Sustainable Energy Management for Underground Stations: Lighting Upgrade

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ABSTRACT: Underground transportation systems are big energy consumers and have significant impacts at a regional scale. One third of the networks' energy is required for operating metro stations. A 5% saving in non-traction electricity consumption is equivalent to the electricity consumed in more than 340 households. The EU-funded project SEAM4US (Sustainable Energy Management for Underground Stations) will create a system for optimized energy management that, acquiring user and environmental models through a sensor network, will effectively reduce the energy consumption of the station by 5% - 10% in a real-world pilot conditions, a metro station in Barcelona. This paper reports the preliminary study developed in order to estimate the possibility of reduction of lighting consumption thanks to the retrofitting of the lighting system and the installation of controls. After an analysis of the current system, lighting performance models were developed and a scenario analysis performed, for investigating the saving potentials achievable.

1 INTRODUCTION

1.1 *Overview*

The role of lighting systems is to provide adequate visual conditions for human activities that must carried out efficiently and comfortably. Public buildings require specific care when designing, purchasing, commissioning and maintaining lighting systems. On the other and, the Energy Performance of Buildings Directive (EPBD) strongly recommends to produce and retrofit buildings to near-zero energy use levels. Lighting is one area where energy savings are possible at reasonable cost in new buildings as well as in retrofit projects (Dubois et al. 2011). (Enkvist et al. 2007) indicated that investments in energy-efficient lighting is one of the most cost-effective ways to reduce CO2 emissions.

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. In 2005 grid-based electricity consumption for indoor lighting was estimated at about 17.5% of the total global electricity consumption (IEA 2010). Indoor lighting accounts for a significant part of electricity consumption in buildings: in Europe office buildings use 50% of their total electricity consumption for lighting, while the share of electricity for lighting is 20-30% in hospitals, 15% in factories, 10-15% in schools and 10% in residential buildings (Volpe 2012). Furthermore, the heat produced by lighting represents a significant fraction of the cooling load in many offices contributing to further indirect consumption of electricity.

In terms of environmental impact, the key factor is the use phase. Energy consumption and associated Greenhouse Gas (GHG) emissions can reach amounts up 90% depending on the lamp type (ELCFED 2013).

Reducing electricity consumption of lighting during the use phase includes mainly two complementary phases:

- retrofitting the lighting equipment to a more efficient one,

- enhancing the lighting control policy and system.

1.2 *Lighting Energy Saving in Public Buildings*

For public buildings, these two steps differ highly in terms of costs, much more than for any other building typology. Retrofitting of the equipment of a public building is usually a very expensive strategy, often requiring major capital investments. On the contrary, the use of advanced control system can lead to great savings requiring minor investment costs.

Regarding the lighting equipment, in most public buildings still have lighting systems with fluorescent tubes, usually T8. Fluorescent tubes are cheap and reliable; they tend to be less glaring than more compact, brighter sources; they can be switched and dimmed readily; can be quite efficient, with good color rendering (e.g. T5). Unfortunately, not every lighting installations can be retrofitted with more efficient lamp types. T5 fluorescent lamps need an appropriate luminaire and they cannot replace T8 lamps in older luminaires without special adaptors, and so in many cases this will require replacement of the whole installation: luminaire, lamp and ballast. If the building needs the replacement of the existing indoor lighting stock, Light Emitting Diode (LED) lamps are now a valuable alternative in terms of energy efficiency and quality of light. LEDs are directional sources so are ideal for display or accent lighting, but can also be incorporated in general lighting fittings. Within a few years, it is expected that the efficacies of LED chips will rise up to 200 lm/W, so lower wattage lamps may then be able to provide the required amounts of light. Concerning the lighting systems, LED based systems can be more flexibly controlled in terms of beam angle, light color, dimming or frequent switching (EU DG ENV 2011). In general, replacing existing lamps with energy efficient lamps gives saving on maintenance costs as well as on energy consumed: maintenance staff costs can be drastically reduced as the lamp life is longer and it has not to be replaced.

