D3.1.2 FINAL ENERGY AUDITING REPORT

2014.07.25

Short Description

This deliverable, originally due on M27 (January, 3rd 2014) and then postponed on M33 (July, 3rd 2014), is the second and final release of the energy auditing for the SEAM4US project.

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EXECUTIVE SUMMARY

This document is the final release of the energy audit report that aims at describing the current state of the Passeig de Gracia - Line 3 pilot station (from now on also referred to as PdG-L3) in terms of energy consumption behaviour and rate. The Energy Audit (T3.1) was set up on the basis of the requirements identified in WP2 (@ D2.1.2) and it is mainly aimed at:

- generating the background knowledge to drive the modelling phases,
- guiding the planning of the environmental and energy monitoring network,
- providing an overall view of the energy uses in the pilot station,
- analysing the data gathered through the energy monitoring network and providing the consumption baseline of the systems monitored,
- identifying inefficiencies, possible solutions and optimization strategies,
- estimating the energy savings potentials achievable by implementing the optimization strategies developed in the project.

The energy audit procedure for Passeig de Gracia – Line 3 was structured in two iterative stages. The first stage was mainly oriented to collect geometrical, operational and technical information regarding the station building and the systems included. This phase was also needed to acquire preliminary measurements used for designing the environmental and energy monitoring network (@ D5.1.2 for details about the monitoring networks). Preliminary energy surveys were carried out in this phase with the aim to elaborate a preliminary picture of annual energy consumptions in Passeig de Gracia - Line 3 station. In this way, the main energy intensive systems of the metro station were identified and quantified in terms of consumption. It emerged that these systems are lighting, ventilation and escalators. The information collected about the station's spatial features was used for modelling phases too (@ D3.2.2 for details). To this aim, a detailed reference nomenclature of all the pilot station's areas was defined.

In the second and final stage, the energy audit was improved, mainly performing detailed measurements of all the loads of the pilot station with the aim to provide a comprehensive view of the energy uses in Passeig de Gracia – Line 3. The measurements were carried out in two different periods of the year, one in winter and the other in summers, using hand-held instruments. These energy surveys allowed to elaborate a comprehensive picture of the PdG-L3 annual consumption, which was estimated to be about 600 ± 5 MWh/year. That analysis pointed out that the lighting, ventilation and escalators absorb about the 60% of overall annual consumption of the station. The other significant consumptions in PdG-L3 are due to backlit advertising panels, the telecommunication system and split units.

During the final phase of the energy audit, power data was measured and recorded by the energy monitoring network. These data was then processed with the aim to define the consumption baseline of the systems monitored. The consumption baseline for the ventilation system was defined both in winter and in summertime, according to the different operating speeds of the fans in these seasons. In winter, the baseline for the two fans in PdG-L3 was calculated to be 2423 ± 23 VA and 2514 ± 30 VA. In summer, when the fans runs at the higher speed, the baseline was evaluated to be 11205 ± 70 VA and 12042 ± 99 VA. The consumption baseline for the lighting was evaluated for the lighting pilot that involves two areas of the

station, i.e. a platform one hall. The average values of power for these areas was calculated to be respectively 4442 ± 5 VA and 5701 ± 16 VA. Finally, the consumption baseline for the two escalators in PdG-L3 was computed to be 2492 ± 47 W and 2100 ± 62 W.

A detailed analysis of inefficiencies was carried out in the second stage of the energy audit so that, for the main station's systems, it was possible to define the control strategies for achieving savings. As for what concerns the ventilation, the current control system is set to perform two-step adjustment of the fan speed, which is used just for varying its rate between the summer and winter seasons but it does not consider the actual user needs and the internal environmental needs. Moreover, the airflow rates for which the fans were selected are not required continuously. Therefore, the energy savings can be achieved implementing a real-time control of the fans' speed. For the lighting system the main problem emerging was the absence of a control system in the station's current configuration, so the strategy emerged for the energy saving is the implementation of an automatic control system for dimming the illuminance level according to the actual needs. Finally, the main inefficiency emerged for the escalators concerns their wide speed variation, which occurs many times a day and without considering the actual number of people transported. Therefore, the strategy proposed is the design of a control system which optimizes the escalators' operating speed according to the actual number of passengers.

Finally, savings potentials achievable by implementing the control strategies proposed were estimated in this final phase of the energy audit. These estimations were carried out by means of preliminary simulation with models (the final calculations of the energy savings achievable will be included in D6.3). For ventilation, the relative energy savings achievable was estimated to be at least 21% maintaining almost the original comfort conditions. For the lighting system, the simulation pointed out that the relative saving obtainable through dimming control is about 32%. Finally, the relative saving potential calculated for the two escalators in PdG-L3 by using the simulator is more than 13%.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

This document, which is the final release of the energy audit report, is made up of five sections. Section 2 reports on the energy audit approach, defining scopes and procedures, firstly from a general point of view and then specifically as applied to the pilot station.

Section 3 reports concise data regarding the pilot station's spatial features and defines a reference nomenclature. So, each spatial portion of Passeig de Gracia – line 3 was identified by a code defined within a comprehensive nomenclature which was mainly elaborated for the modelling of the pilot station. The details concerning the spatial features of the pilot station can be found in D.2.1.2.

Section 4 illustrates the measurements carried out in the on-site surveys on the pilot station. In the second phase of the energy audit, two on-site surveys were carried out, one in winter and the other in summer. Handy meters were used for the measurements, i.e. clamp meters and a network analyser. Furthermore, this section describes the electrical system framework in the pilot station and the related load operating conditions. All the loads in the station are grouped in some categories and for each of them it is provided an estimation of the annual energy consumption.

Section 5 reports on all the information gathered which concerns the station's main systems, i.e. lighting, ventilation and escalators. For each of the systems, a description of the equipment installed in the pilot station is provided in detail. Then, the current performances are analysed and finally it is defined the consumption baselines. These baseline are specified by using data recorded by the energy monitoring network and will be used for the validation phase.

Section 6 comments the technical and energetic data gathered in order to identify emerging inefficiencies. Moreover, this section briefly illustrates the optimizing strategies to be implemented in the pilot station. These energy savings scenarios concern the main systems in the station. For each of them, it is reported an estimation of the saving potentials achievable calculated through first releases of the systems models (the final and detailed analysis of the saving potentials will be provided in the D6.3).

2. THE ENERGY AUDIT APPROACH

This section describes the energy audit approach, firstly from a general point of view and then specifically as applied to the Passeig de Gracia – Line 3 station. So, it is explained the general meaning of energy audit, its objectives, structure, and the procedure characterizing such a process. Then, the specific case of the Barcelona pilot station is considered, defining the objectives, methodology and phases that led to the final stage of the energy audit.

2.1. Description of energy auditing

Simply said, an energy audit can be defined as being the investigation of a system's energy consumption, aimed at identifying possible system inefficiencies and, its critical urgencies, in terms of energy. The EN 16247-1[1] European Standard Draft, gives the following definition for energy audit:

"*Systematic inspection and analysis of energy use and energy consumption of a system or organization with the objective of identifying energy flows and the potential for energy efficiency improvements*".

In other words, an energy audit is a systematic procedure through which a system can be characterized in terms of the energy consumption of the plants and equipment making up the said system, in order to identify potential energy savings and to recommend technical solutions for achieving such reductions. The aims of an energy audit are the identification of efficiency potentials and the individuation of methods, which can be used to rationalization energy needs and, cut back energy consumption.

2.1.1. Levels of energy audit

The complexity of an energy audit depends on a number of factors, including the size of the system being analysed and its typology, how in depth the energy survey is and, the entity of the aspired energy savings. For these reasons, an auditing process can be subdivided into various, progressive and increasingly complex levels. In this regard, ASHRAE – the America Society of Heating, Refrigerating and Air-Conditioning Engineers – defines three audit levels or audit types[2]:

- Level 1 – Walk-through audit. This level represents the basic auditing level and consists in the collection of essential information regarding the subsystems and devices that make up the system under analysis. It is an on-the-spot inspection of the structure, analysed in order to carry out a visual inspection of the various system plants and devices. This level includes a preliminary energy consumption estimate and an approximate indication in terms of potential savings. Information collected in the first audit level can then be used for a subsequent, more detailed diagnostic process.

[1] CEN, "Energy audits – Part 1: General requirements", draft
[2] A. Thumann, W. J. Younger, T. Niehus, "Handbook of Energy Audits"(2007), Taylor & Francis, Inc., 7th ed. and ASHRAE, "Procedures for Commercial Building Energy Audits"(2011),2nd ed.

- Level 2 – Standard audit. A more precise quantification of energy consumption is achieved in the standard audit level where the technical and management characteristics of elements making up the system are analysed more closely. Such analysis include on-site measurements and the elaboration of the said measurements in order to calculate potential energetic savings in relation to the optimization of operations, the changes to control systems and, the use of automation solutions and proposed technical operations aimed at improving system efficiency. Particularly complex systems, which require extensive technical investigation and important financial investments, may call for more in depth investigation: in this case, the following level becomes essential.
- Level 3 – Detailed audit. The level three audit includes a detailed comprehension of how system subsystems and equipment work. The plants and devices making up the system are modelled in order to obtain predictive instruments capable of forecasting their functioning at variable environmental and use conditions. Hence, potential benefits, in terms of energy consumption and costs, are described in detail, through proposed improvement solutions.

2.1.2. Energy audit procedures

The ‘photograph’ of a system’s energy status, which can be obtained through the auditing process, foresees a series of operations which, starting from a data survey regarding the system (geometric/dimensional data, characteristics related to technical aspects, devices and plant operation, etc.), arrive at the energy consumption analysis of the various equipment and plants making up the system itself. The objective of the diagnosis is, as seen, to spot system inefficiencies and point out possible improvement solutions. An auditing process can be also schematized according to the phases listed below. It must be underlined that each energy level described above includes a part of the said process phases and that the process phases do not necessarily follow a precise progressive order:

- harvesting of information regarding the spatial layout, plants and system devices;
- on-site survey and inspection of facilities and devices;
- analysis of energy consumption data obtained through historic series or experimental measurements;
- system plant and device modelling;
- individuation of potential energy savings and evaluation of energy/economic benefits (recommendations regarding solutions and potential savings).

The process begins with the collection of information concerning the system under investigation. The information should be as detailed as possible and should include: the geometric/dimension characteristics such as, for example, the structure’s architectonic schemas, the technical schemas of electric and mechanical system plants, all information regarding the operation and maintenance of the various system plants and equipment, etc. During this phase of the process, all matters concerning the running and maintenance of the plants and their technical operative characteristics must be specified and clarified during meetings with the personnel responsible for system operations. On-site inspections are carried out following the data-harvesting phase in order to verify the consistency of the data collected and to inspect the plants and equipment making up the system. The macro areas undergoing the audit process can be finally identified in this phase and the preliminary objective in terms of achievable savings can be defined. This phase is fundamental in determining which equipment and plants must eventually undergo measurements in order to obtain energy consumption data. Hence, consumption data can be obtained either, through historical data contained in energy bills, or by installing monitoring devices. Obviously, the vaster the historical series available (that is, the longer the time during which monitoring is carried out), the better the understanding of plant and equipment' performance and consumption according to the hours of the day, the seasons and the different use conditions. This phase, which regards the collection of energy data, is fundamental even in terms of the plant and equipment' modelling phase, where predictive system instruments are elaborated as a function of environmental and operating variables. Potential energy efficiency measures can be identified following the analysis of consumption data and, possibly, of simulation results through models. Potential technological improvements and/or improvements in management that can be applied to the system under investigation are determined in this phase. A financial feasibility study must be carried out based on the previous results in order to highlight financial benefits as well as energy saving benefits.

Once completed the audit process, the previously defined operations are implemented. The post audit activity can thus be summarized through the following phases:

- the drafting of an action plan for implementing the energy efficient measures recommended in the audit;
- the creation of an action plan for the execution of the operations;
- the analysis and verification of efficiency results actually achieved.

2.2. Energy audit of Passeig de Gracia - Line 3 station

The Passeig de Gracia station is a junction of three Barcelona subway lines: lines L2, L3 and L4. The pilot of the SEAM4US project is being implemented in the L3 station in particular. The choice of Passeig de Gracia – Line 3 station is widely described in the D2.1.2. Some of the reasons of this choice are briefly listed below:

- this line is the most critical PdG station link, because it is the most complex and the most highly congested one;
- there are a diversity of rooms in terms of finishes, shapes, building materials and lighting fixtures which offer the chance for performing extended experiments;
- the high number of corridors and passageways leading to the platform determine complex fluid dynamics studies which are an excellent test-bed for model validations.

An energy diagnosis was carried out in PdG-L3 in order to analyse the energy uses in the station, identify inefficiencies and estimate achievable saving potentials. Therefore, a detailed calculation of the energy consumptions of various systems and equipment inside the station was carried out. The description of such energy consumptions, obtained through the elaboration of on-site measurements is contained in the section 4 of the present report. The objective of the audit process was the determination of inefficiencies and the identification of potential technical improvements, in terms of control of systems and equipment. Three main consumption actors were identified in the station, i.e. lighting system, ventilation system and escalators. Therefore, the analysis in the following sections is especially focused on these three points.

2.2.1. Levels of audit

The energy diagnosis for PdG-L3 station was structured using two analysis levels, increasing in complexity and extensiveness.

- Preliminary energy audit. The first process level was completed and described in the earlier release of the energy audit report, i.e. D3.1.1 Energy Auditing Report - Preliminary;

- Final energy audit. The second stage of the energy audit is reported in this deliverable. In this level, the results and information obtained in the preliminary stage were used to proceed towards a more finely detailed analysis.

Some on-site surveys were carried out in the station during the first stage of the energy audit. This allowed to identifying the circuits of equipment to be monitored in detail. Thanks to the information collected in the preliminary level of audit, a sensor network was designed in order to analyse in-depth the energy consumption of the more relevant circuits in the station (details concerning the energy monitoring network can be found in the D5.1.2). The first view of the annual energy uses in the station, performed during the preliminary stage of audit and reported in D3.1.1, was improved in the final energy audit. All the loads in the station were measured by means of on-site surveys performed during this second level. So, a detailed description of the energy uses in the station was elaborated and it is reported in section 4 of the present deliverable. The energy monitoring network was implemented and the data recorded was used to define the consumption baselines of the main loads in the stations, as described in section 5. These baselines will be used in the validation process that will be reported in D6.3. In the second stage of audit, the availability of higher detailed energy consumption information allowed the complete definition of the inefficiencies in the station. Finally, the energy savings achievable were estimated using first releases of models which simulate the lighting systems, the ventilation systems and the escalator of PdG-L3 (details about the simulation models will be given in the D3.2.2).

2.2.2. Energy audit procedures

The two levels of energy audit of PdG-L3 station were carried out according to the following operational phases:

- collection, analysis and organization of information concerning the subway station’s spatial features and technical information (@ section 3);
- detailed on-site surveys comprising all the loads of the station in order to obtain a complete energy consumption estimation (@ section 4).
- information regarding plant operations and equipment of the main consumption sectors in PdG-L3, i.e. lighting, ventilation and escalators (@ section 5);
- processing the data recorded by the energy monitoring network in order to define the consumption baseline of the main consumption sectors in PdG-L3 (@ section 5).

The reasons behind inefficiencies were identified for the main consumption sectors thanks to the analyses and the measurements made. Hence, control strategies for achieving energy savings were elaborated and the savings potentials achievable was estimated (@ section 6).

3. METRO STATION SPATIAL SURVEY

The spatial survey of PdG-L3 subway station was derived by CAD drawings and documents provided by TMB. A rather detailed description can be found in D.2.1.2. In this deliverable, only essential information pertaining to main data and layout are reported in order to set the spatial reference for all the other data. To this aim, a nomenclature is also set, and its relation to the internal TMB nomenclature is defined.

3.1. Spatial features

PdG is one of the few 3-line connection stations of the Metro network: L2 (Purple), L3 (Green) and L4 (Yellow) (@ Figure 1). PdG - Line 3 station is the northern one and the northern accesses are shared with the Adif station (regional trains, operated by Rodalies de Catalunya; and mid-distance service, operated by Renfe Operadora). This means that officially TMB manages only three accesses to PdG-L3 stations, but operatively there are five. Another access is the Station Link, a very long underground corridor that connects L3 and L4 stations.

A metro station is a very complex system, where different needs must be covered by several spaces. From commercial activities to safety purposes, each endeavour has a space. In addition, some of the activities relate to essential services: ventilation, lighting, management. Each of the aforementioned tasks requires specific equipment. Figure 2 and Figure 3 show the main layouts of PdG-L3 station at different scales.

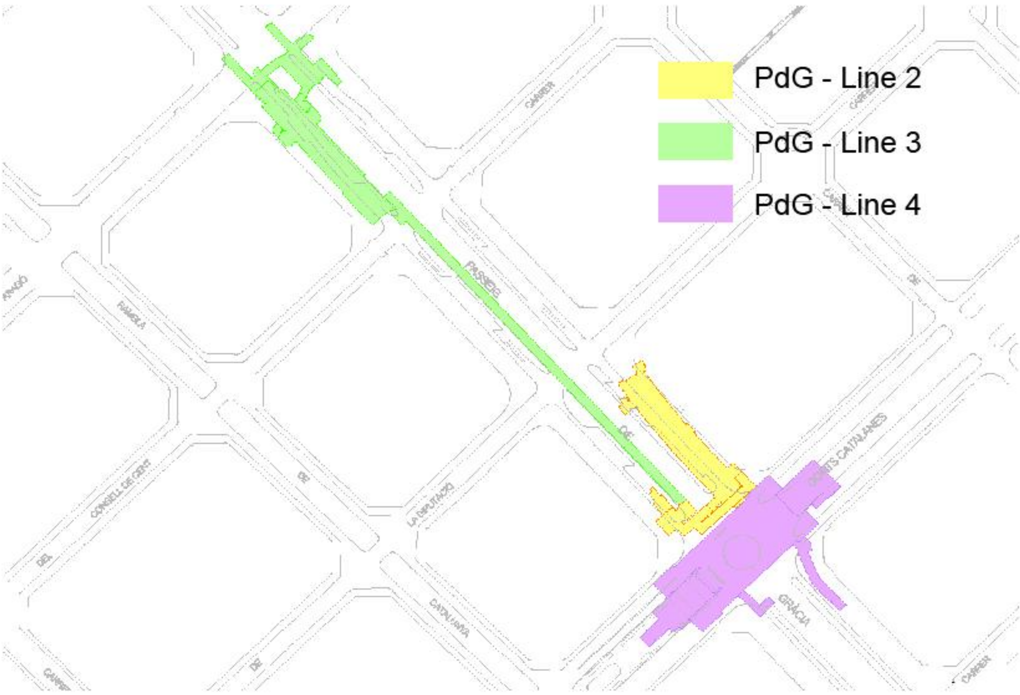


Figure 1. City blocks and general layout of the three Passeig de Gracia stations.

The most relevant areas considered can be divided into two groups: public access or staff only. In the Table 1 the zones have been classified according to this criterion.

Table 1. Classification of the main spaces of a metro station.

Public access	Staff only

• Accesses
• Transit zones
  ○ Halls
  ○ Corridors
• Platforms
• Concessionaries
	• Technical rooms
	• Staff Dependencies

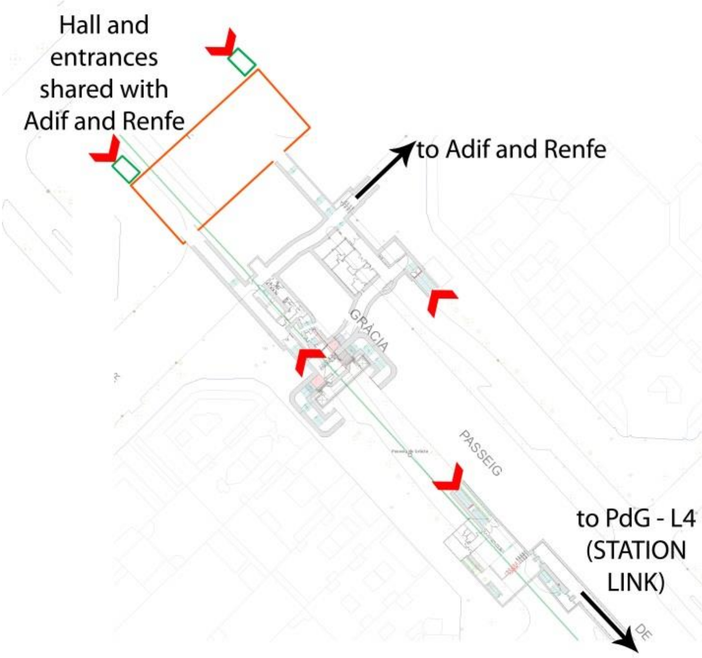


Figure 2. Entrances and shared spaces in PdG - Line 3 station.

Figure 3. PdG - Line 3 Station: layout of entrances and transit spaces.

3.2. Nomenclature in the SEAM4US project

In order to have a single name for each spatial portion of PdG station, a nomenclature was set. The nomenclature was also used in the modelling phase. The official names used by TMB were not adequate in this phase because:

- TMB attributes names only platform and halls, not to corridors;
- TMB uses the same name for similar spaces in different stations (e.g. there is a Vestibul 0 in PdG-L3 but there is also one in PdG-L4);
- Parts of the stations shared with other companies (e.g. hall and entrances shared with Adif) are not named by TMB.

The nomenclature used in the SEAM4US project was conceived in order to:

- Use code/names that can unambiguously identify different station spaces, even if they are included in different substations (for instance halls in PdG-L3 substation and PdG-L2 substation), to avoid having ambiguous names in future phases of the project;
- Name each spatial portion that could have/need specific identification (portions of corridors, for instance).

Thus, the introduced nomenclature was defined following these criteria:

- First position: capital letter defining the type of spatial zone;
- Second position: capital letter defining the reference part (N-North or S-South for the connection spaces, L-Line for the platforms);
- Third position: progressive numbering (number for entrances, halls and platforms; lower-case letter for corridors and rooms) of the specific typology defined by the first two letters.

The only exception is the Station Link, coded SL (Station Link). The third position still represents the progressive numbering of the portion considered. Spatial zones (first position of the code) considered are:

- E: Entrances (accesses in Table 1);
- H: Halls;
- C: Corridors;
- P: Platform;
- R: Room (including Staff Only group in Table 1).

