintained currents peaks up to 4.6 A.

4.3. Economic Analysis and Calculation of Break-Even Points

Using the case study as an example, we analyzed the basic economic profitability thresholds to justify a renewal in the lighting-installation investment depending on the luminaire replacement cost and their power consumption. We paid special attention to the way this threshold is affected by any power overrun with respect to the nominal values declared by the projector manufacturer.

The total power consumption measured with the original 63 MH projectors is 57.85 kW·h with a 0.918 lagging PF. This consumption is slightly lower than the 63 kW nominal value. This is due mainly to a voltage drop in the electric lines feeding the luminaires that reduces their consumption as well as also their light emission [32].

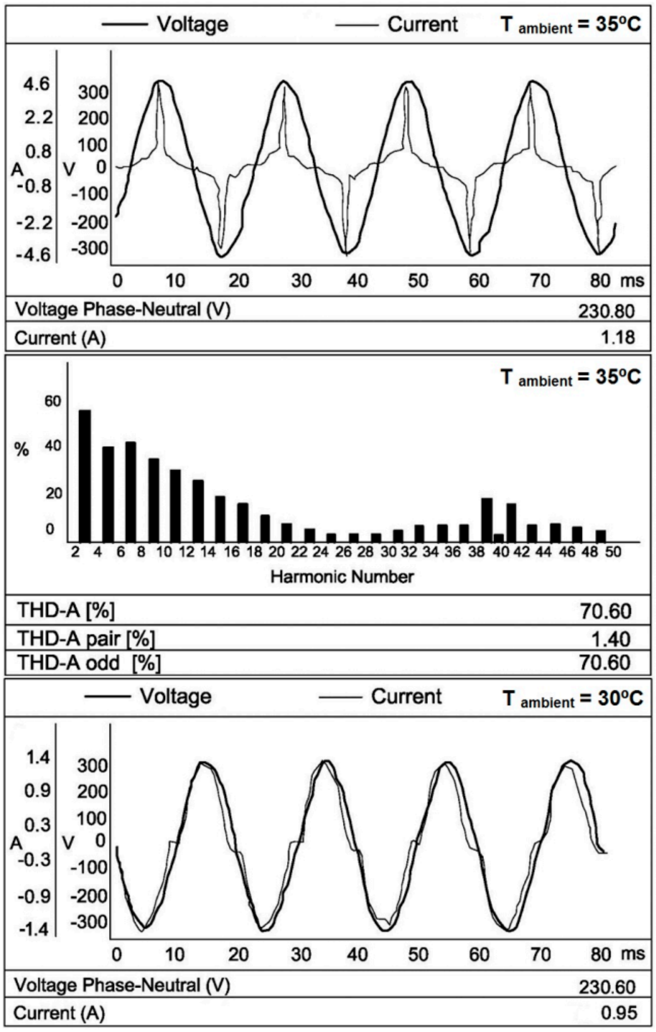

Figure 4. Voltage and current waveforms and harmonics measured from Projector 5 working with ambient temperatures of 30 °C and 35 °C inside a climate chamber.

The possible LED power-consumption scenarios cover four cases of LED sources: 180, 190, 200 and 210 W respectively. The electrical costs for all the cases established are shown in Table 3. The analysis of our installation established an average daily use of 7 h 365 days per year and an energy cost for all the cases of 0.14 €/kWh (information given by the municipal technician). The total cost of the installed power contracted for each electrical panel with the MH lamps and the expected one for the different LED luminaires analyzed are also detailed.

Table 3. Analysis of energy consumption and electrical costs between MH projectors and variable power LED luminaires.

Consumption Costs	MH (Real Data)	LED 180 W	LED 190 W	LED 200 W	LED 210 W
Total energy consumption (kWh/year)	147,807	79,815	84,249	88,682	93,117
Cost of energy consumption (€/year)	20,692.98	11,174.14	11,794.79	12,415.45	13,036.44
Cost of maximum power contracted (€/year)	10,212.30	5514.61	5820.91	6127.21	6433.68
Total energy cost (€/year)	30,905.28	16,688.75	17,615.70	18,542.66	19,470.12

To perform the economic profitability analysis we have used three economic indicators of those commonly used in similar studies to compare investments. We evaluate the return period of the investment (pay-back), the net present value (NPV) and the internal rate of return (IRR) for each type of LED projector, based on an initial exit price for the calculation of the total investment [3,33].

Analyzing different costs of projectors, we look for the threshold price that obtains optimal values for the three analyzed indicators. For different unitary purchase and replacement prices (removal of existing projectors and installation of new LED projectors, auxiliary lifting equipment and materials and labor costs) assuming a fixed interest rate of 3%, we calculated different values of economic return of the investment, as indicated in Table 4. Figure 5 shows the profitability thresholds which determine the maximum, minimum, and break-even point prices (€/LED projector) for the acquisition, calculated according to the real power consumption.

Table 4. Economic and financial analysis for different luminaire-replacement costs and variations in power consumption: Pay-back, NPV and IRR.