Energy saving due to optimized control (i.e. that regulate the dimming level) depends on numerous factors including the application, site orientation and occupation, building design, interior reflectance, occupant behavior, tuning and configuration during installation, commissioning. These concurrent factors make the overall energy savings less easy to predict. Many type of controls are possible, from the manually activated systems to the automatically modulated lighting on the basis of occupancy demand and/or natural daylight available. (Williams et al. 2011) estimates average lighting energy savings potential of 24 percent for occupancy, 28 percent for daylighting, 31 percent for personal tuning, 36 percent for institutional tuning, and 38 percent for multiple approaches. Other studies state that using optimized automatic controls will save 30-40% and can be highly cost effective (Littlefair 2006). In fact, in a new installation the cost of installing advanced lighting controls may be the same as that of a conventional manual control system, while they have a typical payback periods of 2-4 years when retrofit to an existing installation (EU DG Env. 2011).

Summarizing, the optimized control is a very promising candidate to sustainable investments for the energy efficiency of public buildings. The US National Electrical Manufacturers Association (NEMA) has argued that controls have greater potential for energy savings in major applications than do increases in source efficacies (DOE 2011).

1.3 *Lighting Retrofit Strategies in SEAM4US*

Underground transportation systems are big energy consumers and have significant impacts at a regional scale. Approximately 30% of the total electrical power is needed for non-traction subsystem, meaning mainly the subsystems in the station buildings: air-conditioning and lighting. On average, a subway station consumes 50 times more energy than a residential building. Considering that usually a single institution manages hundreds of stations, it emerges clearly that energy efficiency in subway stations involves great absolute savings, even with small percentage savings. The EU-funded project SEAM4US (Sustainable Energy Management for Underground Stations) is aimed at creating a system for optimized integrated energy management and developing a decision support system to drive mid-term investments. SEAM4US integrates additional energy metering and sensor-actuator networks with the existing systems (e.g. surveillance, passenger information and train scheduling), by means of middleware as abstraction layer, to acquire grounded user, environmental and scheduling data (Ansuini et al. 2012). The data set update and enable a set of adaptive energy consumption and environmental models to control proactively and optimally the metro stations.

In relation to lighting, even if the main purpose of the SEAM4US project is to save energy by improved management, rather than by applying expensive retrofit measures, in the first phase of the project, saving potentials must be investigated both for lighting equipment updating and for lighting control inclusion. Specifically, the SEAM4US project is being developing a referring to a real-world pilot in the Passeig de Gracia – Line 3 (PdG-L3) station, managed by TMB – Transports Metropolitans de Barcelona. One of the project objectives is to transfer results to other subway stations. Thus it was important to identify saving potentials not only in relation to a specific lighting system, but also considering alternative ones. The comparison among scenarios involving different lighting technologies was based on the analysis of the platform, since it is the subway stations' most critical space, and usually involves the greater part of the fixtures used in the station. The current lighting system is briefly described in Section 2. A model of the actual state was developed based on technical information and survey data, and it is used as the baseline for the scenario analysis. The different scenarios considered for technology upgrading and control are reported in sections 3 and 4. Finally, section 5 presents the main results achieved

2 CURRENT LIGHTING SYSTEM

2.1 *Actual Lighting System*

In the public areas of the PdG-L3 station, there are basically 3 types of fixtures, and one type of emergency light (Fig. 1). Almost all the fixtures use T8 fluorescent tubes of 36 W. Other lamps can be found within private dependencies, but since they represent a very small amount of the total expenditure, they have not been taken into account in detail. All lamps use standard electronic ballasts. Table 1 shows that most part of the lamps are in the platform, that , consequently, the space that has been used for the scenario analysis.

Table 1. Main data for PdG –Line 3 station.

	Platform	Halls	Corridors / Stairs	Private Rooms	Total
Number of lamps	264	97	170	18	549
Power [W]	9504	3492	6120	570	19686
Power [%]	48%	18%	31%	3%	100%