Figure 4 shows the nomenclature applied to PdG - Line 3. PdG - Line 3 is the North Part of PdG station, while PdG Line 2 and PdG Line 4 are referred as South Part of PdG station and, as they are not yet taken into account in the pilot, nomenclature is not reported.

(a)

(b)

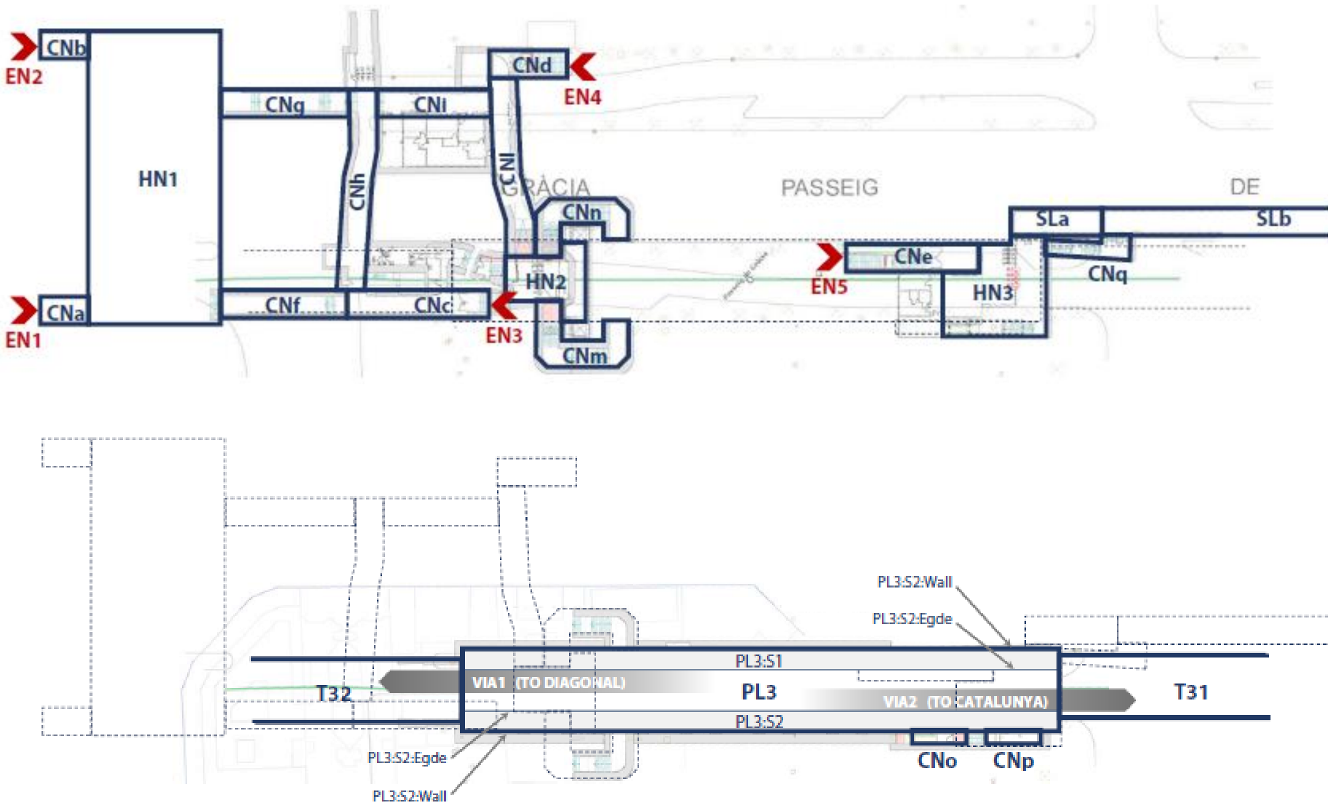


Figure 4. SEAM4US nomenclature applied to PdG-L3 layouts of the upper level (a) and of the lower level (b).

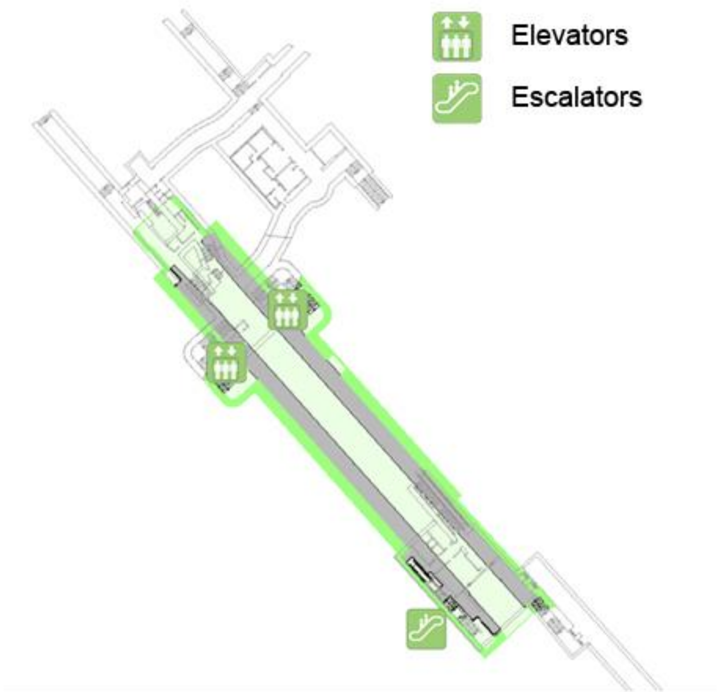


Figure 5. PdG - Line 3 Station: platform level layout

4. METRO STATION ENERGY SURVEY

This section provides a picture of the energy consumptions in PdG-L3. The calculations of energy consumptions were performed on the basis of measurements of the electrical parameters (i.e. voltage, current, power factor, etc.) collected in two on-site surveys conducted at different times of the year, one during the winter and the other during the summer. Many of the data collected in the aforementioned surveys are included in the tables of Appendix B.

The present section initially illustrates the analysis of the PdG-L3's electrical network and subsequently describes the load operating conditions and the assumptions for the calculation. The audit results in terms of annual energy consumption of the station are included at the end of this section.

4.1. Electrical system analysis

4.1.1. Operating condition of the station

The hours of operation for the station depend on the day of the week. Table 2 below shows the timetable for the station in a working day, Saturday (and public holiday) and Sunday.

Table 2. Operating conditions of PdG-L3.

Days of the week	opening and closing time	operating hours (h)
working day	5:00 - 00:00	19
Saturday (and public holiday)	5:00 - 2:00	21
Sunday	h 24	24

The operation of some systems (e.g. the ventilation system) depends on the seasonal weather conditions. The two following seasonal periods were considered for the calculation of the annual energy consumption:

- Winter, from November to the beginning of May for a total of 30 weeks;
- Summer, from the beginning of May to October for a total of 22 weeks.

4.1.2. Load categories in the station

The loads of the station were subdivided into the following categories (the number of devices belonging to some of the load categories is reported in brackets):

- lighting system;
- ventilation system (2 fans);
- escalators (2);
- elevators (2);
- air conditioning, that is split systems;
- backlit advertising panels (49) and vending machines (4);
- telecommunication system;

- validation machines;
- ticket machines (6);
- photo booths (1);
- television sets (6).

In addition to these categories of load, a category called other was defined. This category includes for example the power absorbed by the sockets or for the signalling.

4.1.3. Electrical circuit typologies and framework

The electric circuits in the station of Passeig de Gracia - Line 3 are separated into three typologies defined as follows: critical, not critical and auxiliary (identifiable by respectively the letters C, NC and A in the identification code of circuits). The auxiliary circuits are in service 24/7. The difference between the critical and not critical circuits is that the first ones can be connected to an external power source in case of failure of the TMB's network.

The electrical system in the station is made of three power supply lines, one in low voltage (220 V) and the other two in medium voltage (6 kV). The medium voltage lines are connected to transformers (circuit codes 2NC-1 and 3NC-1) and feed the critical and not critical circuits of the station. On the other hand the auxiliary circuits are fed by the low voltage line (the circuit number of the low voltage feed is 2A-1). Figure 6 shows the framework of the power supply system in the station of Passeig de Gracia - Line 3; all the electrical circuits of the station are pointed out through own identification codes (e.g. 2A-3, 3NC-2, etc.) and are grouped into the load categories described in section 4.1.2.

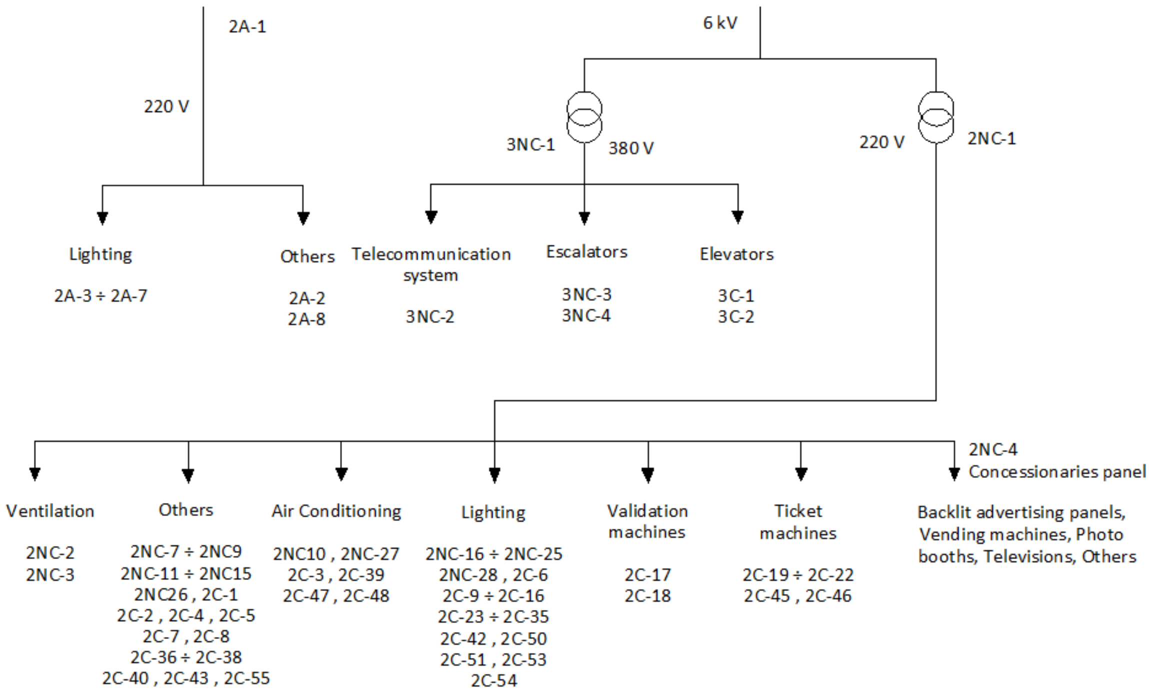


Figure 6. Framework of the power supply system in PdG-L3.

4.2. Load operating conditions and calculation assumptions

4.2.1. Lighting, ventilation and vertical transport systems

The lighting system is split into three groups of circuits: one group belonged to the circuit typology named not critical (circuits identified by the codes 2NC-x), one group which belongs to the typology critical (circuit identification codes 2C-x) and another group of the typology auxiliary (circuit identification codes 2A-x). During the opening time of the station, all the circuits of the lighting system are switched on except for the circuits 2C-15 and 2C-16 (regular lighting tunnel) that are only turned on during the closing time of the station. When the station is closed all the circuits belonged to the not critical group and those belonged to the critical group[3] are switched off while all the auxiliary circuits remains turned on.

The ventilation system is set on the low mode during the winter period (from November to the beginning of May) and on the high mode during summer period (from the beginning of May to October). That system is turned on from the 7 a.m. to 10 p.m. in every day of the week and in every period of the year.

The escalators and elevators, that are devices widely variable with the load, are supplied during the opening time of the station while their consumption is quite zero during the closing time. The consumption calculation for the escalators was performed on the basis of the measurements of active power carried out using the network analyser Fluke 435-II during the summer survey. In that survey it was measured the power absorbed by the circuit 3NC-3 (escalator hall 1 - access D) from the 5:00 am to the 10:00 pm. The estimation of the daily consumption of the escalator 3NC-3 is then obtained by integrating the aforementioned measurements; from this daily consumption it was finally inferred the annual consumption of one escalator in the station. The annual consumption of elevators was estimated in a similar way; for this purpose it was used the measurements of active power carried out in the summer survey on the circuit 3C-2 from the 2:30 pm to midnight.

4.2.2. Other load categories

The split air conditioners are switched off during the winter (except for the circuit 2NC-27 that is the AC L3 management) whereas these systems are always supplied h24 during the summer. Illuminated advertising signs, vending machines and the telecommunication system are supplied h24 whereas the other load categories (i.e. validation machines, ticket machines, televisions and photo booths) are assumed to be only switched on during the opening time of the station.

4.3. Energy surveys results

The results of the energy audit are reported in this section. It is primarily shown the active power calculations carried out on the basis of the current, voltage and power factor measurements. Then it is illustrated the results in terms of energy consumption obtained

[3] A few circuits belonged to the critical group remain switched on during the nights, that is the circuits 2C-9 (regular lighting staff rooms), the circuits from 2C-23 to 2C-34 (emergency lighting), the circuit 2C-35 (regular lighting technical rooms) and those from code 2C-50 to 2C-51 (escalator's lighting).

through the analysis of the station's electrical network, load operating conditions and calculation assumptions described in previous sections.

The current, voltage and power factor measurements for all the circuits of the station are shown in the tables of the Appendix B. In this Appendix it is also provided for each circuit the values of the three-phases apparent and active power obtained through the relations:

$$S = E\,(I_1 + I_2 + I_3)$$

$$P = S\ \cos\varphi$$

S	apparent power;
P	active power;
I_1, I_2, I_3	current in each of the phases;
E	phase voltage ($U = \sqrt{3}E$, where U is the line voltage that is 220 V or 380 V);
$\cos\varphi$	power factor.

In case of single phase circuits, the apparent power is obtained from the relation:

$$S = UI$$

Two energy audit surveys were carried out in the station of Passeig de Gracia - Line 3 during the second year of the project, one in the winter (from the 12th to the 14th of February, 2013) and another in the summer (from the 15th to the 18th of July, 2013). There were used two measuring instruments for the energy audit surveys: the clamp meter Fluke 376 and the network analyser Fluke 435-II.

Figure 7. Analyser Fluke 435-II connected to one circuit of the station during the measurements.

Table 3 shows the active power absorbed by each load category in the winter and summer period.

Table 3. Calculation of power absorbed by each load category in winter and summer.

Load category	Winter		Summer	
	Active power (kW)	Percentage power	Active power (kW)	Percentage power
lighting system	30.274 ± 0.991	45.5%	30.467 ± 0.992	32.0%
ventilation system	5.444 ± 0.290	8.2%	25.396 ± 0.628	26.7%
escalators	4.570 ± 0.031	6.9%	4.570 ± 0.031	4.8%
elevators	0.895 ± 0.012	1.3%	0.895 ± 0.012	0.9%
air conditioning	0.334 ± 0.119	0.5%	5.492 ± 0.360	5.8%
backlit advertising panels and vending machines	10.302 ± 0.345	15.5%	9.904 ± 0.333	10.4%
telecommunication system	7.938 ± 0.408	11.9%	9.043 ± 0.438	9.5%
validation machines	0.417 ± 0.191	0.6%	0.458 ± 0.192	0.5%
ticket machines	0.691 ± 0.215	1.0%	0.465 ± 0.211	0.5%
photo booths	0.154 ± 0.114	0.2%	0.143 ± 0.113	0.2%
televisions	0.483 ± 0.165	0.7%	0.461 ± 0.164	0.5%
others	5.080 ± 0.400	7.6%	7.855 ± 0.404	8.3%
Total	66.583 ± 1.284	-	95.149 ± 1.448	-

As shown in the table above, the higher value of power is absorbed by the lighting system which takes up to the 45% of the entire power absorbed in the station Pdg-L3. The absorption of the ventilation system increases more than three times from the winter to the summer when it almost reaches the lighting system's power. The percentage of power absorbed by the escalators is high enough, especially if it is borne in mind that there are only two escalators in the station. Other important loads in terms of power absorbed are represented by the backlit advertising panels/vending machines and the telecommunication system inside the station. The other categories of loads present small values of power, except of the air conditioning (the split systems) in the summertime. Tables 4 shows the consumption for each load category.

Table 4. Annual consumption for each load category.

Load category	Annual consumption (MWh)	Percentage consumption
lighting system	239.9 ± 3.7	39.9%
ventilation system	75.8 ± 1.7	12.6%
escalators	37.4 ± 0.1	6.2%
elevators	6.2 ± 0.1	1.0%
air conditioning	22.0 ± 0.9	3.7%
backlit advertising panels and vending machines	88.5 ± 1.3	14.7%
telecommunication system	73.4 ± 1.6	12.2%
validation machines	3.2 ± 0.7	0.5%
ticket machines	4.3 ± 0.8	0.7%
photo booths	1.1 ± 0.4	0.2%
televisions	3.4 ± 0.6	0.6%
others	45.5 ± 1.5	7.6%

Total	**600.7 ± 5.1**	-

Table 4 shows that the lighting and ventilation systems absorb more than the 50% of the total annual consumption of the station PdG-L3. Other considerable loads are the backlit advertising panels/vending machines and the telecommunication system, which are respectively the second and fourth energy consumers in the station. Furthermore, the escalators and the split systems reach significant percentage of the energy consumption. Figure 8 shows a pie chart of the percentages of the annual energy absorbed by each load category.

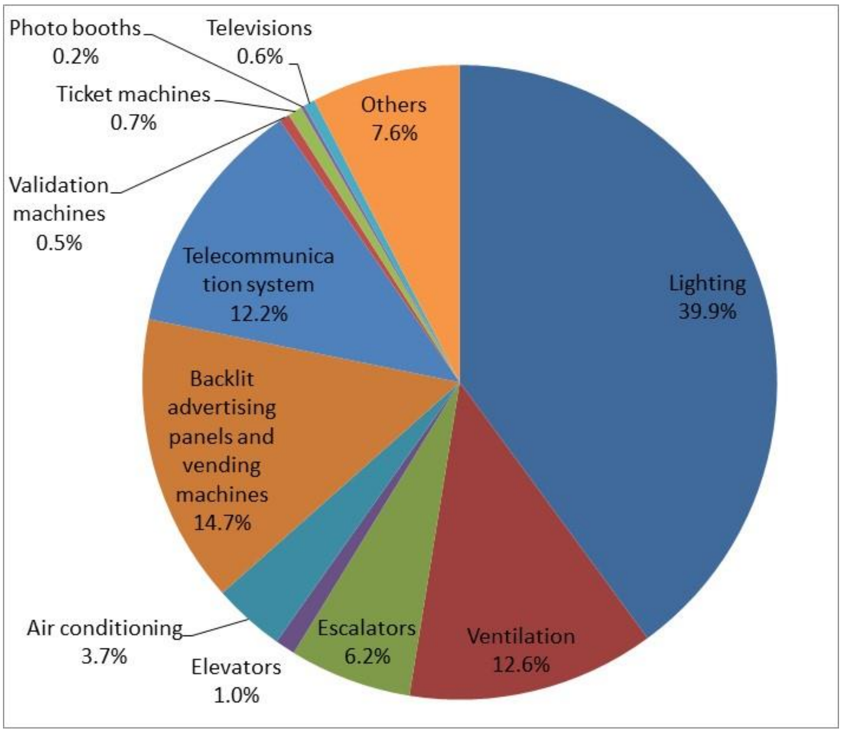


Figure 8. Pie chart of the percentages of annual consumption

5. SURVEY OF METRO STATION MAIN SYSTEMS

5.1. Ventilation

5.1.1. Equipment

As metro stations include many polluting sources (causing rather high CO_2 and PM_{10} levels), an accurate control of these indicators is usually set. Acceptable thermal comfort is generally attained as a secondary objective provided the first requirement is fulfilled.

As a matter of fact, no explicit limits of pollutant levels are in force for metro stations. As far as concerns thermal comfort, because of the presence of users in metro stations is limited to a few minutes (while their permanence in carriages is usually longer), metro operators are not obliged to stick to the temperature limits dictated by standards on thermal comfort in regular buildings. This happens because those people who transit through the metro come from outdoors, and then exit to the outdoors again, so the basic requirement is that the conditions indoor are not too different from those outdoors[4]. Referring to the scheme of the mechanical air supply system, "ventilation shafts" rooms play the role of exchanging air between the station and the outside environment, that is to say, pushing outside clean air into the station and extracting indoor exhausted air. To that purpose, supply fans operating in PdG station are coordinated with the operation of extracting fans, placed in adjacent tunnels. The overall ventilation is operated separately in the three lines of the PdG station. PdG-L3 hosts two fans installed in the station (codes: VE 3-27-2 and VE 3-27-3), whose operation is coordinated with that of other three fans installed in adjacent tunnels: two of them in the tunnel segment leading to "Diagonal" station (codes: VT 3-28-1 and VT 3-28-2) and one in the tunnel segment leading to "Catalunya" station (code: VT 3-26-3). One fan is installed in L4 part of PdG (code: VE 4-25-1), another one in the tunnel segment leading to "Girona" station (code: VT 4-26-1) and one in the tunnel segment stretching towards the opposite direction, towards "Urquinaona" station (code: VT 4-25-2). Similar statements apply to line L2 of PdG: one fan (code: VE 2-13-2) is located inside the station, another one is located in the tunnel segment leading to the next station called "Tetuan" (code: VT 2-14-1) and another one in the opposite direction tunnel segment pointing towards "Universitat" station (fan code: VT 2-13-2). Ventilation equipment plays the role of providing continuous air exchange, so as to limit pollution and avoid dramatic temperature rise, inside the station, during summer periods. Considering that line 3 was selected as the demonstrator for SEAM4US, we will present the scheme valid for the ventilation shafts of Line L3, which is also representative of similar situations encountered in the other two lines, L2 and L4. Figure 9 depicts the ventilation shafts located along L3 within a line segment centered around PdG: the aforementioned fan codes (i.e. VE 3-27-2 and VE 3-27-3 in the station, VT 3-26-3, VT 3-28-1 and VT 3-28-2 in tunnels) are labelled in the same figure. Every fan's technical room is quoted and corresponds to the presence of a ventilation shaft. Just to give an example, Figure 10 shows the ventilation shafts and the air distribution system present in L3 and corresponding to the codes VE 3-27-2 and VE 3-27-3, because the two fans are located in the same room of the station. In particular, Figure 10-a shows the cross section of the plenum

[4] NITIS – US Department of Transportation (1976) "Subway Environmental Design Handbook, Volume I: Principles and Applications", 2nd edition, UMTA-DC-06-0010-76-1.

pushing air into the platform of L3. To be noticed that thirteen vents are distributed on each side of the plenum above the platform, in order to distribute ventilation air properly. More technical details can be inferred from part b of the same figure where the longitudinal section shows the full air path from outdoor to the platform. The air intake is located on the fan room ceiling at road level; the fans in the same room provide the pressure rise needed to push air into the distribution system, until it is released onto the platform. This configuration is justified by the fact that the fans in the station always work as injectors, whereas the fans in the tunnels are reversed, according to the time of the day.