Replacement Cost €/Luminaire	LED Consumption: 180 W			LED Consumption: 190 W		
	Pay-Back (Years)	NPV (5 Years)	IRR (%)	Pay-back (Years)	NPV (5 Years)	IRR (%)
250	3.32	21,748.96	15.36	3.56	13,612.37	12.56
275	3.66	17,023.96	11.43	3.91	8887.37	8.79
300	3.99	12,298.96	8.04	4.27	4162.37	5.53
325	4.32	7573.96	5.07	4.62	−562.63	2.68
350	4.65	2848.96	2.45	4.98	−5287.63	0.15
375	4.99	−1876.04	0.10	5.33	−10,012.63	−2.11
Replacement Cost €/Luminaire	**LED Consumption: 200 W**			**LED Consumption: 210 W**		
	Pay-Back (Years)	**NPV (5 Years)**	**IRR (%)**	**Pay-Back (Years)**	**NPV (5 Years)**	**IRR (%)**
250	3.82	9367.19	9.68	4.13	5119.68	6.71
275	4.20	4642.19	6.07	4.55	394.68	3.27
300	4.59	−82.81	2.95	4.96	−4330.32	−0.28
325	4.97	−4807.81	0.21	5.37	−9055.32	−2.34
350	5.35	−9532.81	−2.22	5.78	−13,780.32	−4.67
375	5.73	−14,257.81	−4.39	6.20	−18,505.32	−6.76

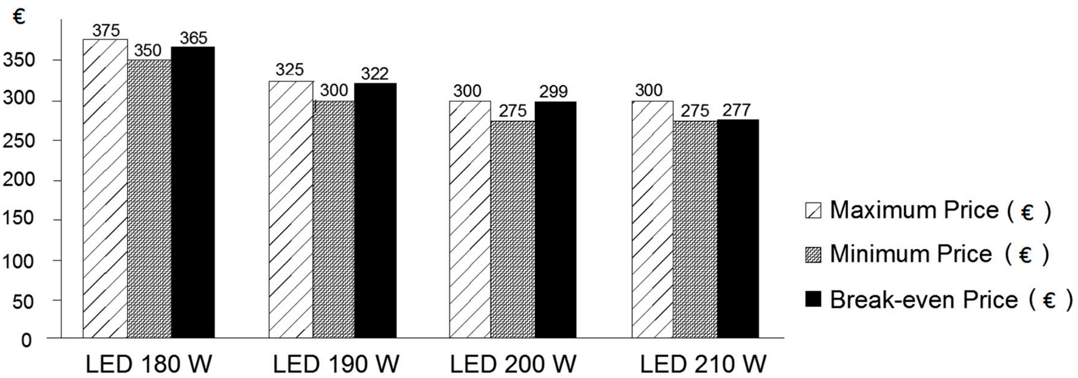

Figure 5. Analysis of the maximum, minimum, and break-even point prices that justifies a MH to LED luminaires renewal investment depending on real LED power consumption.

5. Discussion

5.1. Power Consumption

All the LED luminaires generate real power consumption higher than the nominal value declared by the manufacturer. In some cases it is negligible, as in the P5, where the discrepancy is barely 0.1 W, and in the worst case, found in the P6, with a 12.5 W overconsumption (a rise of a 6.5% over the nominal value). These are not large amounts but they have substantial relevance, as analyzed in Section 5.6.

5.2. Reactive Currents

All the projectors generated a reactive current on the network, but they were low values and similar in all the cases tested where the power factors lay within the range of 0.96 to 0.98. These values are categorized at the highest level that can be found in these types of lighting installations. It is relevant that, in all cases, the reactive currents had a capacitive nature, whereas the reactive currents generated by the ballasts of the discharge lamp are inductive.

5.3. Current Harmonics

Spanish regulation allows up to a 20% of harmonics. However, these values can still origin electricity over costs and possible failures or malfunctions of the luminaires or other equipment powered in this grids [36]. The current harmonics measured oscillate around a mean value of a 10%, but the dispersion in this case is a significant element. In three projectors, these values are found to be around the 6–7% range, but in the three remaining luminaires this parameter rises significantly above that 10% and in the case of P3 it rose around 18% (i.e., 3-fold more than the lowest value). Consequently, a proper selection of the projector significantly influences the power quality of the lighting grid.

5.4. Inrush Currents

The maximum inrush currents were measured in the cold-start case and they were, on average, 5.5-fold higher than their steady state values. These power-on peak values dropped in an inverse relationship with the restart period. However, it was found that for projector 6 the inrush current variations with respect to its steady state were negligible in all the cases. This was the same projector with the highest levels of harmonics.

The different performance of P6 compared with the other luminaries in these last two parameters was due to its LED array. All equipment from P1 to P5 drives the diodes with voltages of below 48 V_{DC}. However, P6 is the only one that used chip on board (COB) packages as light sources that work at approx. 120 V_{DC}. Despite offering an appropriate power factor, this system seems to exploit its smaller voltage reduction, both in the AC input rectification and in the DC output stabilization, less efficiently than all the other systems, considering parameters that significantly affect the power-grid quality and that are not fully analyzed in the common commercial specifications of these types of products.