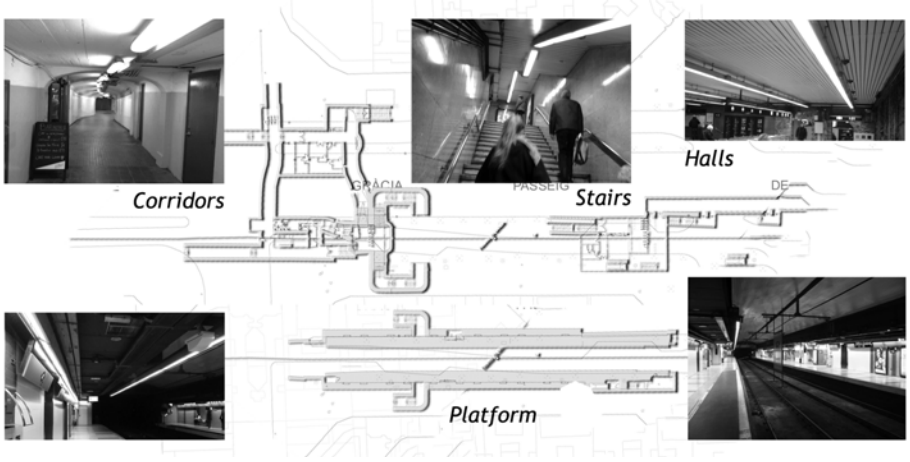

Figure 1. Overview of the lighting system in different spaces of PdG-L3 station [lux].

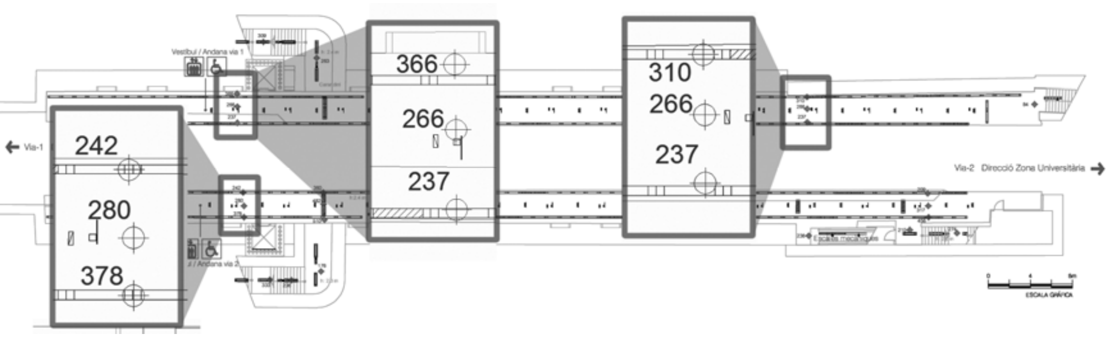

Figure 2. Lighting Survey in PL3: measures used for computing average illuminance [lux].

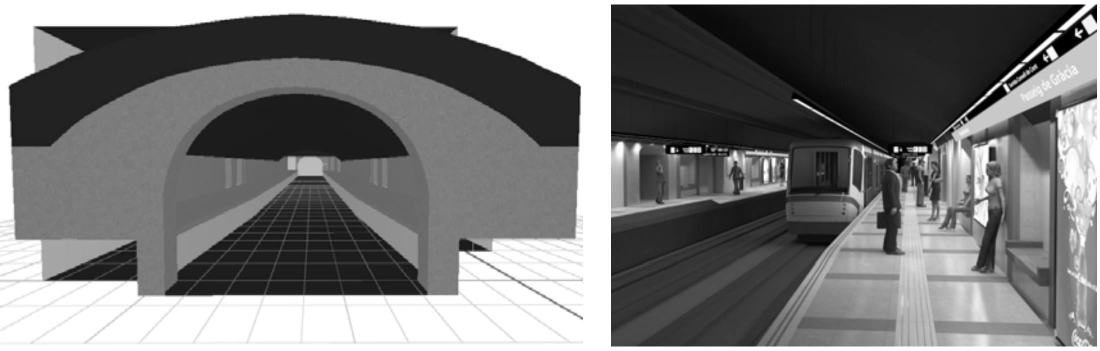

Figure 3. PL3 Model, Scenario: T8 – No Control. 3D image of the model and a photorealistic rendering.