(a)

(b)

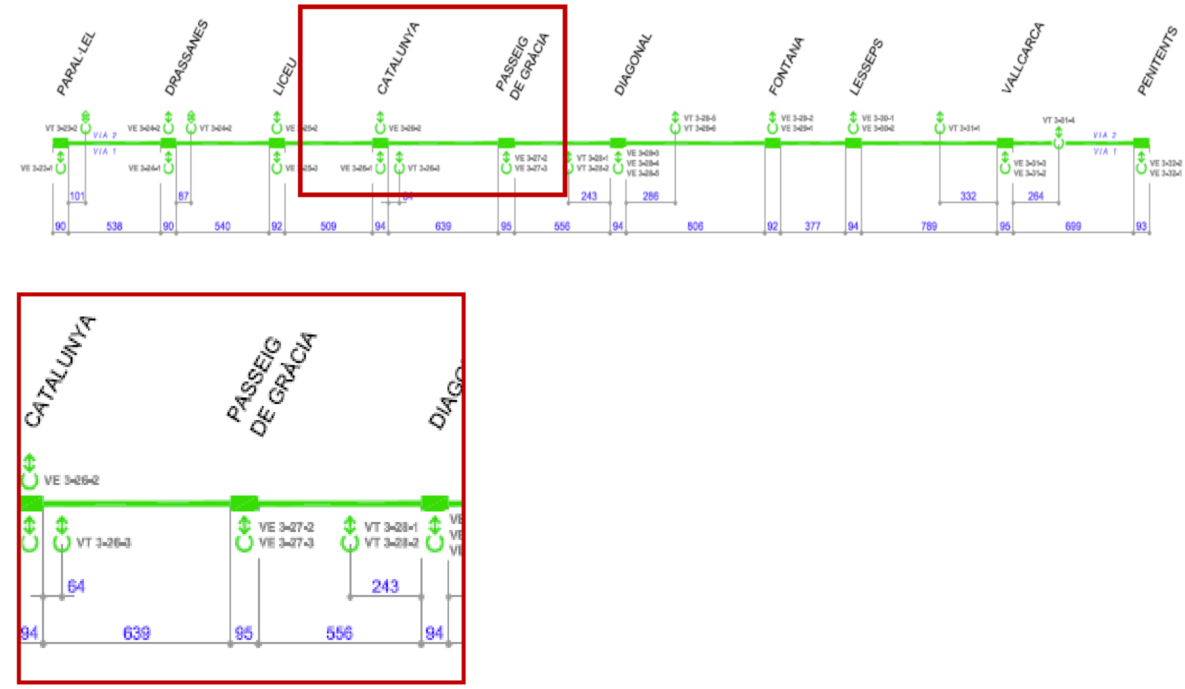
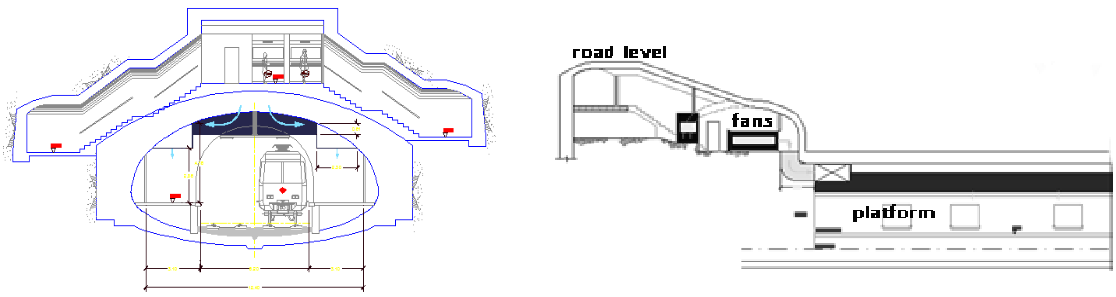


Figure 9. Location of fans along Line 3 in the segment stretching from PdG's station (a) and zoom centered on PdG-L3 (b).



(a) (b)

Figure 10. Cross sections of the mechanical air supply system in PdG-L3.

Presently, all the fans are controlled by a pre-set time schedule, which is the same in all the stations. Let us take the case of L3 in PdG station for the sake of further clarification. Two main ventilation configurations are foreseen: daytime schedule and nighttime schedule. The daytime schedule extends from 7 a.m. to 10 p.m.: this is the case depicted in Figure 11, where the fans in the station inject air onto the platform (purple arrows in Figure 11), while the fans in the adjacent tunnels extract air from inside to outside (yellow arrows in the same figure). However, the inward airflow rate through the station is lower than the airflow rate through the tunnels' shafts. As a consequence, some ventilation is induced through the corridors and other passageways (blue arrows in the figure). The night-time schedule stretches from 10 p.m. to 5 a.m.: in this operational configuration, the fans in the station are kept off and the ones in the tunnels are reversed. Consequently, exhausted air is extracted from the tunnels and forced to pass through the platform and the corridors leading outside. Clean outdoor air is injected into the tunnels through the ventilation shafts located along the tunnels. The qualitative behaviour of ventilation is kept as described above in both seasons; the only difference between summer and winter lies in the amount of air moved by the fans: in winter the airflow generated by the fans is halved if compared to summer periods.

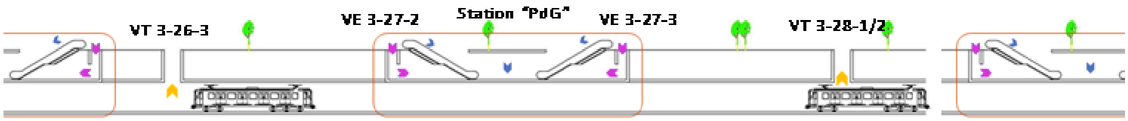


Figure 11. Qualitative behaviour of ventilation valid in daytime, referring to PdG-L3.

In Figure 12-a, the characteristic curve of the two fans installed in the PdG-L3 is shown: the volume flow rate is always plotted along the base, with the fan total (or static) pressure (and other performance quantities) as ordinates.

(a)

(b)

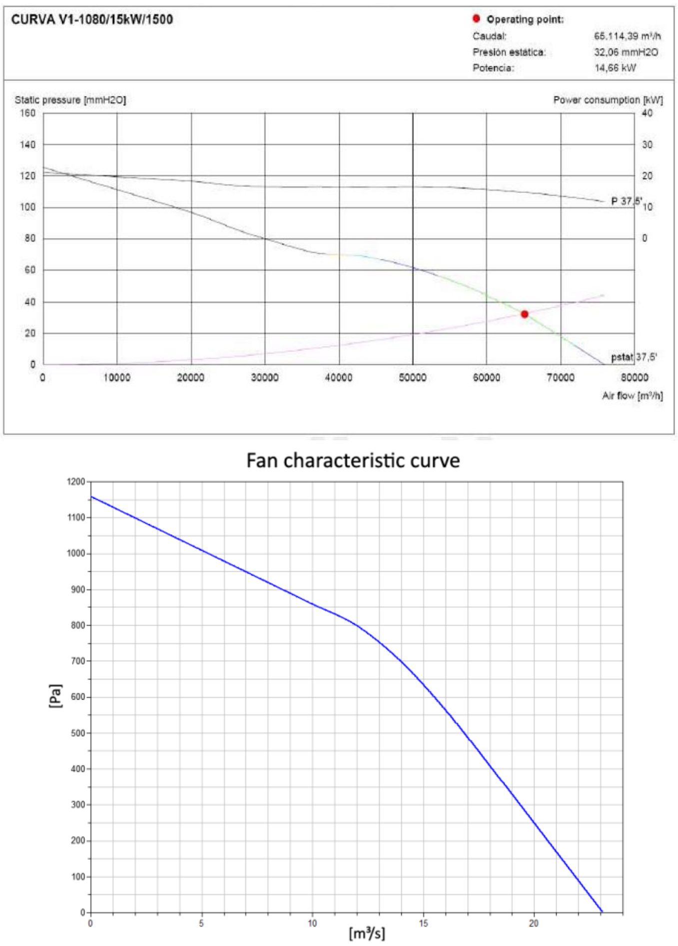


Figure 12. Fan's characteristic relative to the ventilation equipment installed in PdG-L3 (a) and characteristic curve computed from the data provided by the manufacturer.

To be noticed that the best efficiency point of the fans in PdG-L3 falls around Q = 62,500 m^3/h and a static pressure P = 35 mmH_2O, that is 343 Pa, which generates a 15 kW power consumption. The fans operating in PdG-L3 station belong to the type named "axial flow fans". Another characteristic curve is plotted between mass flow rate (expressed as kg/s) and total pressure rise (Pa), in Figure 12-b, which has been numerically estimated starting from the data provided by the manufacturer and used in the simulation model. The two curves are in good agreement.

It comes out that these fans are rather powerful and can provide a total pressure rise around 400 Pa. Each fan is of the CONAU V11080 model that is run by a 15 kW electric motor power and at 1500 rpm at no load. At its maximum speed the nominal airflow rate is 62,500 m^3/h, which is had thanks to a blade pitch equal to approximately 35°-40°, and it is not dynamically adjustable. However, as Tables 5 show, the motor speed of the fans can be adjusted and they are reversible. The three-phase alternating current motors are powered by tension and current inputs as depicted in Tables 5.

Table 5. Main features of the fans in PdG-L3.

Technical Features of fans in PdG-L3	
Maximum Power	15 kW
Number of poles	4
Rpm	1500 rpm
Nominal current	29 A
Load	0.85
Airflow rate	62,500 m^3/h
Grate size (mxm)	1.6x5

Electric motors of the fans in PdG-L3	
Codes of fans	VE 3-27-2 VE 3-27-3
Motor power	18.5 CV
Manufacturer/model	CONAU ASEA V1-1080
Motor no.	14575
Tension (V)	3x230 NC
In (A)	42.7
Reversible	Yes
VFD	Yes

In order to adjust the air supply according to the aforementioned schedule, a control system is installed in the station PdG-L3.

The so-called CCIF (Control Centralitzat de Instalaciones Fijas - Central Control of Fixed Installations) system is installed to control escalators, lifts, fans, water pumps and the low voltage rooms. CCIF is implemented with a commercial SCADA system (Proficy HMI/SCADA - Cimplicity 8.1, from GE Intelligent Platforms). Two servers (CCIF server 1 and CCIF Server 2) control all PLCs in the Metro network. The servers work in a redundant configuration.

On each station, every device is controlled by a PLC. PLCs communicate with a master PLC called CXL. CCIF servers communicate with the CXL PLC of PdG-L3 station (as well as any other station) through a proprietary serial protocol called SNP-X. The picture in Figure 13 shows the structure of the CCIF system but it does not include another server, CCIF server 3, because it implements a web gateway for external users and is not oriented to control station equipment.

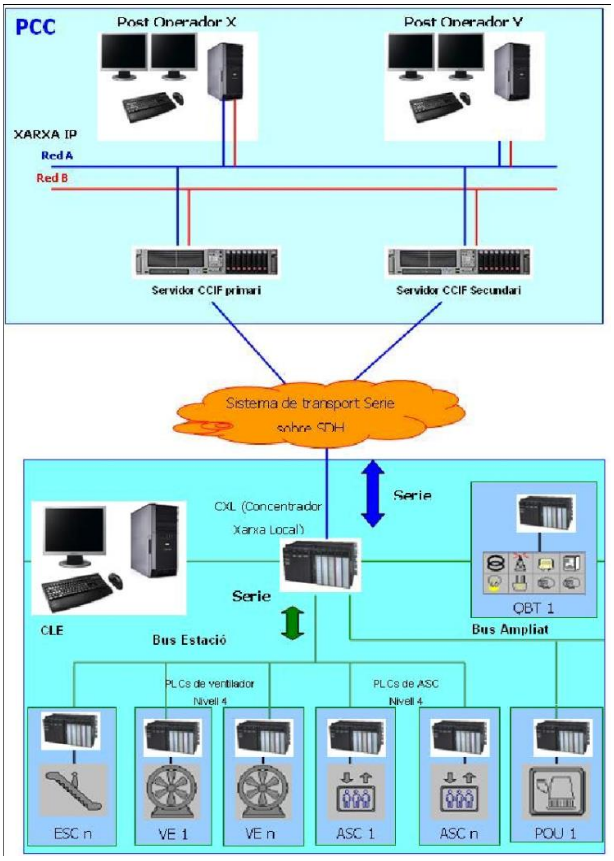


Figure 13. CCIF system.

The SCADA interface proposed in Figure 14 is the system's high-level interface. In the case of fan control, for instance, this interface allows sending five different commands:

- Stop
- Direct mode, slow speed
- Direct mode, fast speed
- Reverse mode, slow speed
- Reverse mode, fast speed

For station fans:

- "Direct mode" means injecting air from the street to the station.
- "Reverse mode" means extracting air from the station to the street.

Please note that this codification is not the same one that was used for tunnel's fans, where:

- Direct mode means extracting air from the tunnel to the street.
- Reverse mode means injecting air from the street to the tunnel.

Finally, the direct control of the frequency driver of the fan is not allowed.

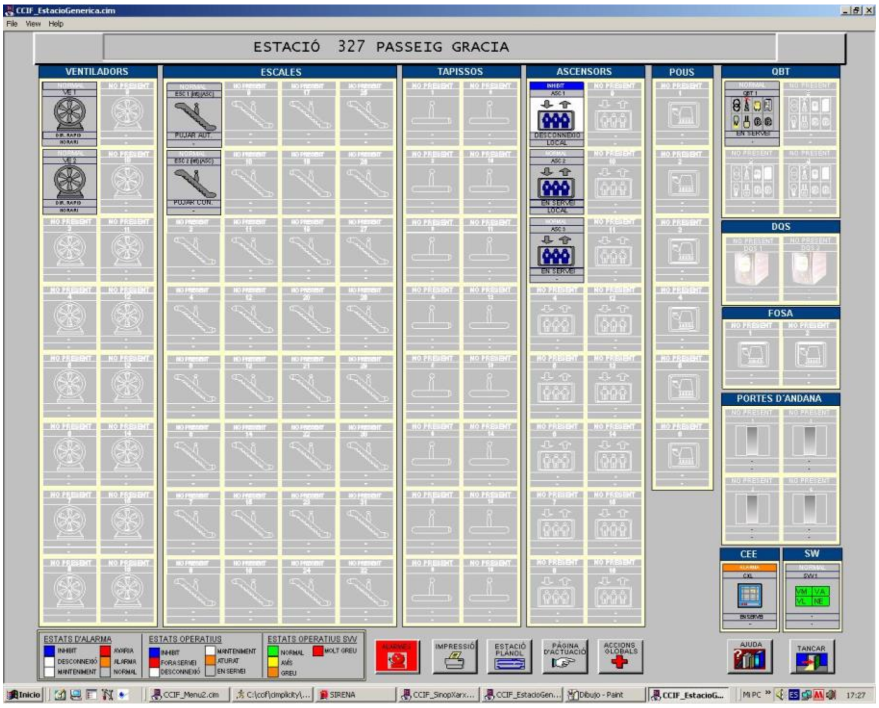


Figure 14. SCADA interface for PdG-L3.

Each of the aforementioned states for the ventilator are codified by the CCIF system's protocol, so as to communicate the real state of the device. The following excerpt describes the five basic states of a fan in PdG-L3, as supplied by the CCIF system:

EST001R	state: stoped	boolean	set to "1" when state is true
EST002R	state: direct mode, slow speed	boolean	set to "1" when state is true
EST003R	state: direct mode, fast speed	boolean	set to "1" when state is true
EST004R	state: reverse mode, slow speed	boolean	set to "1" when state is true
EST005R	state: reverse mode, fast speed	boolean	set to "1" when state is true

Other more complex strings may be used to query the CCIF system, e.g. to verify whether the device is communicating with CXL, or if it is in maintenance mode or again if it has any failure indication.

5.1.2. Current performances[5]

The target of ventilation is to guarantee comfort conditions and acceptable air quality; that is to keep environmental indicators within prescribed values. Comfort conditions are mainly determined by indoor air temperature. Air quality was evaluated through two indicators: CO_2 and PM_{10} concentration. For that reason, air temperature values, CO_2 levels and PM_{10} levels will be used by the control system to adjust mechanical air supply rates according to environmental performances. In particular, we expect that the SEAM4US system will improve energy management while keeping environmental indicators within the range experience in the benchmark scenario, i.e. the current situation. In order to learn more about the benchmark, in the following some excerpts from the summer and winter seasons will be presented. In fact, the PdG-L3 station basically switches between a summer and a winter functional mode, which are the two extreme scenarios which can be had during the year.

[5] The data provided in this section are for internal use only. These data was included for the Final Review and cannot be share or use in any other way previously TMB authorization.

Figures 15-20 show the plots of the aforementioned environmental parameters relative to those two seasons, because they are representative of the overall behaviour all over the year. Figure 15 shows the average temperature measured in the platform in the time window 17th - 20th September 2013, when the station is run in summer mode. It can be noticed that the whole temperature plot swings between 28 and 32°C. The highest peaks were registered late in the afternoon, when tunnel fans reverse their rotation and start injecting air into the platform. In fact they refresh tunnels and heat up the platform until regular daily operation is re-established.

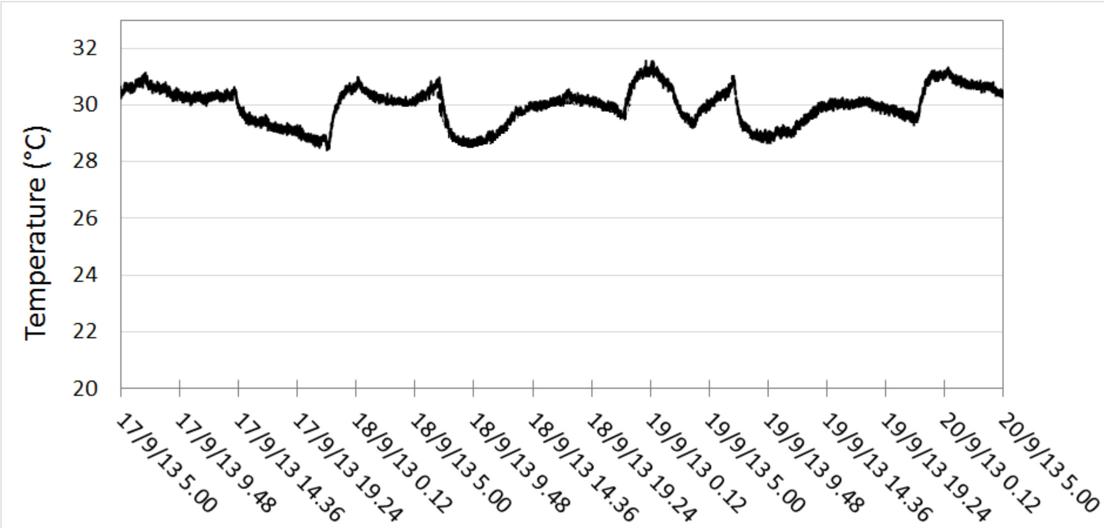


Figure 15. Average air temperature in PdG-L3 platform relative to the time period between 17-20th September 2013[6].

Figure 16 shows the CO_2 plot measured in the platform in the days from 17th to 20th September 2013. From this figure, it emerged that CO_2 is always included between 800 ppm and 1400 ppm, and is higher during the day.

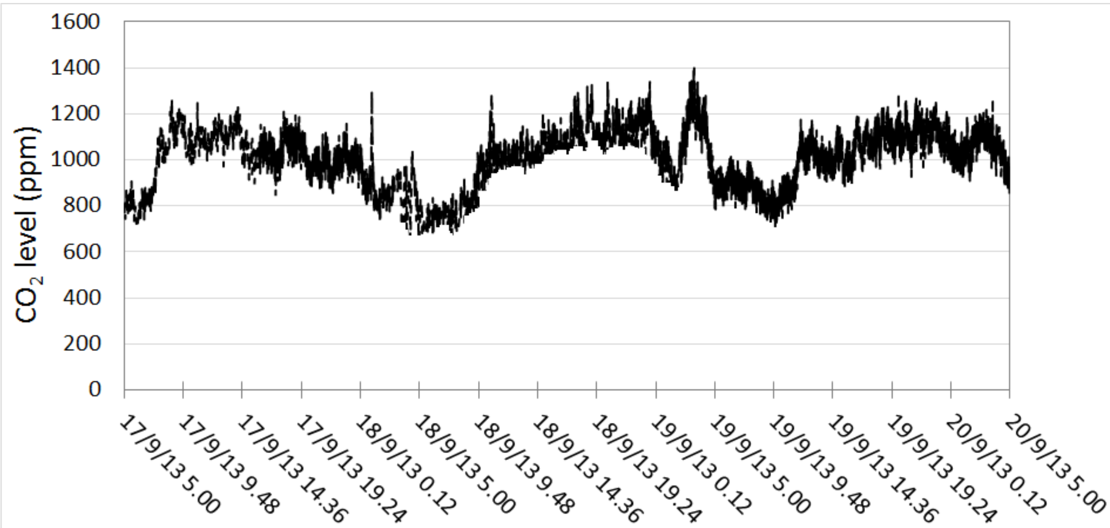


Figure 16. CO_2 measurements collected in the platform PL3 in the time window 17th - 20th September 2013[5].