Comparing cold and hot restarts, inrush currents decreased by half in the 20-s restarts, with a clear trend to increase as the drivers were off for a longer period. We have found that after 5 min from a luminaire reset, the inrush currents again reached values in the range of 10% of the maximum values due to the total discharge of capacitors included in the drivers of the luminaires.

5.5. Temperature Effect

A worsening of the electrical power quality was found in all the equipment as the ambient temperature rose. In some cases, as with P5, an increment of only five degrees in this temperature (from 30 °C to 35 °C) increased the deforming of the current waveform by more than a 50%. The temperature is southern Europe can rise up to this level during the night—in this particular location punctually, at some points during summer, values of 38 °C at 23:00 and 34 °C at 05:00 have been measured. Because of this, a full characterization of the working-temperature range should be added in the testing and certification protocols of LED luminaires and this information should be given in their technical specifications.

In addition, warm temperatures substantially augment power consumption in the economic analysis of the inversion. The average local temperature should be used as a significant parameter in any test applied to verify the real consumption in our installation.

5.6. Economic Analysis

These data show how the economic and financial performance of the equipment depends on the real power consumption of the equipment. Increases of 10 W per luminaire significantly change the indicators of economic and financial profitability in a negative way, lengthening the return on investment (ROI) periods and considerably lowering the NPV calculated over 5 years, which is the warranty period of the LED luminaires, the IRR and the BEP. Renewal investments may be deficient if, as has been found to be likely, the consumption values of the luminaires are greater than cited in their nominal specifications even though these have only about 5% deviation. For P6, the discrepancy between its rated and real power consumption increased the BEP by more than 25€ per luminaire.

6. Conclusions

In Spain, where this study is done, the main criteria (in many cases the only one) by municipalities to accomplish an installation renewal is the payback of the inversion and technical specifications are taken from granted based on the general information of the manufacturers of the equipment. However, in most of the cases, that data is not valid in the real working conditions found in warm emplacements (as in South Europe) and standard tests do not fully cover this situation.

In this work, we have developed an experimental process of analysis and practical assessment to compare sample LED luminaires from the standpoints of energy efficiency, electrical power quality and the economic profits before accomplishing a large number of LED luminaires replacement. This is necessary to verify, with sample luminaires in outdoor working conditions, that the deviation of real working parameters from manufacturer data are not large enough as to generate significant technical or economic problems. We have specified the basic minimum tests that can be performed to verify the most significant parameters of the luminaires behavior.

We have studied a set of six sample projectors with similar power consumption and illuminance performance to evaluate their real energy saving and power grid quality possibilities and to choose the optimum model for any specific lighting grid presented.

For LED projectors, in general, it was found that the main power-quality distortion elements are the odd harmonic current generated and the inrush power-on currents. The latter have averaged significantly higher values with respect to their steady state current and they are much higher than those found in discharge lamps.

The main consequence of these inrush currents is that the circuit breakers of the electrical panel may be adapted if conventional lamps are massively replaced by LEDs. New magneto-thermal switches with higher hysteresis that allows filtering higher spikes should be used to avoid random disconnection on power-on process as the detecting the sum of many luminaire peaks is considered a network failure. This effect is widespread but not absolute, since some LED luminaires, such as the P6 model analyzed, do not produce these peaks.

Considering the odd THD, they measured average distortions of 10% but the specific values of a single device may differ significantly from that value. The highest harmonic distortion measured at a 25 °C ambient temperature reached the 18%, which is 3-fold higher than the lowest one of the projectors analyzed. However, all these values are below the 20% that has been set as the level used to quantify acceptable power quality by many regulation standards applicable worldwide [36]. The study performed shows that, with the luminaires analyzed, a massive change of luminaires in order to achieve significant power savings will not generate severe energy-quality problems unless projector 5 is used, which, in the case of high ambient temperatures, would generate unacceptable high harmonic values. This effect can be possibly found on more LED drivers models and it is true that all the driver testes have, in case of higher working temperatures, a worst harmonic behavior and, consequently it is generates a loss in the power quality.

In terms of economic and financial profitability, the results of a massive change toward a LED lighting equivalent depends strongly on the cost of the luminaires and their replacement process, which will give similar or better lighting outcomes with much lower consumption. However, the real consumption of these LED luminaires depends on many factors, such as the working temperature, and it has been found that under field conditions these are, in many cases, higher than the values indicated by the manufacturers. Thus, we consider relevant, for large renewal processes, to test sample luminaires under real working conditions in order to determine the exact operational costs (stable energy consumption) of the equipment for each particular installation to make a realistic economic evaluation of the project. All these technical and economic parameters together must be taken into consideration before undertaking a large lighting-equipment renewal with LED technology.

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