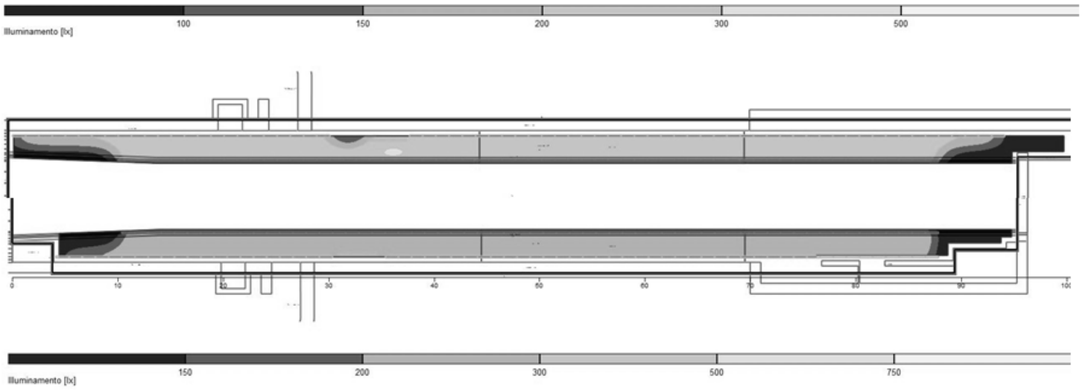

Figure 4. PL3 Model, Scenario: T8 – No Control. Map illuminance levels on the floor.

On the platform (PL3), there are two continuous lines of lamps, one near the wall, illuminating the information posters and signs and, another, above the edge of the platform (Fig. 2). The fixture used is produced by STI, and uses two TL8 36W fluorescent tubes, disposed longitudinally in line (Table 3).

2.2 *Main data from the Lighting Survey*

A performance survey was carried out in March 2012 to map current illuminance levels provided by the lighting installation.

According to current regulations (EN 12464-1:2003), minimum illuminance level requirements vary depending on the use of the space. Hence, the maximum required is 300 lux at ground level in ticketing zones (selling and validating) and the minimum required is 150 lux at ground level for most of the remaining spaces (stairs, corridors, ramps, etc.). In the platform, 200 lux have to be granted on the edge, while 150 lux are required as average.

The survey revealed that current illuminance distribution throughout the station is not uniform, even in zones that share luminary types and distribution, along with surface materials. As an example, a comparison between two corridors, both using the same fixtures, revealed a difference of almost +50% (202 lux versus 300 lux). In the platform, 9 point measurements along the platform were considered sufficient for computing the average illuminance in the platform, resulting as 287 lux (+ 90% than average level required by regulation).

2.3 *Actual State Model*

A model of the actual state was developed in the Relux ® Simulation Environment and preliminarily calibrated with the survey data. This model was used for achieving a reference simulation in the comparison and as simulation context for the alternative lighting systems to be investigated. Main assumptions done for this model are:

- Lamp and luminaires used: unfortunately, in the Relux model, the luminaires used are not exactly the products deployed, as the brand did not develop compatible software files. Among the products available in the Relux repositories, 3Brothers® products (Table 2) were identified as being the most similar to the installed appliances.
- Reflectance factors for the surfaces of the indoor environment : hypothesized with expert advice and confirmed in the preliminary model calibration
- Maintenance Factor: preliminary model calibration for the platform fixed MF = 0.8.

Figure 6-14 reports an image of the actual state model of the platform in PdG-L3. Figure 3 shows a 3D image of the model and a photorealistic rendering while Figure 4 shows the illuminance levels on the floor. A typical task area (red rectangle) was used for the analysis of the meaningful lighting performance parameters, reported in Table 4.

3 LIGHTING TECHNOLOGY RETROFIT

Lighting design is the result of ballast/lamp/fixture combinations that will maximize efficiency while balancing the lighting requirements specified. At this stage, only macroscopic alternatives were considered. As electronic ballasts are already used in the station, possible improvements can be achieved by maximizing the efficiency of light sources and luminaries.

Regarding the lamps, realistic constraints limit the options to three lighting technologies: keeping current T8, or switching to state of the art fluorescent (T5) or LED. Intervention would be needed in any case: T8 would need new ballasts and wiring amongst them for control purposes, and T5 or LED lighting would require new fixtures on top of the control system.

T5 tubular lamps are designed to run hotter than the T8 lamps, giving improved efficiency in enclosed luminaires. Compared with T8 lamps they are shorter in length, allowing them to be used in fittings that fit into smaller ceiling grids, and use smaller sockets. Luminaires designed specifically for the T5 lamp tend to be more efficient because of the reduced source size. For all these reasons, T5 lamps cannot be simply retrofit into existing T8 luminaires without a special conversion kit (Benya et al. 2011)

Table 2. Main data of the lighting fixtures used in the models.