[6] The data included in this figure are for internal use only . These data was included for the Final Review and cannot be share or use in any other way previously TMB authorization.

Figure 17 depicts the PM_{10} concentration levels measured in the platform (node 26) and in the station link (node 35) in the same period in September 2013. PM_{10} can reach concentration levels as high as 700 $\mu g/m^3$ during peak time moments. While its average is around 300 $\mu g/m^3$ in the rest of the time span. PM_{10} peaks are had either in early morning or in the evening. In both these cases, the station's fans are off and trains are still passing by. For example, early in the morning trains start at about 6 am, which is also the time when tunnel's fans are reversed, but station's fans are not turned on, yet. So PM_{10} released by trains stands in the station and increase its concentration in air. After that, it decreases when the station's fans are switched on. A similar behaviour is registered in the evening, too. The PM_{10} level in the station link is much lower, as expected, because of the absence of trains. All in all, the values in the platform are the reference values for control purposes.

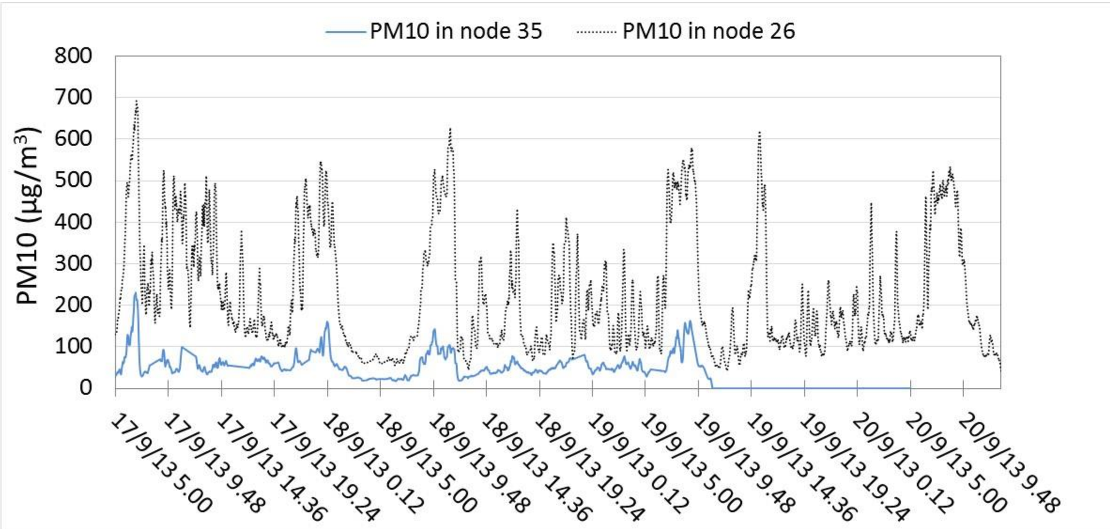


Figure 17. PM_{10} measurements collected in the platform (node 26) and in the station link (node 35) from 17th to 20th September 2013[7].

Similarly to what explained above, the same reference values were evaluated in the case of a month when the station works in winter mode, i.e. March 2014. So Figures 18-20 depict the typical plots relative to temperature in the platform, CO_2 levels in the platform and PM_{10} concentration levels in the same space. In general, air temperature is lower due to cool outdoor air; CO_2 levels and PM_{10} are quite unvaried. Air temperature values follow the outdoor trend, and are lower than in the summer (Figure 18). CO_2 levels are quite similar to the summer period (Figure 19). Also, PM_{10} follows a plot that is very similar to that one of summer months (Figure 20), but the concentration level is slightly higher.

[7] The data included in this figure are for internal use only. These data was included for the Final Review and cannot be share or use in any other way previously TMB authorization.

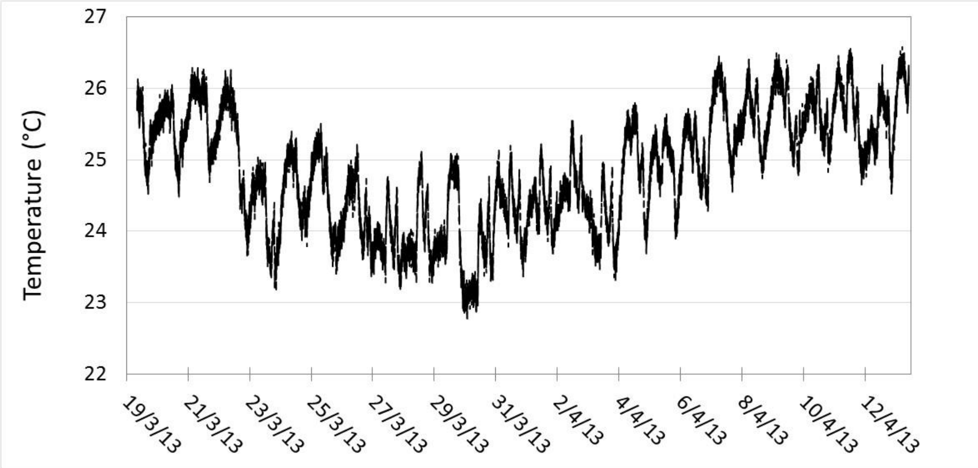


Figure 18. Average air temperature in PdG-L3 platform from 19th March to 13th April 2014[6].

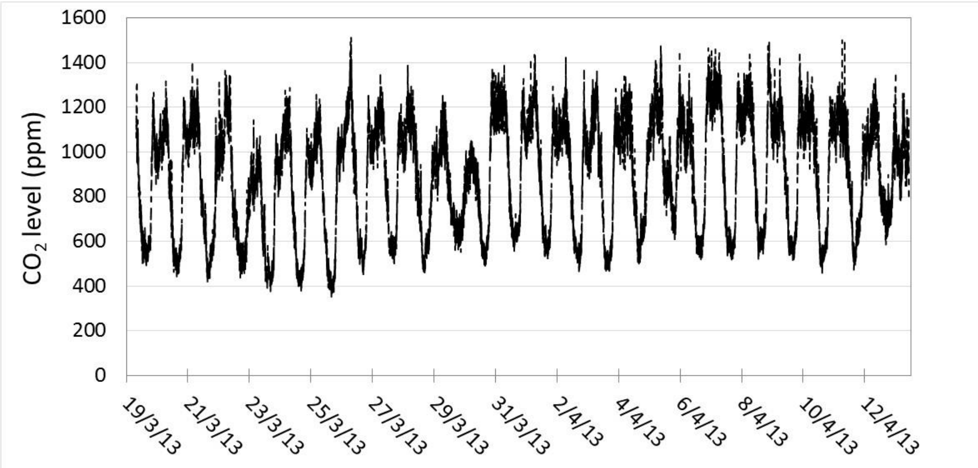


Figure 19. CO_2 measurements collected in PdG-L3 platform from 19th March to 13th April 2014[8].

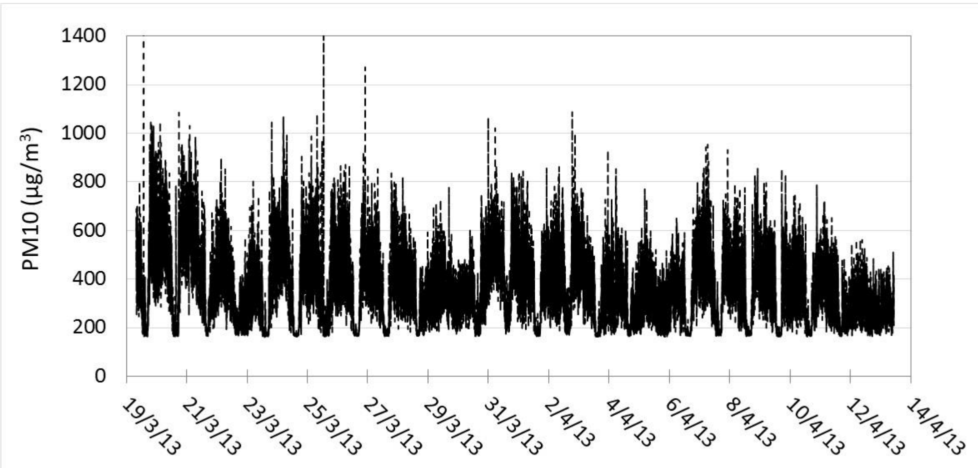


Figure 20. PM_{10} measurements collected in PdG-L3 platform from 19th March to 13th April 2014[7].

The two time periods chosen as a reference are well representative and will be used to compare their behaviour in the current situation with that one in the controlled condition.

[8] The data included in this figure are for internal use only. These data was included for the Final Review and cannot be share or use in any other way previously TMB authorization.

5.1.3. Consumption baseline

As described in section 4.2, the fans in PdG-L3 can be set at two different speeds, a lower value for the wintertime and the other higher for the summertime. Therefore, two consumption baselines were defined using the data recorded by the energy monitoring network. The consumption baseline for winter season was specified considering the data available from the 1st of April to the 8th of May 2014. Table 6 shows averages of the apparent power absorbed during the operating time of the fans by day. The uncertainty was estimated referring to the Type A evaluation defined in the GUM and considering a coverage factor for a level of confidence of 95%, as described in the Appendix C.

Table 6. Daily averages of apparent power absorbed by the fans from the 1st of April to the 8th of May 2014.

	Station ventilation 1 (circuit 2NC-2)		Station ventilation 2 (circuit 2NC-3)	
Day	Apparent power (VA)	Expanded uncertainty (VA)	Apparent power (VA)	Expanded uncertainty (VA)
1-Apr	2491	53	2437	66
2-Apr	2477	55	2423	70
3-Apr	2467	61	2412	68
4-Apr	2466	40	2411	66
5-Apr	2479	46	2430	71
6-Apr	2466	55	2429	69
9-Apr	2398	48	2553	65
10-Apr	2284	167	2442	173
25-Apr	2415	13	2532	88
26-Apr	2389	46	2517	73
27-Apr	2363	49	2520	75
28-Apr	2394	42	2515	68
29-Apr	2462	48	2570	69
30-Apr	2458	52	2599	68
1-May	2515	11	2660	16
2-May	2406	16	2553	6
3-May	2404	12	2556	16
4-May	2395	7	2530	12
5-May	2393	9	2555	9
6-May	2401	7	2557	9
7-May	2400	6	2564	5
8-May	2380	11	2534	13
Average	**2423**	**23**	**2514**	**30**

As shown in the table above, the 22-day averages for the two fans, which represent the winter consumption baselines, are 2423 ± 23 VA for the station ventilation 1 and 2514 ± 30 VA for the station ventilation 2. Figure 21 shows the daily average power absorbed by the two fans and the related overall average value. The apparent power curve is approximately constant over the period of measurement; indeed, the mean and the highest values of fluctuations over the period of measurement are respectively 1.1% and 4.8%.

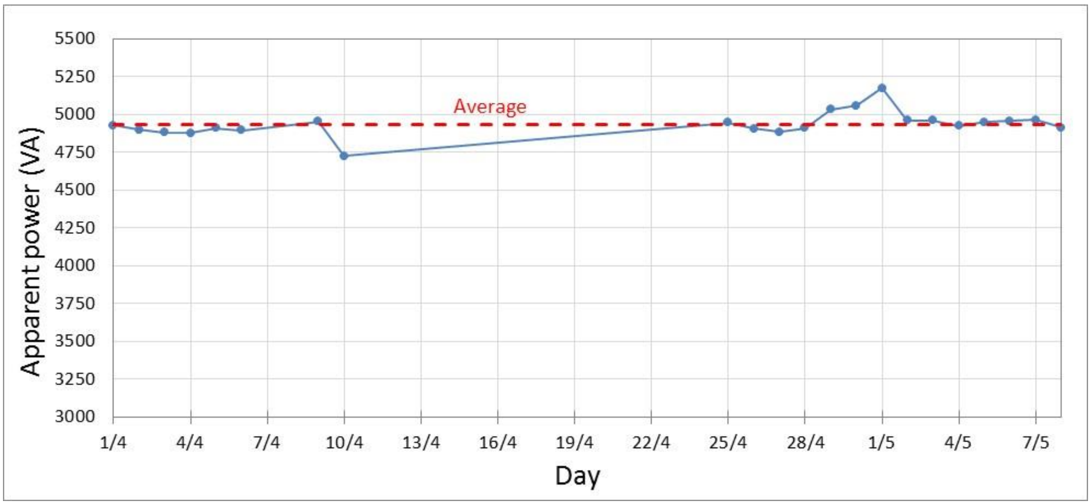


Figure 21. Daily average powers absorbed by the two fans in PdG-L3 during winter.

The consumption baseline for summer season was defined considering the power values recorded by the energy monitoring network from the 10th of May to the 8th of July 2014. The daily average powers in this period of time are shown in Table 7. The average values were calculated over the operating time of the fans and the uncertainties were estimated in the same way as described above for the winter consumption baseline.

Table 7. Daily averages of apparent power absorbed by the fans from the 10th of May to the 8th of July 2014.

	Station ventilation 1 (circuit 2NC-2)		Station ventilation 2 (circuit 2NC-3)	
Day	**Apparent power (VA)**	**Expanded uncertainty (VA)**	**Apparent power (VA)**	**Expanded uncertainty (VA)**
10-May	10653	388	12025	410
11-May	10854	44	12263	43
12-May	11028	19	12361	25
13-May	11129	19	12627	16
16-May	11068	30	12352	37
17-May	10957	14	12313	32
18-May	10989	23	12387	19
19-May	11126	24	12301	32
20-May	11073	31	12344	11
21-May	10892	43	12203	33
22-May	10935	39	12214	45
23-May	10975	38	12189	52
24-May	11159	24	12439	29
25-May	11118	22	12371	37
26-May	11206	33	12437	62
27-May	11129	52	12336	63
28-May	11071	29	12282	29
29-May	11068	43	12318	44
30-May	11150	32	12403	23
1-Jun	11025	15	12261	25
2-Jun	11033	22	12269	23
3-Jun	10983	23	12215	36

Day	Station ventilation 1 (circuit 2NC-2)		Station ventilation 2 (circuit 2NC-3)	
	Apparent power (VA)	Expanded uncertainty (VA)	Apparent power (VA)	Expanded uncertainty (VA)
16-Jun	11161	121	11571	150
17-Jun	11394	21	11790	26
18-Jun	11503	50	11853	28
19-Jun	11403	67	11799	26
21-Jun	11329	28	11663	22
22-Jun	11485	26	11764	22
23-Jun	11460	18	11745	13
24-Jun	11421	18	11707	14
25-Jun	11481	34	11753	27
26-Jun	11373	39	11634	34
27-Jun	11436	31	11741	31
28-Jun	11355	32	11655	31
29-Jun	11428	44	11724	34
2-Jul	11413	22	11741	26
3-Jul	11462	59	11778	50
4-Jul	11371	57	11658	52
5-Jul	11382	55	11684	47
6-Jul	11336	32	11650	29
8-Jul	11601	30	11894	29
Average	**11205**	**70**	**12042**	**99**

Therefore, the summer consumption baselines for the two fans are defined by the 42-day average values of the power measured, i.e. 11205 ± 70 VA for the station ventilation 1 and 12042 ± 99 VA for the station ventilation 2. Figure 22 shows the daily average power absorbed by the two fans and the related overall average value. Even in this case, the apparent power curve shown in the figure below is approximately constant over the period of measurement. The mean and the highest values of the fluctuations around the average power are indeed respectively 0.7% and 2.4%.

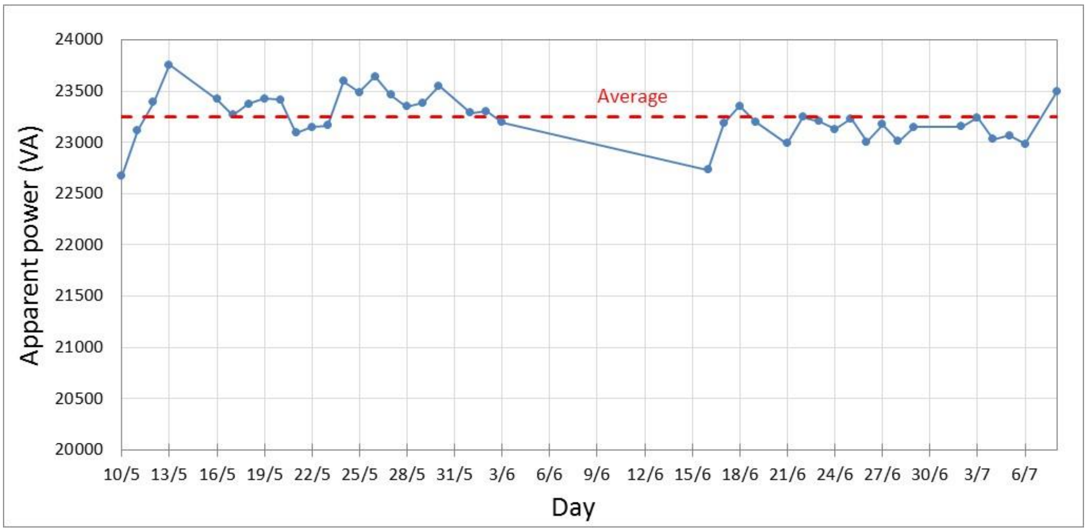


Figure 22. Daily average powers absorbed by the two fans in PdG-L3 during summer.

5.2. Lighting

5.2.1. Equipment

In PdG-L3 station there are a total of 39 circuits dedicated to lighting purposes, 27 of which are for regular lighting and the rest for emergency lighting. All the emergency lamp circuits (12) belong to the critical subsection. The rest are divided in Auxiliary (5), Critic (12) and Non-Critic (10). For each sector of the station, the lighting system is composed by four circuits (1 Critic shown in purple in Figure 23, 1 auxiliary in blue and 2 not critical ones in red and orange. The Figure 23 shows also the names of circuits in the areas).

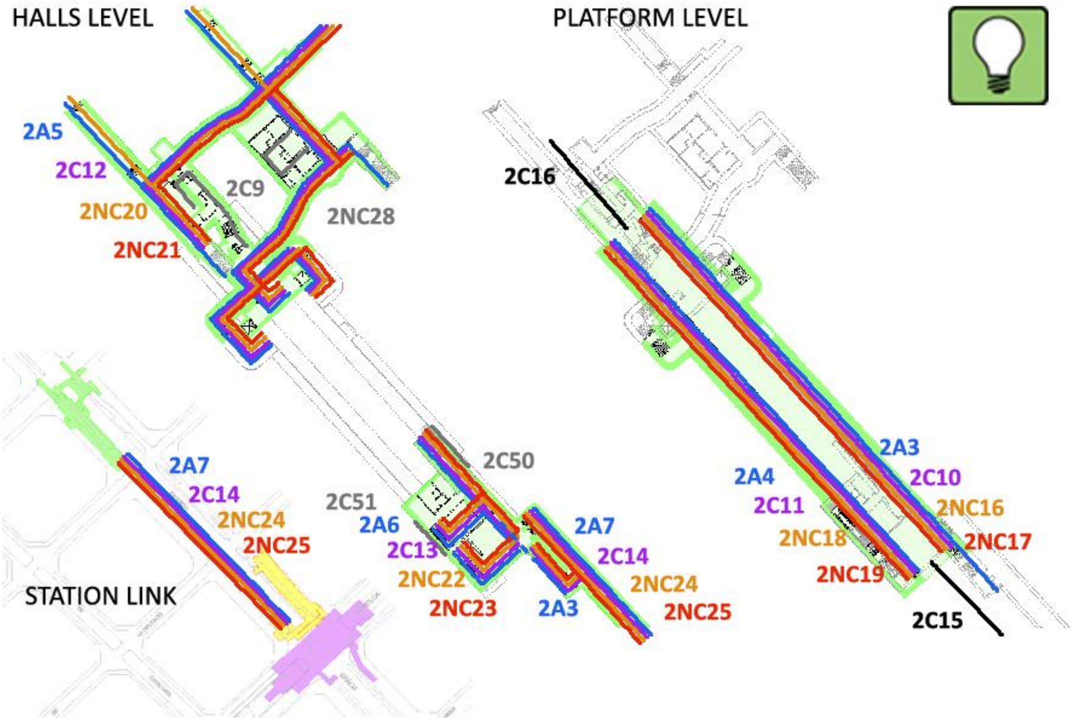


Figure 23. Lighting Circuits Plan

In public areas, there are basically 3 types of lamps, and one type of emergency light. Other lamps can be found within private dependencies, but since they represent a very small amount of the total energy expenditure, they have not been taken into account.

In the north part of the L3 station (CNc, Cnd, CNf, CNg, CNh, CNl, CNm, CNn) the most used luminary is manufactured by Carandini, model HF[9] (Figure 24), which currently uses two fluorescent T8 lamps of 36W arranged side by side. It is also used in the connection corridor to line 4. The total amount of Carandini lamps installed is approximately 176.

[9] Information available at: http://www.carandini.com/es/catalogo/producto.php?pid=40&f=4&car#car

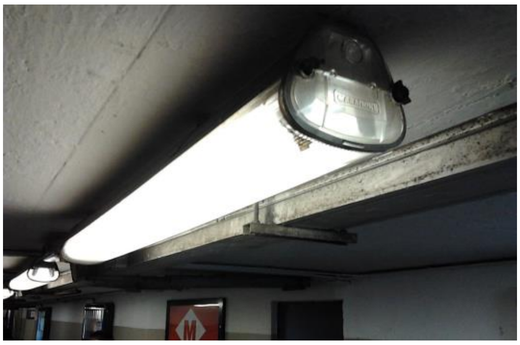


Figure 24. Carandini 2x36W lamp in L3 PdG.

Lighting distribution is different on the platform (PL3), with one continuous line of lamps near the wall, illuminating the information posters and signs and, another, above the edge of the platform (Figure 25). The model used in this case is produced by STI; it also mounts two TL8 36W fluorescent tubes, disposed longitudinally in line. There are a total amount of 150 in the entire station.

Figure 25. STI Lamp configuration 1x36 + 1x36.

The third model, which is mainly found in hall N3, but also in hall N2, is produced by LAMP (Figure 26). These luminaries adopt the same linear configuration as the STI ones, explained above. In L3 PdG Station there are approximately 58.5[10] such fixtures.

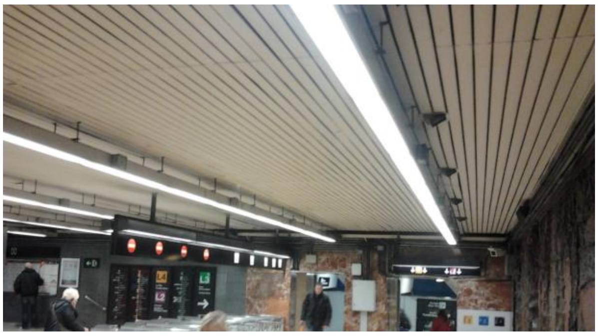


Figure 26. LAMP lamps configuration 1x36 + 1x36.

The emergency lights are spread homogeneously across the station. The model used is not defined, neither is their power. The number of emergency lights is approximately 110. The

[10] The half lamp means a luminary with one single lamp, while generally this type of luminary includes two fluorescent tubes.

sum total of fluorescent T8 36W is 765, meaning more than 26 kW installed. The Detailed Plan and quantity surveying can be found in Appendix C of deliverable D3.1.1. All lamps use standard electronic ballasts.


Figure 27. Different configurations of emergency lighting in PdG-L3.

Table 8. Lighting fixtures summary table for PdG-L3.

Manufacturer	STI	Carandini	LAMP
Number of fixtures	150	176	58,5
Number of lamps/fixture	2	2	2
Type of lamp	Fluorescent T8	Fluorescent T8	Fluorescent T8
Watts/lamp	36	36	36
Type of diffuser	Louver	Wrap-Around	Louver
Spaces	PL3 HN2 HN3	CNc CNd CNf CNg CNh CNl CNm CNn CNp Sla SLb	CNi CNo CNq HN3

5.2.2. Current performances

The lighting performance was computed through the measurement collected in the first survey (March 2012) and reported in Appendix A. These measures define the baseline in terms of lighting performances and refer to the original status of the station equipped with fluorescent T8 lamps. It emerges clearly that the lighting performance is almost ever compliant with regulation requirements. Furthermore, the baseline level of performance was defined for the most relevant spaces as shown in Table 9 in terms of illuminance levels (lux) on the floor.

Table 9. Lighting Performance Summary.

Space	Measured Performance (lux)	Regulation Requirement (lux)
Platform - edge	238	200
Platform - general	287	150
Hall HN2 - general	336	200

Space	Measured Performance (lux)	Regulation Requirement (lux)
Hall HN2 - special[11]	680	300
Hall HN3 - general	265	200
Hall HN3 - special	391	300
Corridor CNl	200	150
Corridor CNh	121	150
Corridor CNg	165	150
Stair CNq	228	150
Station Link	320	150

5.2.3. Consumption baseline

The consumption baseline is aimed to set the baseline values to be used as reference in the assessment of the control effectiveness which will be evaluated in the lighting pilot that involves only some areas of the station. In these areas it was necessary to replace the lamps in order to be compatible with the DALI control technology. Existing fluorescent T8 lamps were replaced with LED lamps, as explained in section 6.2. The lighting fixture replacement caused, as expected, a change in the lighting and energetic performance. As the scope of the pilot is to assess through experimental data the savings achievable with lighting control, the definition of the considered baseline is highly influent. Since the first year, in the SEAM4US project it was stated that the baseline to be considered was defined by the lighting performance of the actual state, defined as illuminance levels on the floor through the lighting survey performed in March 2012. After the installation of the new dimmable fixtures, equipped with LED lamps, it was necessary to identify which were the dimming coefficients defining the “original status” Baseline. Thus two steps were needed:

- Measurement of the new power consumption due to the lamp replacement;
- Identification of the dimming coefficient needed in order to obtain the same lighting performance as with the original T8 lamps.

The consumption baseline was measured only for the circuits involved in the lighting pilot, that are some meaningful portions of three typical spaces: side 2 of the platform PL3 (that is PL3:S2), the hall HN2 and the stair CNm. Thus it refers to two group of circuits: 2A-5, 2C-12, 2NC-20, 2NC-21, for hall HN2 and close corridor CNm and 2A-4, 2C11, 2NC-18, 2NC-19, for the platform PL3:S2.

[11] Special indicates the illuminance level on ticket-selling machines and ticket validation machines (@ Section 9.1 of D2.1.2 for details).

(a)

(b)

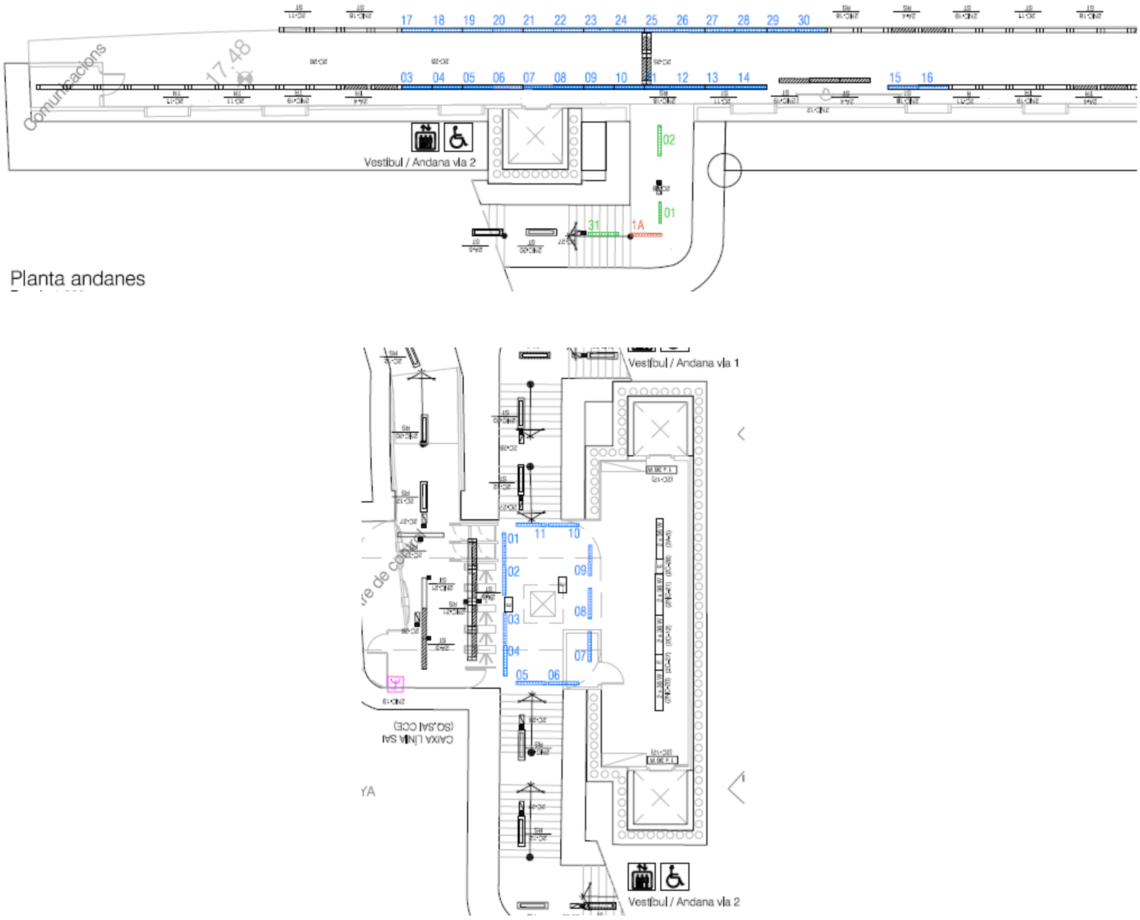


Figure 28. Plants showing the extension of the lighting pilot: lamp replaced in PL3:S2 and HN2.

The consumption baseline was computed considering the average power consumed in the actual circuit, for five days. The average values were considered as the mean value during the working hours. As an example, Figure 29 shows the average values of the apparent power absorbed by the circuit 2A-4 from the 1st to the 5th of April, 2014. It can be noticed that the fluctuations around the overall average value, shown with a red dotted line in the figure, are clearly small.

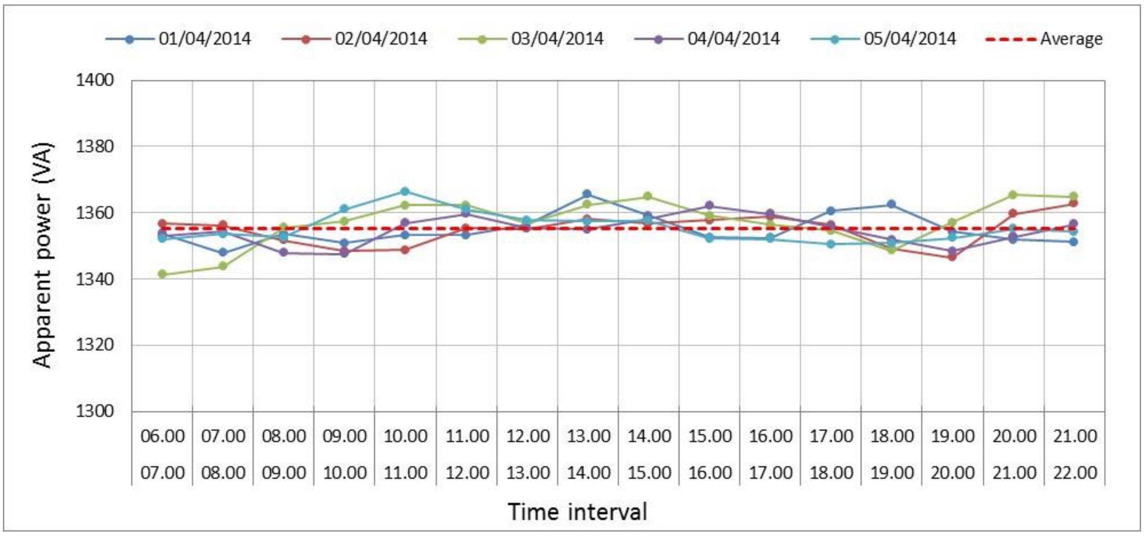


Figure 29. Hourly average apparent power absorbed by the circuit 2A-4 from the 1st to the 5th of April, 2014.

Figure 30 shows instead the sum of the five days average values of the apparent power absorbed by circuits 2A-4, 2C11, 2NC-18, 2NC-19 in each hour from 6 a.m. to 10 p.m.

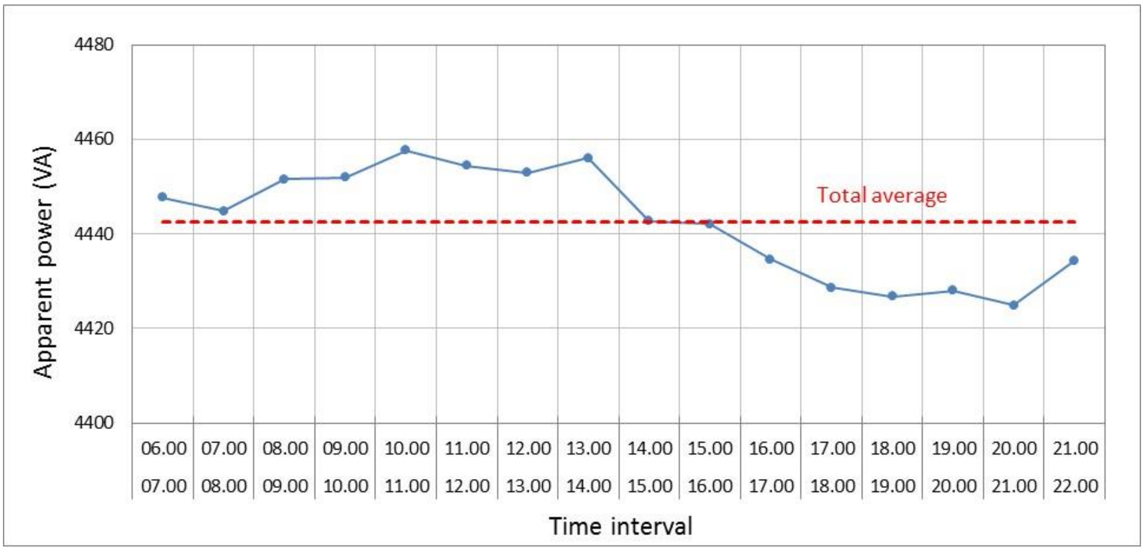


Figure 30. Average values of the apparent power absorbed by circuits 2A-4, 2C11, 2NC-18, 2NC-19 from the 1st to the 5th of April, 2014.

Table 10 reports the average data of power absorbed before and after the works for the lighting pilot (values in VA). Data referred to April 2014 are the newest one, after the replacement of fluorescent T8 lamps with LED lights. The expanded uncertainties shown in the table below were estimated as specified in the GUM for the Type A evaluation (@ Appendix C).

Table 10. Consumption baseline for the circuits involved in the lighting pilot in PdG-L3.

Platform PL3:S2 (VA)					
Circuit	2A-4	2C-11	2NC-18	2NC-19	Total
Average power (April 2013)	1402 ± 3	1273 ± 4	1026 ± 1	1063 ± 1	4763 ± 5
Average power (April 2014)	1355 ± 1	1197 ± 2	913 ± 1	977 ± 5	4442 ± 5
Difference between measurements	-47 (-3%)	-76 (-6%)	-112 (-11%)	-86 (-8%)	-321 (-7%)
Hall HN2 and corridor CNm (VA)					
Circuit	2A-5	2C-12	2NC-20	2NC-21	Total
Average power (April 2013)	1682 ± 14	1525 ± 1	1437 ± 1	1139 ± 1	5784 ± 14
Average power (April 2014)	1650 ± 16	1476 ± 1	1177 ± 1	1398 ± 1	5701 ± 16
Difference between measurements	-32 (-2%)	-49 (-3%)	-261 (-18%)	259[12] (23%)	-83 (-1%)

The second step for defining the consumption baseline was the identification of the dimming coefficients. This identification was based on a new measurement campaign in April 2014. The procedure adopted consisted in collecting measures related to the application of different dimming coefficients. As the relation between the lowering of the lighting

[12] This data is unrepresentative because the opening of a new area in PdG-L3 between April 2013 and April 2014 caused a power increase.

performance and the dimming coefficient is linear, based on the measurement at few dimming states, the relation between lighting performance and dimming could be computed through a linear regression. Then, for defining the consumption baseline, which has to include the application of the dimming coefficient, the illuminance value measured in the original state survey (carried out on March 2012) was considered, as defined in section 5.2.2. Current lighting performance: 287 lux for the platform and 336 lux for hall HN2. Table 11 shows the dimming coefficients obtained for achieving the original lighting performances. These are 0.14 for PL3:S2 and 0.36 for HN2. The dimming coefficients involve the 28 LED lamps of PL3:S2, that therefore have to be dimmed to the 86% of the full power and the 11 LED lamps of the hall HN2, which have to be dimmed to the 64% of the full power.

Table 11. Dimming coefficient for defining the consumption baseline in the lighting pilot.

		Dimming coefficients not applied		**Dimming coefficient applied**			
Areas of lighting pilot	**Numbers of LED lamps involved**	Installed Power (W)	Average illuminance (lux)	Dimming coefficients[13]	Power (W)	Average illuminance (lux)	Power Reduction (W)
PL3:S2	28	560	352	0.14	481.6	286	-78.4
HN2	11	220	444	0.36	140.8	336	-79.2

The consumption baseline for the lighting pilot will be the result of the application of the dimming coefficients to the lamps specified above. The Table 11 reports also an estimation of this power reduction due to the dimming for achieving the lighting performance baseline.

5.3. Escalators

5.3.1. Equipment

There are two escalators in PdG-L3. Hereinafter they will be referred to as:

- Escalator 1, identified as 3NC-3 in the electrical circuits of PdG-L3;
- Escalator 2, identified as 3NC-4 in the electrical circuits of PdG-L3.

Both devices are produced by Thyssenkrupp with the model name Tugela and were installed in 2009. The ramps, moving in an upward direction, have a transportation capacity of 9000 people/h. The induction motor of each escalator is powered by a 400V nominal voltage line. Altogether, the two ramps' nominal rated power is equal to 21kW.

[13] Dimming coefficient = 0 means full power lighting whereas dimming coefficient =1 means light switched off.

Figure 31. Escalator 1 in PdG-L3.

The Table 12 contains a summary of the descriptive information regarding the two escalators in PdG-L3.

Table 12. Description of the escalators in PdG-L3 station.

	Escalator 1 (circuit 3NC-3)	Escalator 2 (circuit 3NC-4)
Manufacturer	THYSSENKRUPP	THYSSENKRUPP
Model	TUGELA	TUGELA
Year	2009	2.009
Capacity (people/h)	9000	9000 people/h
High (m)	6,275	4,22
Speed (m/s)	0.2-0.5	0.2-0.5
Active power (kW)	12.00	9.00
Line nominal current (A)	21.65	16.40
Line nominal voltage (V)	3x400	3x400
Passengers detector	Photocells	Photocells
VFD	YES	YES
Direction	Upward	Upward
Trip	From CNe to street	From CNo to HN3

5.3.2. Current performances

The escalators are managed using the CCIF system described in D2.1.2. This system offers five control modes:

- Stop
- Upwards automatic mode
- Upwards continuous mode
- Downwards automatic mode

- Downwards continuous mode

The escalators in the station PdG-L3 are used only for upward passenger movement, regardless of the fact that, through the CCIF system, passengers can also be transported downward. The continuous operating mode implies a fixed escalator speed kept at a certain value whereas, the more often used automatic operating mode, allows varying the escalator's speed depending on the presence/absence of passengers.

Control in the automatic mode, that is two speeds control of the ramp's movement, is achieved by a variable frequency drive (VFD) and photoelectric detection of passengers at the stairs' entrance. In the absence of passengers, the stair speed is kept low (0.2 m/s) whereas, when the photocells detect a passenger's presence, the speed is increased, to a value rated 0.5 m/s by means of the VFD, which varies the frequency of the motor supply from 20 Hz to 50 Hz. After a 10 second interval in absence of passengers, engine speed is lowered so that the stair steps return to a speed of 0.2 m/s.

Figure 32 shows the measured trend of the power absorbed by an escalator and the related occupancy status. In this figure, it should be noticed the peak of power when the escalator's speed changes from the stand-by to the rated speed of 0.5 m/s. The power absorbed when the escalator runs at the rated speed and there are no passengers is about 1.5 times the power absorbed when it is on stand-by.

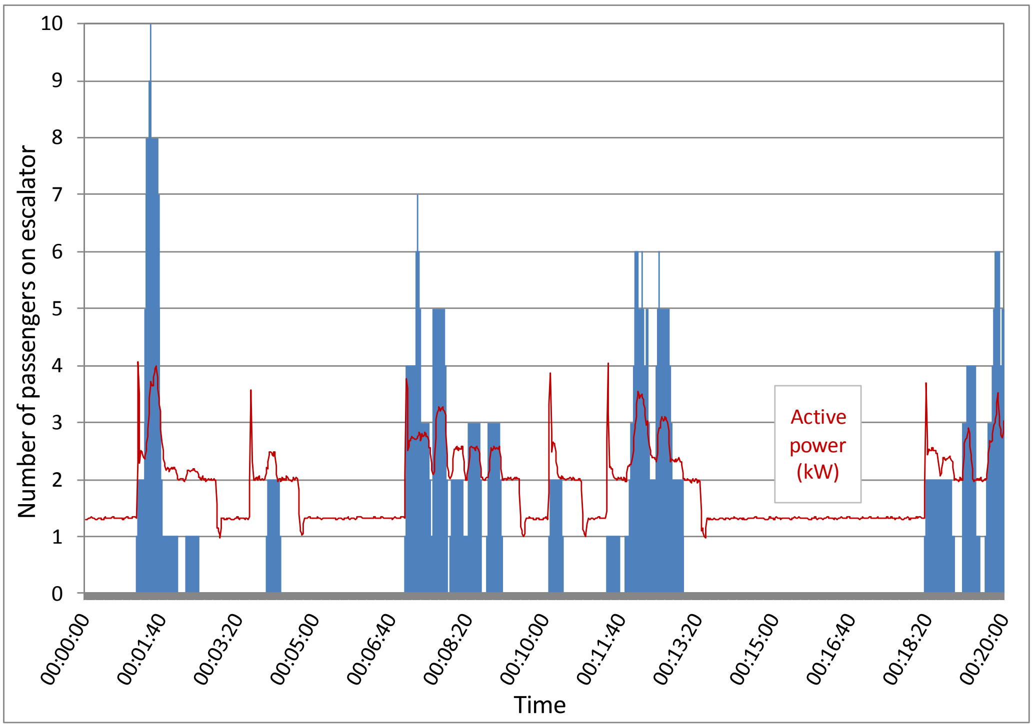


Figure 32. Active power absorbed and number of passengers on an escalator.

5.3.3. Consumption baseline

The consumption baseline for the two escalators in PdG-L3 was defined using the measures of power recorded by the energy monitoring network from the 17th of June to the 8th of July 2014. Table 13 shows the daily averages of the active power absorbed during the operating time of the escalators, i.e. when the station is open. The uncertainties were estimated according to the GUM (@ Appendix C), in the same way as described above for lighting and ventilation systems.

Table 13. Daily averages of active power absorbed by the escalator from the 17th of June to the 8th of July 2014.

	Escalator 1 (circuit 3NC-3)		Escalator 2 (circuit 3NC-4)	
Day	Active power (W)	Expanded uncertainty (W)	Active power (W)	Expanded uncertainty (W)
17-Jun	2512	113	2081	137
18-Jun	n/a	n/a	2049	126
19-Jun	2401	67	2087	134
20-Jun	2429	64	2100	135
21-Jun	2347	34	1931	144
22-Jun	n/a	n/a	1902	149
23-Jun	n/a	n/a	2072	155
24-Jun	2395	30	1852	101
26-Jun	2423	234	2086	129
27-Jun	2611	51	2087	120
28-Jun	2522	39	n/a	n/a
29-Jun	2496	43	n/a	n/a
2-Jul	2619	105	2212	138
3-Jul	2621	100	2173	119
4-Jul	2561	103	2226	94
5-Jul	2386	68	2154	94
6-Jul	2475	38	2156	92
7-Jul	2511	144	2249	86
8-Jul	2566	82	2291	96
Average	**2492**	**47**	**2100**	**62**

Of course, the power absorbed by an escalator varies a lot during a day, as also shown in Figure 33, which illustrates the hourly average powers absorbed by the escalator 3NC-3 in some of the days monitored. Indeed, the average of the maximum fluctuations around the daily average power over the working days in the period of measurements is about 12% whereas the same parameter calculated over the Saturdays and Sundays monitored is about 5%.