		T8	T5	LED
Manufacturer		3Brothers	iGuzzini	LightLED
ID CODE		17320-FL	Linealuce 7864	Lexell Slim V8 NW
Lamp type		FL T26 G13	T5 G5 LFL	LED NW
Lamp power	W	36	28	14
Total luminous flux (for T=4000k)	lm	3450	2600	1495
Length	mm	1238	1238	1000
Width	mm	170	75	30
Height	mm	97	76	76

LEDs are expected to play the main role in the future of efficient lighting, even if so far, they are not very spread in the market. The vast majority of public buildings uses fluorescent lighting, which is less easy to control and dim than is the emerging LED lighting. LEDs are an inherently low-voltage source that can be more cost-effectively dimmed over a wider range than can current technologies and are therefore more amenable to control strategies such as personal tuning. LEDs will not only allow provide additional energy savings, but will also have the potential to enhance occupant comfort by improving control granularity, by allowing better occupant access to local lighting systems, and by the ability to control the light source spectrum according to automatic input and user preferences (Williams et al. 2012).

Finally, concerning the fixtures, as a universe of different products is available today on the market, the criterion used in this study was very operational: simulation were done by using fixtures produced by the prospective associate partners to the project.

In fact, contacts were established with two enterprises of the lighting sector in the first year. These two potential partners offered their contribution in supporting the definition of possible retrofit scenarios for some typical spaces of the pilot station.

Finally, three technological scenarios were splitted (details in Table 2):

- Current T8 fluorescent tubes (17320-FL-T8 36 W by 3Brothers);
- Retrofitting with T5 Fluorescent tubes (LineaLuce FL-T5 28W by iGuzzini);
- Retrofitting with LED technologies (Lexell Slim V8 NW 14 W by LightLED).

The development of the alternative scenarios and related models was based on the assumption of keeping the same lighting layout concept: for each platform, the same amount and position of the actual lamps, placed along two lines, one on the edge and one along the wall. In order to have comparable models and results, the same Reflectance Factors and Maintenance Factor (0.8), were kept.

Two different luminous fluxes were considered, depending on the color temperature performed. In fact, regulations require 6000K on the edge of platforms, while 4000K is sufficient elsewhere.

Table 3 reports a summary of the number of lamps considered in the T5 and LED scenario, and the related installed powers. Meaningful performance results are reported in Table 4.

Table 3. Scenarios in platform: lamps, dimming coefficient and power main data.

Setting			PL3 side 1		PL3 side 2		Total PL3		Total PL3
			edge	wall	edge	wall	edge	wall	
Lamp Number			62	71	62	69	124	140	264
T8	Current State	Power	2232	2556	2232	2484	4464	5040	9504
	Control	Dimming coefficient	0.78	0.375	0.78	0.375			
		Power	1741	959	1741	932	3482	1890	5372
T5	Retrofit	Power	1736	1988	1736	1932	3472	3920	7392
	Control	Dimming coefficient	0.75	0.319	0.75	0.319			
		Power	1302	634	1302	616	2604	1254	3854
LED	Retrofit	Power	868	994	868	966	1736	1960	3696
	Control	Dimming coefficient	0.75	0.319	0.75	0.319			
		Power	693	388	694	377	1389	764	2153

4 LIGHTING CONTROL

The lighting control system being considered is DALI (Digital Addressable Lighting Interface), a protocol backed by the lighting industry, fully described in IEC standard 62386 (2009). It was designed with the aim of updating current analog dimming controls based on 1-10V control interfaces, while introducing computer-based control systems. The DALI control system will have an interface with the general SEAM4US control system, that will generate the control policies, on the basis of the manager constraints, regulations and models. At this stage, the dynamic control policy was not yet defined, since it depends on detailed occupancy data that are not yet available. Thus, simulation-based investigations were done for the three scenarios (actual T8, new T5, new LED), with the aim of defining the maximum saving potentials related to control. An iterative process was used, varying the luminous flux of the lamps in the model and simulating it, until the minimum levels of illuminance and uniformity (allowed by regulation) were reached. Specifically, the illuminance levels (Eavg > 200 lux on the edge; Eavg > 150 lux in general) and the uniformity (Emin/Emax > 0.5) were checked on a restricted task area, avoiding the anomalous point of the platform.