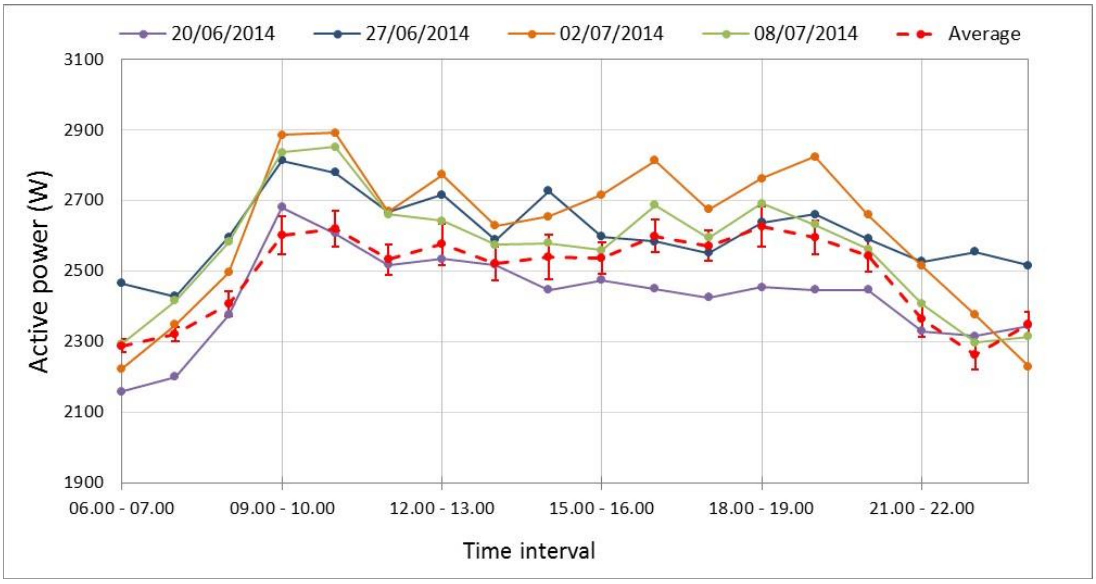


Figure 33. Hourly average active power absorbed by the escalator 3NC-3 in some days within the period of measurement.

Nevertheless, the figure above also shows that the daily curve of hurly average powers present approximately the same trend. In addition, it has to be noticed that the mean fluctuation around the average power calculated over the entire period of measurement is about 3%, which means that the differences between the daily average powers are not so large. This is highlighted in Figure 34 that shows the trend of the daily average power absorbed by the escalator 3NC-3 during the period of observation.

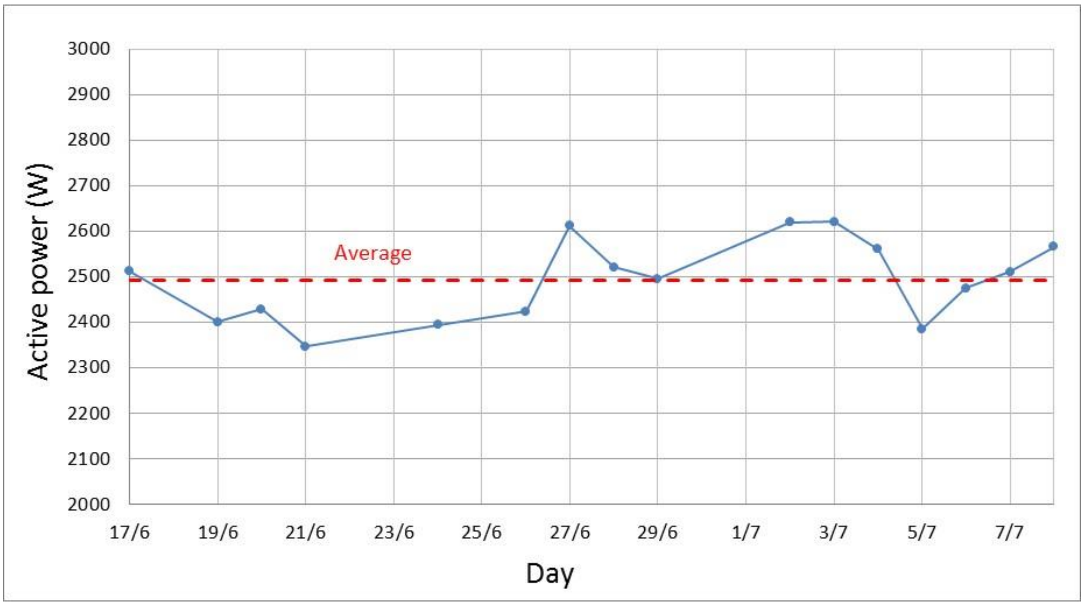


Figure 34. Daily average powers absorbed by the escalator 3NC-3 during the period of measurement.

Referring to the weekly average, the differences between the average powers become even smaller. The weekly average powers for the escalator 3NC-3 in the period of measurement are the following: 2422 W for the 3rd week of June (from the 16th to the 23rd of June 2014), 2489 W for the 4th week of June (from the 24th to the 30th of June 2014) and 2529 W for the 1st week of July (from the 1st to the 7th of July 2014). Therefore, the weekly mean fluctuation around the average power over the entire period of measurement is about 1.5%, which means that the escalator's consumption is about the same week by week.

From what is stated above, it is evident that the consumption baseline for the escalators can be reliably computed as the average power over the selected period of measurement. As shown in the Table 13, the global average value of the power absorbed during the operating time of the escalators is 2492 ± 47 W for the escalator 3NC-3 and 2100 ± 62 W for the escalator 3NC-4.

6. FINAL DIAGNOSIS ABOUT INEFFICIENCIES

This section is basically focused on the station's equipment controlled through the SEAM4US control system, i.e. lighting system, ventilation system and escalators. These equipment are responsible for about the 60% of the annual consumption of the PdG-L3 station as shown in the section 3. So, in the following paragraphs the aforementioned equipment are deeply analysed in terms of inefficiencies identified. Hence, for each of these equipment, preliminary estimations of the potential energy savings achievable by implementing the SEAM4US approach are provided[14]. At the end of the section, such an analysis is then carried out also for the others equipment which are not controlled by the SEAM4US system.

6.1. Ventilation system

6.1.1. Diagnosis of inefficiencies

The ventilation equipment in PdG-L3 is designed to keep internal conditions healthy (against pollution) and comfortable (against unacceptable temperature rise). The air exchange is dimensioned according to the time extension passengers remain inside the station. Following our analysis of the ventilation system we may highlight that:

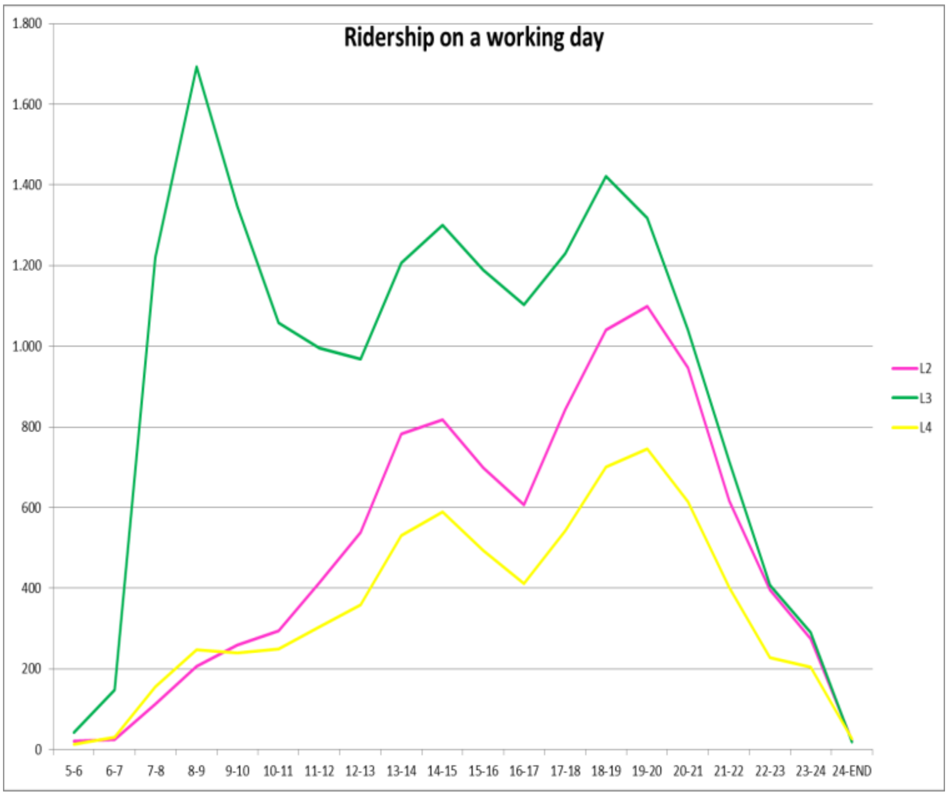
- Airflow rates for which the fans were selected are not required continuously and to leave the fans operating as if they were is a waste of energy. In particular, there are two main reasons why the design based solely on the most demanding operational conditions is not the best approach to driving the fans:
  - as the fans inject clean air from the outside and extract exhaust air from the platform passing through the tunnels, they basically produce air changes to decrease the pollution concentration determined by the presence of people and the passage of trains. However, the particulate matter and CO_2 emitted by approaching and departing trains is not constant but changes with the frequency of trains and their acceleration and deceleration rates when close to the platform; in addition, the presence of people also varies during the day, hence even polluting loads are subject to changes (Figure 35-a);
  - the second function of air changes is keeping comfort conditions inside the station through a control on the internal temperature; in fact mixing indoor exhaust air with fresh air from the outside leads to an intermediate temperature which is more accepted by passengers; however, also in this case, the effectiveness of the approach is strongly related to external air temperature, which is changeable. Figure 35-b shows that the technical room's air intake is placed on the road surface, so the effectiveness of air changes on comfort in that area is affected by its micro-climatic conditions.
- There is no feedback system to measure the real performance of the fans: the ventilation strategies rely on two main contributions: on one hand, the air injected into the station by the two fans, which is released straight onto the platform; on the other hand, by the amount of air induced in the form of ventilation through corridors, which draws outside air through the corridors and passageways into the platform.

[14] The final savings estimations will be provided in the D6.3.

However, there is no ventilation monitoring system provided by the fans, so the air supply rate determined by design is not verified. As a consequence, the estimation of the induced air ventilation rate is also quite rough.

- The current CCIF system is set to perform two-step adjustment of the fan speed, which is used just for varying its rate between the summer and winter seasons: such a technical approach is not used to adjust ventilation rates according to real user needs and internal environmental needs. In addition, the variation step is rather coarse: “high speed” means the two fans are running at their highest frequency and “low speed” means the two fans are running at half their available maximum rotational speed.

(a)



(b)

Figure 35. Typical ridership for a weekday in PdG-L3 (only people entering the station are counted, however it is quite representative of the daily variability and peak times are clearly occurring at hours

8-9 and 19-20) (a) and air intake located on the ceiling of the technical room of the ventilation equipment (b).

Before envisaging future scenarios for future improvements, it is worth noticing that the current ventilation equipment's setup is well organized in terms of:

- air distribution system: the two fans inject air directly into the ducts leading air to the platform, in this way they exploit the total pressure available by the fans well: both dynamic and static pressures contribute to the total pressure rise determined by the two fans and used to convey air into the platform;
- management of starting currents: when an induction motor is simply connected to the electrical grid (across-the-line starting), since the rotational speed of the rotor is zero and the magnetic field of the stator builds up abruptly to synchronous speed, the slip speed is very large, hence the starting current is very high: of the order of 5 - 6 times the rated full-load current. In the case of PdG-L3, the CCIF system controls a PLC which automatically starts the fans through a gradual approach.

Given what is stated above, the scenarios we propose for improving equipment's efficiency are the following ones:

- Real-time control of the airflow rates in the station through the installation of an environmental monitoring network;
- Setting up a system for accurate control of actual fan performances;
- Integrating the currently available fan's local control in order to achieve on-the-run speed variation potentials and, possibly, continuous speed control.

6.1.2. Saving potentials

The LPM model described in D3.2.2 has been used - to the purpose of this deliverable - to perform a preliminary analysis of the potential energy savings attainable using an adaptive control. Of course, just a very preliminary policy was applied and the real purpose of this analysis is to show how big saving potentials are, because the adaptive control approach used for the estimation in this paragraph is less effective, but easier to be implemented, than the predictive control that will be used to carry out the final saving estimations presented in D6.3.

"Adaptive control" is a special type of nonlinear control system that can alter its parameters to adapt to a changing environment; the changes (i.e. counteractions) are activated to smooth deviations from targets determined by all the actions acting on a building.

These simulations were performed on the assumption that the mechanical air supply system must always provide a minimum amount of air changes. These values were estimated through the following reasoning:

- the evaluation was limited to PdG-L3;
- the past total occupancy was estimated starting from the number of entries detected by the gates, which is shown in Table 14;
- the average occupancy at each hour was estimated considering that a person occupies the station for about 3 min (n'= n/60*3);

- the minimum amount of air changes per hourwas estimated as the sum of ventilation required by the presence of people (whoase minimum values was sized according to EN15251) and ventilation required by the passage of trains. This second value was obtained as the ration of the current air changes provided by fans and the numebr of trains in the peak hour;
- then mechanical ventilation was modulated according to the variation in time in the number of trains and the number of people.

Table 14. Estimated occupancy in PdG-L3.

Time		No. of entries	Coefficient	Total occupancy	Time averaged occupancy
5	6	50	2	100	5
6	7	150	2	300	15
7	8	1220	2	2440	122
8	9	1700	2	3400	170
9	10	1400	2	2800	140
10	11	1080	2	2160	108
11	12	1000	2	2000	100
12	13	950	2	1900	95
13	14	1200	2	2400	120
14	15	1300	2	2600	130
15	16	1200	2	2400	120
16	17	1100	2	2200	110
17	18	1220	2	2440	122
18	19	1430	2	2860	143
19	20	1320	2	2640	132
20	21	1050	2	2100	105
21	22	750	2	1500	75
22	23	400	2	800	40
23	24	300	2	600	30

Figure 36-a depicts the air supplied by the two station fans in the platform in the present situation. However, just the amount shown by the red dotted line would be strictly required, according to occupancy and train passages. In fact, presently the fans are driven according to the frequency plot represented in Figure 36-b, and they absorb the electric power indicated in Figure 36-c. Figure 36-d shows the environmental temperature estimated in the platform when all the conditions are set like in the current situation.

As the station's current environmental temperature was considered fine by the transport service provider in Barcelona, a first evaluation of attainable energy savings was carried out through the application of a PID control, which aimed at providing air changes rate sized on the actual number of people in the station and trains passing through the platform. Figure 37-a depicts the air changes provided in the platform by the adaptively controlled fans; Figure 37-b shows the required fans frequency in this case, while the corresponding electric power consumption is shown in Figure 37-c. Finally, Figure 37-d witnesses the almost unchanged comfort had in case that PID control is applied to the fans. Not only was the comfort maintained, but consumption was also reduced by as much as 21%. This preliminary simulation demonstrates that the current air change rates are not strictly required to keep comfort conditions within the values considered as acceptable. Hence there is room for reducing operating air frequency of fans, which would lead to considerable energy savings. A better estimation of energy savings will be presented in D6.3, and will follow from the application of a predictive control system, which will help drive the fans in a more smoothed way while monitoring the two air quality variables CO_2 and PM_{10}. It is expected that this mode will allow further energy savings and will keep comfort conditions.

(a)

(b
)

(c)

(d
)

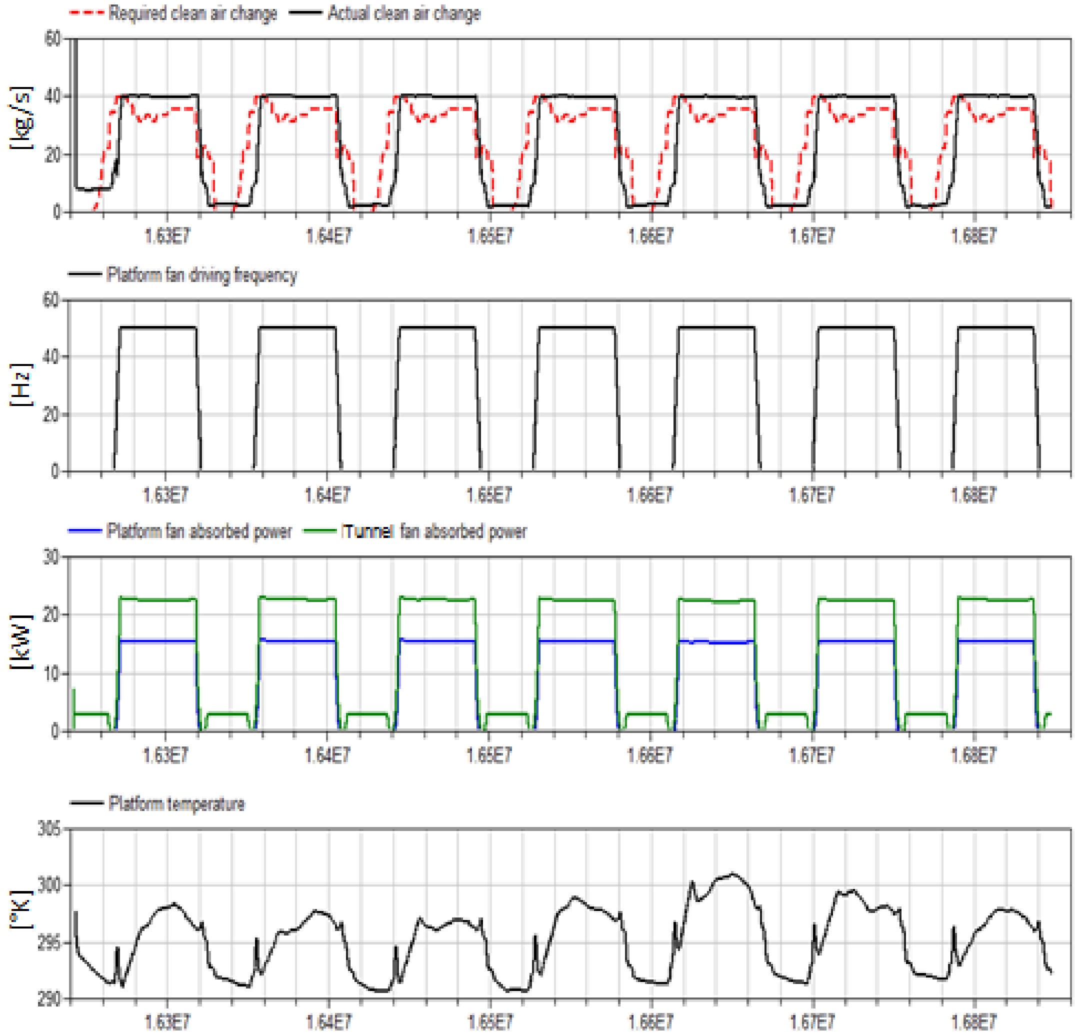
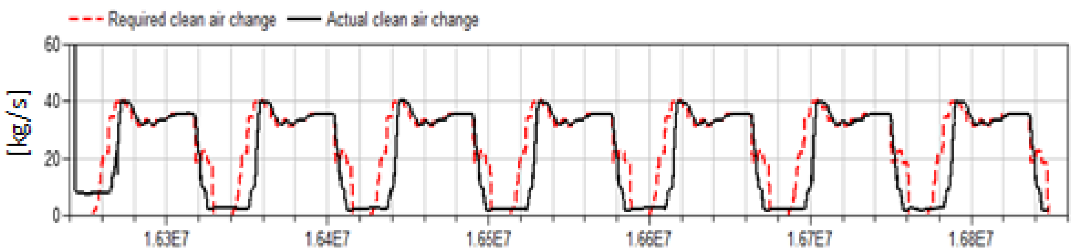


Figure 36. Present design mechanical air supply determined by the fans in the station (a), corresponding fans frequency (b) and electrical power consumption (c), and air temperature resulting in the platform in the current situation (c).

(a)



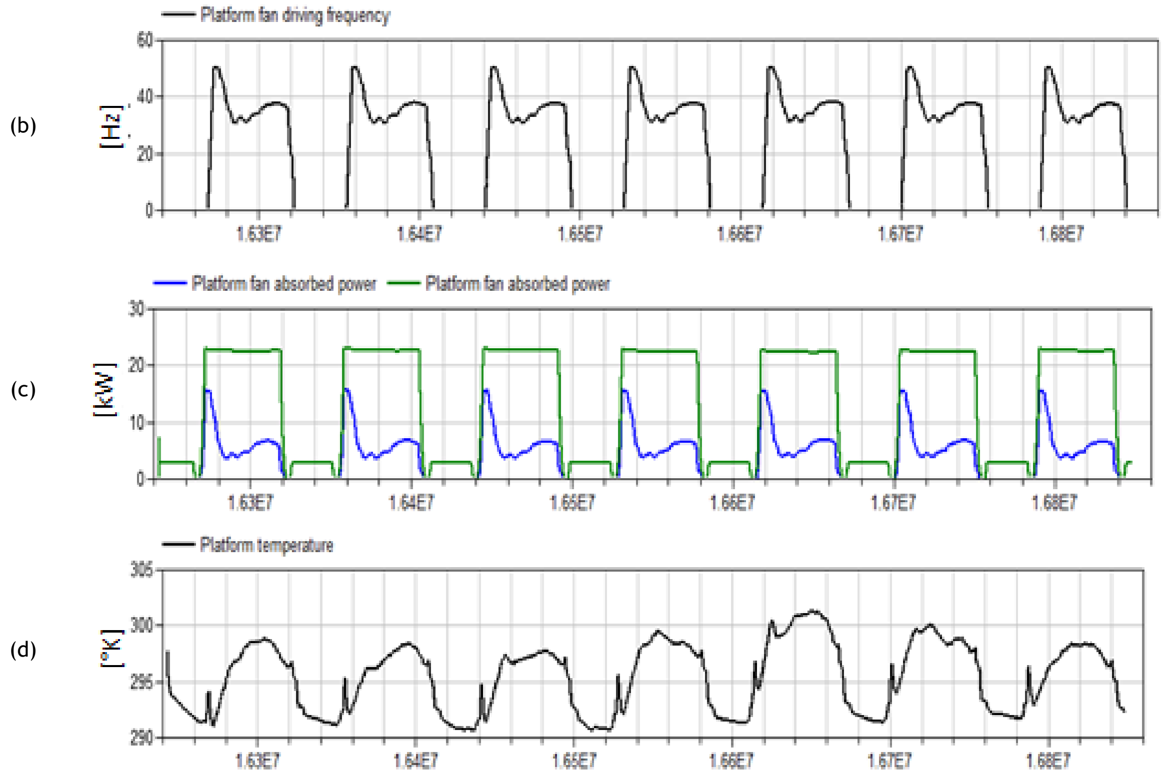


Figure 37. Air change rates required according to actual occupancy and train passage (a), corresponding required fans frequency according to a PID control (b) the electrical power consumption (c) and air temperature resulting in the platform in the case of PID controlled situation (d).

6.2. Lighting system

6.2.1. Diagnosis of inefficiencies

In the lighting system deployed so far:

- The lamp lifecycle is not fully exploited. A lamp's actual luminous flux is almost always different from the nominal luminous flux used for designing the lighting system. In fact, lamps have a decadent performance in time, and in order to guarantee their nominal luminous flux even at the end of their average life, they emit more initially. They could emit less, but still be in service after their end-life time. For T8 lamps, average life time is usually 20000 hours, meaning about 140 weeks considering the common opening hours of TMB stations (140 hours/week). Consequently, it can happen that:
  - Lamps are emitting more than their nominal luminous flux (before their end-life value);
  - Lamps are emitting less than their nominal luminous flux (after their end-life value).

  The energetic consumption stays basically constant nevertheless, if a control system were available, the emitted luminous flux in the first period of life of the lamp could be modulated on the basis of actual need, saving energy and obtaining a more uniform lighting performance.
- Reflectivity factors of the space surfaces are not optimal. In some spaces, there is a high environmental context variability that affects lighting performance. For instance, in HN3 (Figure 38) it can be noted that the measured illuminance levels decrease from the centre towards the south wall (on the right of Figure 38) even if the lighting devices'

spatial distribution is constant. This probably depends on the reflectivity index of walls and furniture. In fact, the south wall has a dark, coarse finish while, in the central part of the hall, there are white metallic gates with a high reflectivity index.

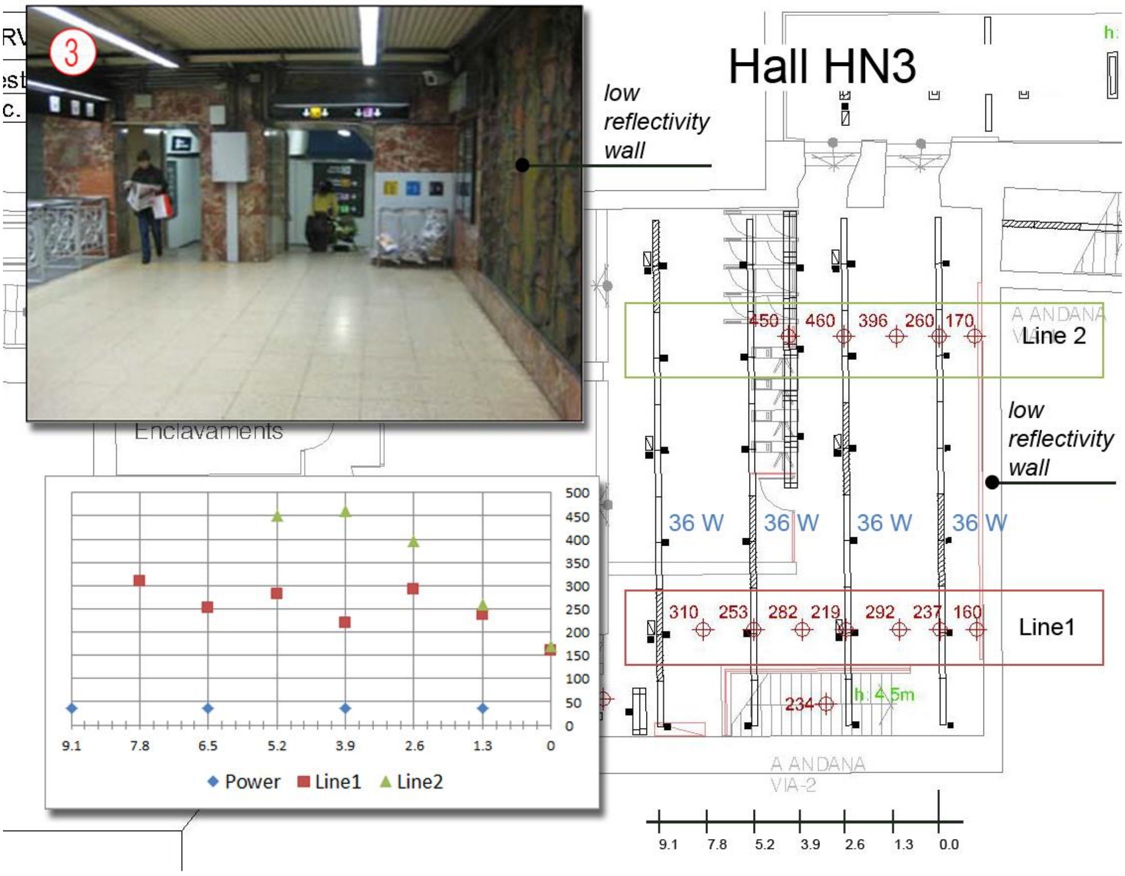


Figure 38. Example of the role of context in lighting performance. In HN3 measured illuminance levels decrease from the centre to the south (right) wall, coherently with the reflectivity of walls and furniture.

The actual state of the lighting system calls for two types of intervention; these could be faced singularly or as a combination:

- Improving Lighting Design (in terms of sources and luminaries);
- Automatic Control.

Reducing the connected load of the lighting system represents only one part of the potential for maximizing energy savings. The other part is minimizing the use of that load through automatic controls. Automatic controls switch or dim lighting based on time, occupancy, lighting level strategies, or a combination of the three. The general control strategies that could be used include:

- Occupancy sensing, where lights are turned on and off or dimmed according to occupancy;
- Scheduling, where lights are turned on and off according to a schedule;
- Tuning, where light output is reduced to meet current user needs.

These strategies can be accomplished by means of various control devices, including on-off controls, dimming controls, and systems that combine the use of both types of equipment.

These controls can be quite sophisticated, but in general, they perform two basic functions: They turn lights off when not needed, and they modulate light output so that no more light is produced than the light needed. The equipment required to achieve these functions varies in complexity from simple timers to intricate electronic dimming circuits. Each of these technologies can be applied individually for great effect or combined for even greater benefit.

6.2.2. Saving potentials

As the actual lighting system did not include control devices or a lighting control system, further considerations and a preliminary estimation of saving potentials were performed. The aim of this phase was to orient the future work and choose a direction for the development of this aspect of the project. The main purpose of the SEAM4US project is to save energy by improved management, rather than by applying expensive retrofit measures. However, with the current lighting system and circuit configurations of the Passeig de Gràcia station and, given the strict regulations regarding illuminance levels, the deployment of a new lighting control system appeared reasonable. In fact, preliminary investigations showed that in a technical perspective, the deployment of such a lighting control system would require not only the development and installation of an appropriate controller, but also the replacement of existing ballasts with dimmable ballasts and related data bus cabling between ballasts and controller.

Concerning the second point, contacts were established with two enterprises of the lighting sector in the first year: iGuzzini (head office in Italy, with a branch office in Spain) and LightLED (Spain). These two potential partners offered their contribution in supporting the definition of possible retrofit scenarios for some typical spaces of the pilot station. The consortium decided to split the scenarios:

- Current T8 fluorescent tubes were investigated within the consortium
- Retrofitting with T5 Fluorescent tubes scenario was investigated with the support of iGuzzini;
- Retrofitting with LED technologies scenario was investigated with the support of LightLED.

For the three scenarios (actual T8, new T5, new LED), simulation-based investigations were done for defining the saving potentials, meaning the maximum dimming coefficients needed to achieve the minimum lighting performance admissible by regulation (e.g.: E_{mean} = 150 lux, on the edge E_{min}=200 lux). The details of the simulation-based development of this scenario can be found in D.3.1.1. Here only the main results are reported. For each technology scenarios three configurations were simulated:

- No dimming, where lamps are used considering their full power;
- Baseline, where lamps are dimmed in order to achieve the original lighting performance;
- Maximum saving, where lamps are dimmed to lowest lighting levels accepted by the regulations.

Table 15 shows a synthetic prospect of the simulation results in terms of power absorbed (W) obtained for the three scenarios analysed. The simulation was done for the two platforms. The main emerging considerations are:

- The case where the introduction of a control policy would lead to the best results in terms of percentage savings compared to the baseline is in the case of the actual T8 technology (43%). This is due to the fact that T8 technology is the less efficient intrinsically, thus the achievable savings are higher;
- The case where the introduction of a control policy would lead to the best results in terms of minor absolute consumption is in the case of LED technology (2153 W, saving 77% on the actual estimated power), which is, generally speaking the most efficient technology, also evident if one considers the maximum absolute saving that would be achieved in the event of no control (No dimming, 61% for LED);
- Considering the "savings achievable on the related No dimming scenario", it emerges clearly 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;
- Achieving the baseline status (new lighting system dimmed to actual illuminance levels) with T5 and LED technologies would increase efficiency in both cases, given that they would consume 37% and 67% less respectively.

Table 15. Comparison between simulation results for T8, T5 and LED scenarios.

	No dimming	Baseline		Control (maximum saving)			
	Power (W)	Power (W)	Saving on its No dimming	Power (W)	Saving on its Baseline	Saving on its No dimming	Saving on original power (T8)
T8 (36W)	9504	9504		5372	**43.5%**	43.5%	43.5%
T5 (28W)	7392	5984	19.1%	3854	**35.6%**	47.9%	59.4%
saving on T8	22.2%	37.0%		28.2%			
LED (14W)	3696	3171	14.2%	2153	**32.1%**	41.7%	77.3%
saving on T8	61.1%	66.6%		59.9%			

On the basis of the previous considerations, the picture that emerges is one where considering the "maximum saving on the related baseline" criterion, the choice would fall on the scenario, in any case, also characterized by the least absolute saving (T8).

Considering also the scalability of the project results, this does not appear to be a viable option given that, in general, T8 fluorescent can be considered outdated technology. On the other hand, the relative savings obtainable through dimming control using either one of the "new lighting technology" scenarios (T5 and LED) are very close (32.1%-35.6%). In any case, in the project development and assessment perspective, what is relevant is to fix the baselines for each technology clearly, in order to be able to assess the actual savings achieved.

Table 16 reports a comparison between possible scenarios in a pure technical perspective. T5 FL and LED are both a suitable solution in terms of lighting efficiency (luminaire efficiency and lamp lifetime) and performance. Whereas regular fluorescents lamps have greater efficiency, LED lamps offer greater directionality. This fact results in luminaires (lamp + fixture) with similar performance in terms of lux/W at the work plane[15,16].

Table 16. Comparison between possible technological scenarios.

Concept	Status quo (T8)	Updated status quo	T5	LED
		Characteristics		
Control capabilities	No	DALI	DALI	DALI
Dimming range (as % of nominal power)	No	1 - 100%	1 - 100%	1 - 130%
Rapid dimming cycling	No	Lifetime reduction	Lifetime reduction	No problem
Luminaire efficiency	Medium	Medium	High	High
Lamp lifetime	Medium	Medium	High	Very High
Ballast/driver lifetime	High	High	High	High
Lighting performance	Good	Good	Very Good	Very Good
System complexity	Low	High	High	Medium
		Requirements		
Installation works	No	High	High	Medium
Ballast/driver renewal	No	Yes	Yes	Yes
Fixture renewal	No	No	Yes	Yes

The three scenarios are also suitable for being used in a dimming control scenario, even if LED usually has a better performance in terms of dimming range – LEDs can offer extra power in case of extraordinary need[17] - and in case of rapid cycling. In fact, LEDs are impervious to deleterious effects of on-off cycling. In fact, one method for dimming LEDs is to switch them on and off at a frequency that is undetectable by the human eye. For fluorescent lamps, the high starting voltage erodes the emitter material coating the electrodes. Thus, lifetime is reduced when the rate of on-off cycles is increased[18]. The application of a control system would require, only in the T5 FL and LED cases, a complete fixture renewal. In any case, some associated installation work would be necessary for all three scenarios, as ballast renewal would also be needed for the actual T8 and extensive cabling as well. Installation work would be less onerous in the case of the LED scenario, as overall system complexity is minor in this case: ballast cabling in fluorescents setups is critical and requires special attention being one of the main causes for lamp failing in dimming fluorescent systems (NLPIP, 2006). Finally, in the project development perspective, it emerged that control policies can be evaluated as long as control capabilities are installed, no matter what lighting technology is installed, if the baseline of control saving was fixed.

[15] Ryckaert W.R., Smet K.A.G., Roelandts I.A.A., Van Gils M., Hanselaer P. 2012. Linear LED tubes versus fluorescent lamps: An evaluation, Energy and Buildings, Volume 49, June 2012, Pages 429-436.
[16] Koninklijke Philips Electronics N.V. available at: http://www.ecat.lighting.philips.es/l/lamparas-profesionales/lamparas-fluorescentes/tl5/master-tl5-h-e/26170/cat/?t1=overview#t=overview.
[17] LightLED reports the fact that it is possible to set an output above 100% of the nominal power to achieve higher bright environments when needed.
[18] U.S. Department of Energy, 2012. Using LEDs to their Best Advantage. PNNL-SA-85346. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_advantage.pdf.

Following this preliminary phase however, only LightLED offered its equipment and expertise free of charge, in order to proceed to the executive design and deployment of the investigated scenario and related control devices, while iGuzzini decided to interrupt the collaboration. Thus, as of now, we have reached the objective of having granted at least one scenario for the lighting pilot. The simulation-based investigation can proceed should any other company manifest an interest in supporting, exploring and sponsoring the T5 fluorescent tube scenario. The project will in any case proceed investigating the control policies for lighting and considering the LED Lighting Scenario as the new reference scenario.

6.3. Escalators

6.3.1. Diagnosis of inefficiencies

The escalators in PdG-L3 run on two stair speeds according to passenger presence or absence:

- a stand-by speed, when the ramp is not in use, fixed at 0.2 m/s;
- a rated speed, in the presence of passengers, set at 0.5 m/s.

Therefore, although the system controlling and managing the escalators is already at an advanced level, in terms of optimizing operations to lower energy consumption, a detailed analysis was necessary to focus on the rated speed value chosen. Indeed, the range of speed variation from the stand-by value to operating speed is very wide; furthermore, such an interval is independent from the number of people using the escalator: even when these are few, the speed of the escalator varies according to the same interval. Moreover, as all the escalators are managed in an upward direction, their use is not continuous, but discrete, that is, they are used in correspondence to trains' arrival time. Consequently, the escalators are subjected to wide speed variations several times a day. Therefore, the measure proposed for reducing the energy consumption is the modification of the rated speed of the escalator with the aim of optimizing it according to the actual number of passengers. Indeed, this measure has a result a double impact on the energy saving. On the one hand, the energy consumption is reduced by keeping the operating speed lower than the actual rated speed when few people are using the escalator and on the other hand, there is a reduction of the power peak, shown in Figure 39, occurred when speed changes from the stand-by value to the operating value. Especially this second aspect required an in-depth analysis for studying the consumption during escalators' speed variation transients when operating speed changes. Such analysis was performed using suitable calculator simulation as briefly reported in the following section 6.3.2 and detailed in the deliverable D3.2.2.

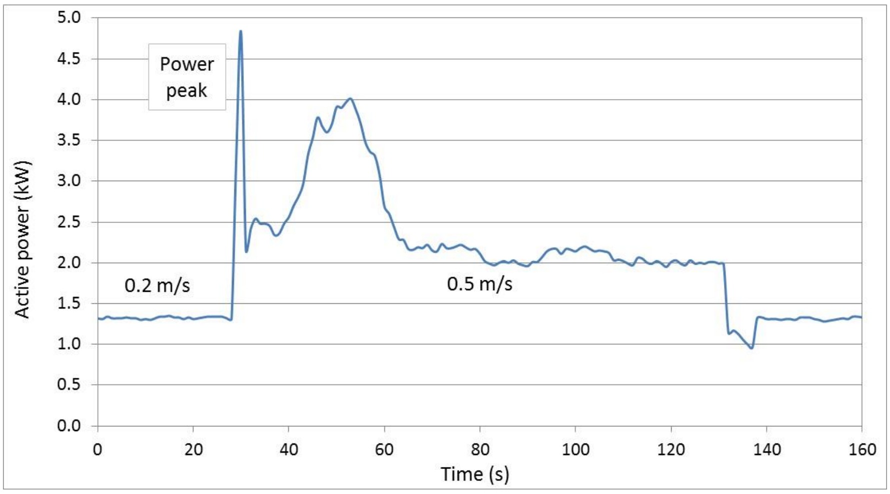


Figure 39. Trend of the active power absorbed by an escalator in PdG-L3.

In addition to what is stated above, another measure for reducing the escalator's consumption was identified. On the contrary of the prior measure, this one concerns the value of the stand-by speed, currently set to 0.2 m/s. Indeed, when the escalator is unused, it is possible to stop it by using specific sensors designed by Thyssenkrupp that is the manufacturer of the escalators installed in PdG-L3. These sensors consist of radar devices that allow the escalator to start only when passengers are detected at the entrance of escalator. In this way, the consumption of the escalator is reduced also in the period of stand-by.

6.3.2. Saving potentials

The analysis of the energy savings achievable by optimizing the operating speed of the escalators according to the predicted use was carried out through a model developed in Dymola code. A first release of the model allowed to simulate the dynamic behaviour of the escalator managed with an optimized control policy. The core of the control policy proposed is based on setting the operating speed of the escalator at lower value than the rated one (i.e. 0.5 m/s) when conditions of low traffic are predicted through the use of the CCTV system. The manufacturer of the escalator installed in PdG-L3, that is Thyssenkrupp, limited the lower value of escalators' speed under-load at 0.4 m/s. So, the Dymola model was used to simulate the escalator running at 0.4 m/s instead of 0.5 m/s during times of low passenger density. Figure 40 shows the outputs of the first release of the escalator model. In this figure, the current power absorbtion is compared with the power that would be absorbed by the escalator managed according to the aforementioned control policy. The saving potentials calculated for the two escalators in PdG-L3 by using the Dymola model is more than 13% referring to the escalators' consumption. Details about the final release of the model and the final estimation of the energy savings will be presented in D3.2.2 and D6.3 respectively.

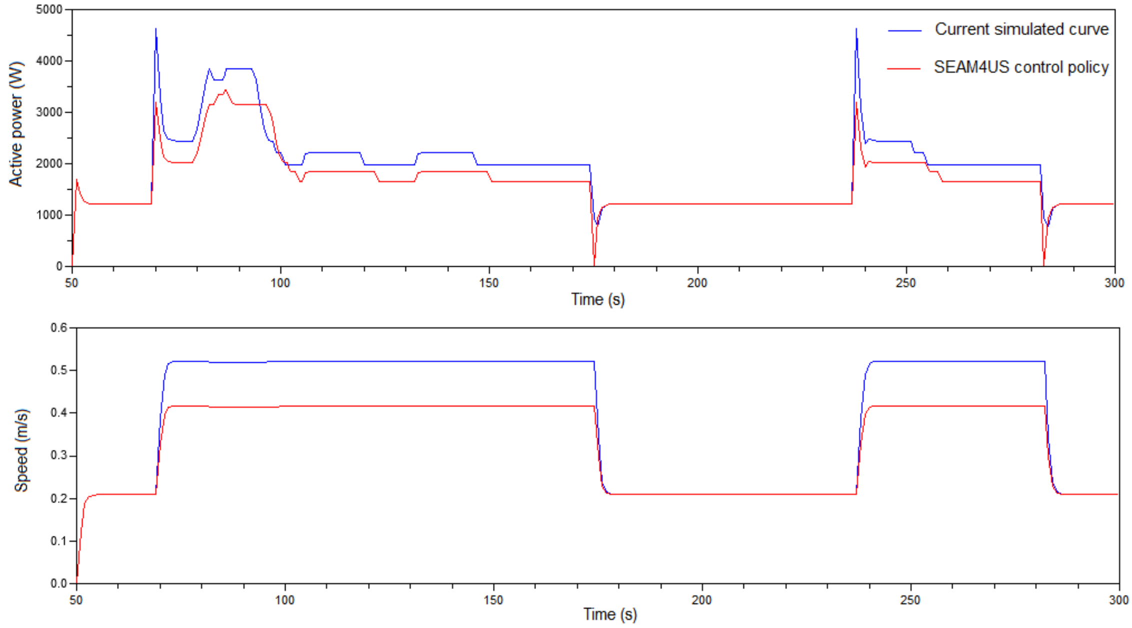


Figure 40. Outputs of the first release of the escalator model in Dymola.

6.4. Other equipment

As described above, the SEAM4US dynamic control system focused on lighting, ventilation and escalators, which represent about the 60% of the annual consumption in PdG-L3. The remaining part is mainly due to the backlit advertising panels, vending machines and systems for telecommunication inside the station, as shown in section 4.3. Some of them (i.e. the telecommunication systems) are out of the project scope. Indeed, a considerable part of the remaining percentage of annual consumption, that is approximately the 21%, includes equipment (e.g. vending machines and televisions) which can be easily controlled through a timer set. These equipment can be therefore controlled through demand-driven policies. For example, it was observed in the energy surveys that the backlit advertising panels and the vending machines, which consumes about the 14% of the annual energy of PdG-L3, was kept on even when the station was closed. So, these equipment could be switched off at night by using timers. Considering the operating condition of PdG-L3 described in section 4.1 and the power measurements reported in section 4.3, the energy saving achievable by means of this simple action was estimated to be about the 16% referring to the load category's consumption.