This led to a forecast regarding the highest applicable dimming coefficients. As the existing standard establishes different levels (for the edge and for the overall floor), two dimming coefficient were obtained, one for lamps on the edge and one for those along the wall (Table 3). Once these coefficients were identified, the related used power was computed, without considering ballast efficiency. The performance results are reported in Table 4.

5 MAIN RESULTS AND DISCUSSION

The scenario analysis finally resulted in six scenarios, only three of them considering a lighting control system, as described in section 4.

Table 4 compares them through the most meaningful lighting performance data: illuminance levels on the floor and uniformity.

Table 5 compares the three lighting technologies (in lines) and the two efficiency strategies (equipment retrofit and control, in columns) through the estimation of used power resulting from each scenarios, and related savings.

Table 4. Comparison between simulation results for T8, T5 and LED scenarios: Lighting Performance.

Setting		No Control			Control		
		Actual State	Equipment Retrofit				
		T8	T5	LED	T8	T5	LED
Illuminance	E_{avg}	272	348	321	190	176	186
E [lux]	E_{min}	221	287	285	142	114	144
	E_{max}	290	386	336	213	213	207
Uniformity		0.76	0.74	0.84	0.66	0.53	0.69

Table 5. Comparison between T8, T5 and LED scenarios: Estimated Power and related savings

Setting	No Control		Maximum Control		Retrofit+Control
	Power	Saving	Power	Control Saving	Total Saving
	W	%	W	%	%
FL T8 36W	9504		5372	43.5	43.5
FL T5 28W	7392		3854	47.9	59.4
Saving T8-T5	*2112*	*22.2*	*1518*	*28.2*	
LED 14W	3696		2153	41.7	77.3
Saving T8-LED	*5808*	*61.1*	*3219*	*59.9*	

The main considerations are:

- equipment retrofit from T8 to T5 or LED is very effective, both in terms of lighting performance and energy efficiency, nevertheless while upgrading to T5 gives 22.2% of saving, upgrading to LED gives 61.1% of savings ;
- obviously, the integration of control is very effective in terms of energy saving, but produces lower illuminance levels, as it is conceived on the basis of minimum regulation requirements;
- comparing the control scenarios it emerges that the amount of saving that can be related to the introduction of a control system is quite constant (42-48%) and only slightly dependent on the technology adopted and the specific products: control seems to be most effective for T5, and this is due to the fact that the T5 “no-control” scenario had the higher illuminance levels, thus it was the most far from the regulation level;
- considering the total savings, achievable in this case between the current situation (T8, no control) and the combined solutions (Retrofit+Control) the highest savings are achievable with LED lamps (77.3%), but also the savings achievable with T5 (59.4%) are considerable.

In the perspective of the SEAM4US research project, the most meaningful data is the 40% of savings achievable through control, not depending on lighting technology. Of course, this number has to be modulated by the dynamic control policy that will be applied. It is highly depending on the strategies of the subway manager too. In any case, considering the percentages in Table 1, it results that installing a control system in the platform of PdG-L3 station (48%of the overall lighting consumption), and keeping constantly the minimum regulation levels, a saving up to 20% of the energy consumption for lighting of the total station can be achieved.

6 CONCLUSIONS

This paper investigates the potential savings related to the upgrading of lighting systems in subway stations. Two lighting upgrading strategies are considered: equipment retrofit and integration of automatic control. A simulation-based scenario analysis was performed, comparing lighting performance and energy savings.

The results show a great potential for energy saving in this subway station, related to lighting system: 22-60% through the equipment upgrading approach, about 40% through the control approach, 60-77% through a combined approach. This analysis guided the initial phases of the SEAM4US project: it was decided to upgrade a part of the lighting system in the platform to LED fixtures and install a DALI control system, to be used as pilot for the research project. The new equipment will be installed in next months. Nevertheless, the good results achieved also with Fluorescent T5 lamps can justify further investigations about both technologies, extending the analysis to other spaces of the subway station, such as halls, corridors and stairs.

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