7. CONCLUSIONS

This deliverable marks the end of the energy auditing in the pilot station of Passeig de Gracia – Line 3. The process required two iterative stages. The first of them was mainly aimed to collect geometrical, technical and operational information regarding the station building and the equipment included. This phase of the audit is reported in the D3.1.1 which also provides a preliminary picture of both the environmental and energetic performances of the station. Furthermore, an analysis of the inefficiencies and a preliminary investigation about the possible strategies for the energy savings were included in the D3.1.1.

In the second and final phase of the energy audit, the information earlier collected was more detailed and the analysis of the possible strategies for achieving savings was refined (@ Section 6). Moreover, comprehensive energy surveys were performed in this final stage of the process and the present report provides detailed measures of the electrical parameters for all the loads in PdG-L3 (@ Section 4). In this deliverable, the consumption baseline of the station's main systems, i.e. lighting, ventilation and escalators, was computed on the basis of the continuous power measures recorded by the energy monitoring network deployed in PdG-L3 (@ Section 5). Finally, the saving potentials for each of the aforementioned systems were estimated by using the models developed (@ Section 6).

Two energy surveys were performed in PdG-L3 for the second stage of the audit, one in winter and the other in summer. In these surveys, the electrical parameters were measured for all the circuits of the station using portable instruments. This allowed to elaborate a comprehensive analysis of the PdG-L3 annual consumption, which was estimated to be about 600 ± 5 MWh/year. That analysis pointed out that the lighting, ventilation and escalators absorb about the 60% of overall annual consumption of the station. It also emerged that other significant consumptions in PdG-L3 are due to the backlit advertising panels and the telecommunication system (@ Section 4.3).

The consumption baselines were computed for each of the main station's systems. The calculation was carried out using the power data recorded continuously by the energy monitoring network over a suitable period of measurement. The consumption baselines were specified as average values of power over the period of observation. As for what concerns the ventilation system, two different baselines were defined according to the two operating speeds of the fans. In the wintertime, when the two fans in the station are set on the low operating speed, the baseline was calculated to be 2423 ± 23 VA for a fan and 2514 ± 30 VA for the other one. Instead, when the fans operate at the high speed, the average values of power over the period of measurement were 11205 ± 70 VA and 12042 ± 99 VA (@ Section 5.1.3). The consumption baseline for the lighting was evaluated for the lighting pilot that involves only two areas of the station, i.e. the platform PL3:S2 and the hall HN2 (and the close corridor CNm). The average values of power for these areas was calculated to be respectively 4442 ± 5 VA and 5701 ± 16 VA (@ Section 5.2.3). Finally, the consumption baseline for the two escalators in PdG-L3 was computed to be 2492 ± 47 W and 2100 ± 62 W (@ section 5.3.3).

In addition to what is described above, an updated analysis of inefficiencies and an improved investigation of control strategies for achieving savings were carried out and reported in this deliverable. For the ventilation system, three main inefficiencies emerged, as listed below:

- airflow rates for which the fans were selected are not required continuously and to leave the fans operating as if they were is a waste of energy;
- there is no ventilation monitoring system provided by the fans, so the air supply rate determined by design is not verified and the estimation of the induced air ventilation rate is also quite rough;
- the current control system is set to perform two-step adjustment of the fan speed, which is used just for varying its rate between the summer and winter seasons. Therefore, such a technical approach is just used for a seasonal scheduling but it is not used to adjust ventilation rates according to real user needs and internal environmental needs.

On the basis of these considerations, the scenarios proposed for achieving the energy savings are the following ones:

- real-time control of the airflow rates in the station through the installation of an environmental monitoring network;
- setting up a system for accurate control of actual fan performances;
- integrating the currently available fan's local control in order to achieve on-the-run speed variation potentials and, possibly, continuous speed control.

For the lighting system the main problem emerging was the absence of a control system in the station's current configuration, hence it is impossible to use whatever type of system operation optimization feature (user based schedule, lamp lifecycle exploitation and so on). Furthermore, a number of additional inefficiencies emerged:

- a recurring "over-lighting" status occurring in a number of station spaces;
- non optimal reflectivity factors on many surfaces of the internal environments;
- non optimal maintenance policy.

On the basis of these considerations, the possible strategies emerging are:

- improving lighting design (in terms of sources and luminaries);
- automatic control.

However, as the focus of the project is investigating the saving achievable through energy control systems, attention was aimed mainly at identifying possible scenarios for the automatic control of the lighting system. Nevertheless, as the lighting control system was not available, and equipping the current lighting system (using T8 fluorescent luminaries) with an automatic control system would in any case require a lot of design and installation work, it was considered reasonable to also investigate the possibility of having a lighting pilot using a more updated lighting technology; easier to integrate in a control system. Thus, after a survey regarding the technologies available, some simulation analysis were performed to define possible alternative scenarios for the lighting pilot, using T5 fluorescent lamps and LED lamps. The baseline for the three possible scenarios (T8, T5 and LED) was defined and a comparison between them was performed considering simulation-based performances, potential savings and technical constraints. It emerged that both T5 and LED technologies would be theoretically suitable for investigation, even if the deployment of a control systems on LED luminaires could be more efficient. This investigation phase was conducted with the expert consultancy of two commercial lighting companies, one for T5 and one for LED. After this first phase, only the LED-related company offered its sponsorship. Thus, so far, only the LED scenario was deployed in the lighting pilot in PdG-L3.

Finally, the main inefficiency emerged for the escalators is that these devices are subjected to a two step mode, in a wide speed variation, various times a day and without considering the actual number of people transported. Therefore, the strategy proposed for reducing the energy consumption of the escalators is the modification of the rated speed with the aim of optimizing it according to the actual number of passengers.

The energy savings was estimated for each of the main systems by using first releases of the models developed (the final version of the models will be presented in the D3.2.2). As for what concerns the ventilation system, the preliminary simulation demonstrates that the relative energy consumption can be reduced by as much as 21% maintaining almost the original comfort conditions. For the lighting system, the simulation pointed out that the relative saving obtainable through dimming control in the pilot (not considering the saving achievable by the T8 tubes replacement with LED lamps) is about 32%. Finally, the relative saving potential calculated for the two escalators in PdG-L3 by using the simulator is more than 13%.

APPENDIX A. LIGHTING PERFORMANCE

Figures in this section show a comparison among the minimum illuminance levels on the horizontal plane required by regulations (background colors) and the illuminance levels measured in the survey (in blue).

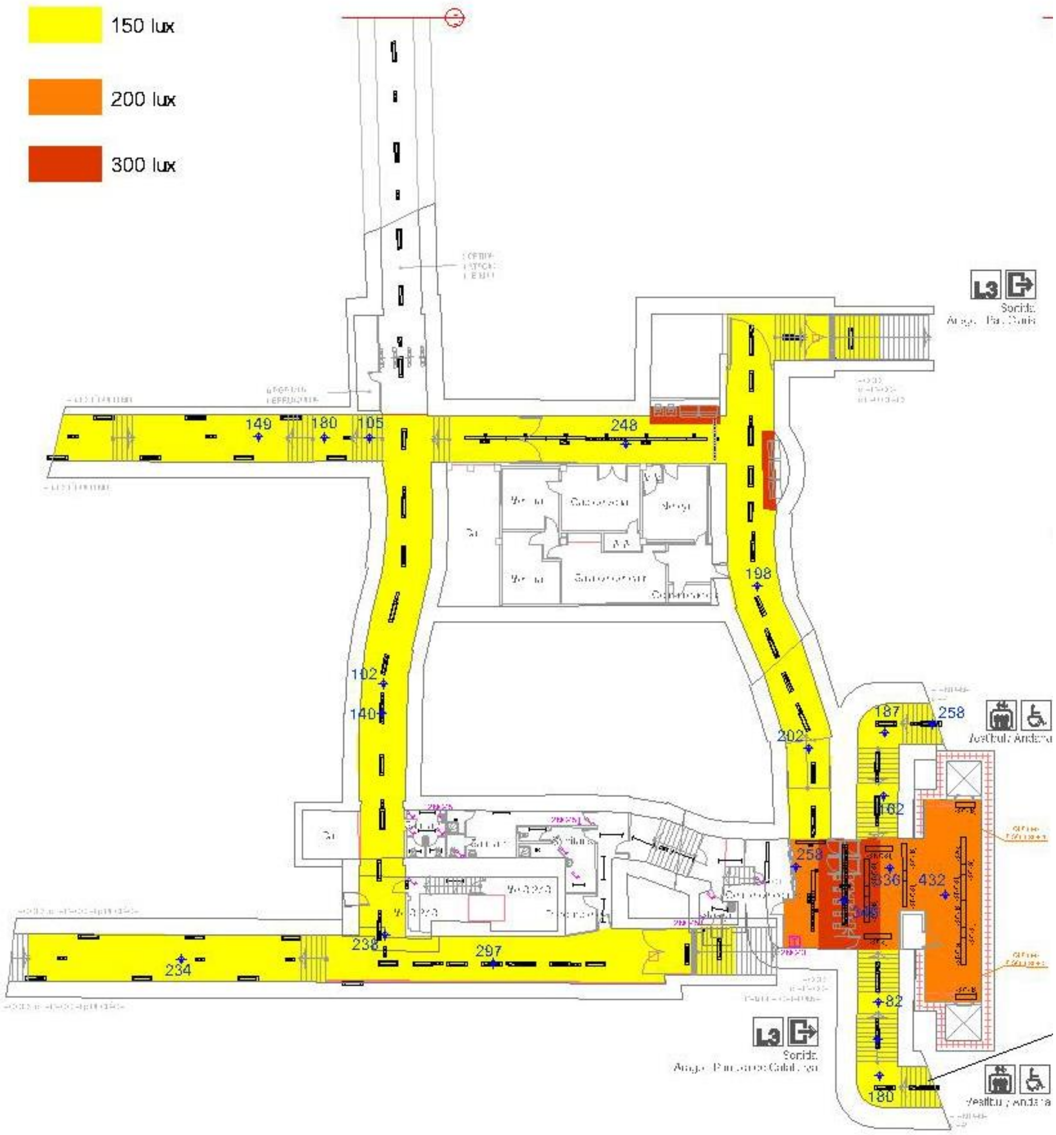


Figure 41. Lighting and regulations comparison 1/4.

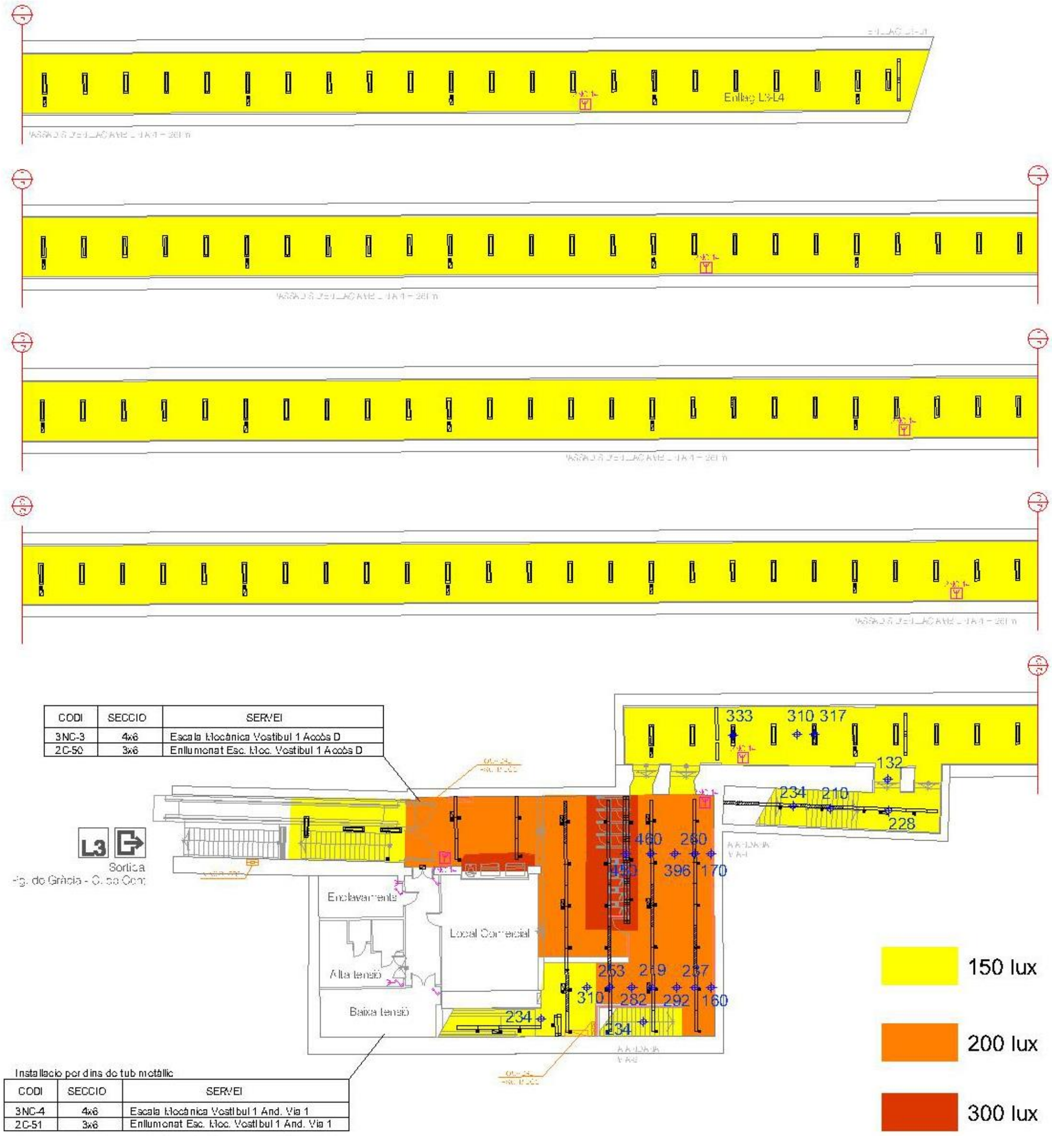


Figure 42. Lighting and regulations comparison 2/4.

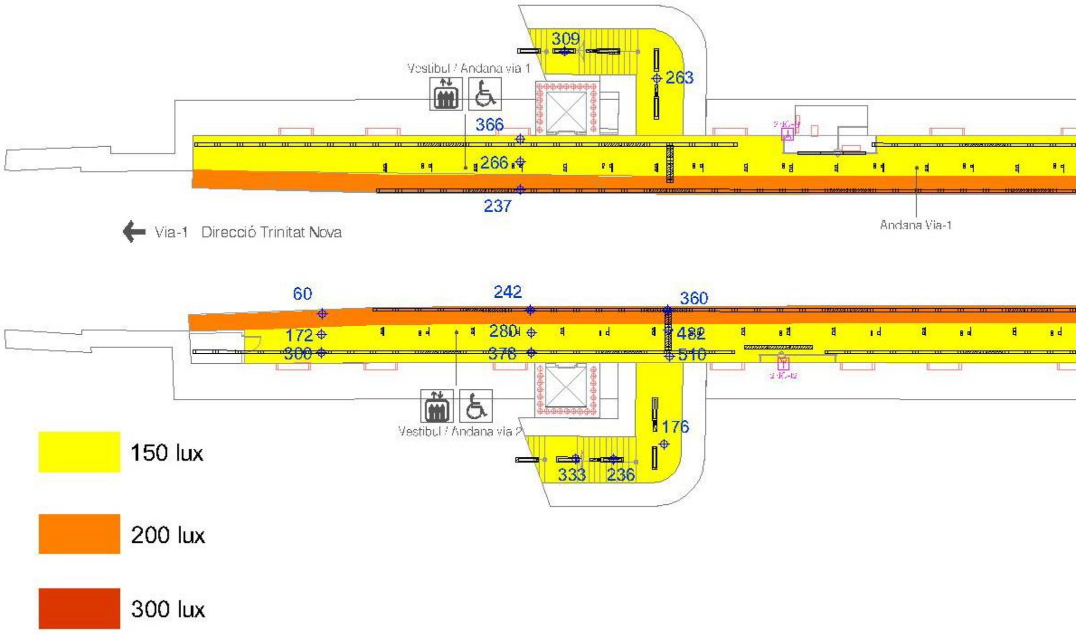
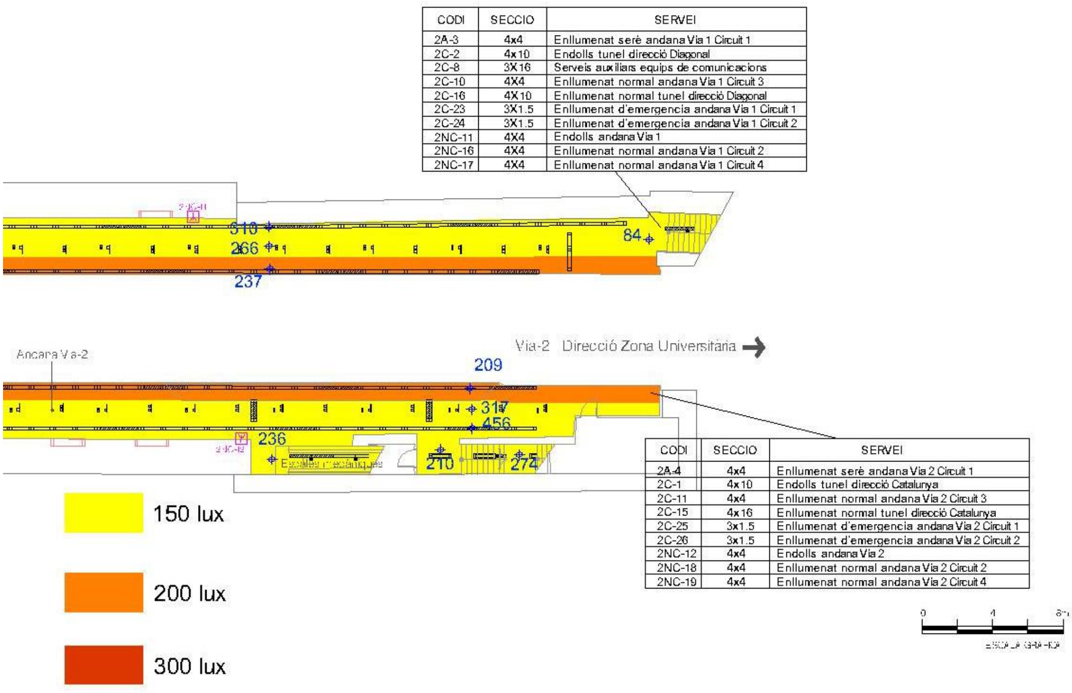


Figure 43. Lighting and regulations comparison 3/4.



CODI	SECCIO	SERVEI
2A-3	4x4	Enllumenat serè andana Via 1 Circuit 1
2C-2	4x10	Endolls tunel direcció Diagonal
2C-8	3X16	Serveis auxiliars equips de comunicacions
2C-10	4X4	Enllumenat normal andana Via 1 Circuit 3
2C-16	4X10	Enllumenat normal tunel direcció Diagonal
2C-23	3X1.5	Enllumenat d'emergencia andana Via 1 Circuit 1
2C-24	3X1.5	Enllumenat d'emergencia andana Via 1 Circuit 2
2NC-11	4X4	Endolls andana Via 1
2NC-16	4X4	Enllumenat normal andana Via 1 Circuit 2
2NC-17	4X4	Enllumenat normal andana Via 1 Circuit 4

CODI	SECCIO	SERVEI
2A-4	4x4	Enllumenat serè andana Via 2 Circuit 1
2C-1	4x10	Endolls tunel direcció Catalunya
2C-11	4x4	Enllumenat normal andana Via 2 Circuit 3
2C-15	4x16	Enllumenat normal tunel direcció Catalunya
2C-25	3x1.5	Enllumenat d'emergencia andana Via 2 Circuit 1
2C-26	3x1.5	Enllumenat d'emergencia andana Via 2 Circuit 2
2NC-12	4x4	Endolls andana Via 2
2NC-18	4x4	Enllumenat normal andana Via 2 Circuit 2
2NC-19	4x4	Enllumenat normal andana Via 2 Circuit 4

Figure 44. Lighting and regulations comparison 4/4.

APPENDIX B. ENERGY SURVEYS DATA.

This appendix shows the measurements carried out during the winter and summer surveys and the calculation of daily, weekly and seasonal energy consumption on the basis of the loads operating conditions and calculation assumptions described in section 4.

B.1. Energy surveys measurement

The tables provided in this section show the measurements of currents and power factors performed during the winter (from the 12th to the 14th of February, 2013) and the summer (from the 15th to the 18th of July, 2013) surveys conducted in the final stage of the energy audit. In addition to the currents and power factors measures, the tables below provides the calculations of the active power for each of the loads. All the measures and calculated values are provided with their uncertainty evaluated according to the GUM, as described in Appendix C.

Table 17. Winter survey measurement and power calculation.

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
2A-1	Input	Low voltage (220 V) company connection	22.2	0.5	20.9	0.5	21.5	0.5	0.990	0.001	8.123	0.338
2A-2	Others	Signalling	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
2A-3	Lighting	Night-watch lighting Circuit 1 Platform 1	3.5	0.3	3.8	0.3	4.0	0.3	0.990	0.001	1.421	0.184
2A-4	Lighting	Night-watch lighting Circuit 1 Platform 2	5.1	0.3	4.7	0.3	3.1	0.3	0.960	0.001	1.573	0.185
2A-5	Lighting	Night-watch lighting Circuit 1 Hall 0	4.8	0.3	4.9	0.3	5.3	0.3	0.990	0.001	1.886	0.194
2A-6	Lighting	Night-watch lighting Circuit 1 Hall 1	2.0	0.3	2.2	0.3	1.4	0.3	0.950	0.001	0.676	0.165
2A-7	Lighting	Night-watch lighting Circuit 1 Corridor	5.5	0.4	5.5	0.4	6.1	0.4	0.970	0.001	2.107	0.195
2A-8	Others	New transformer feed	5.3	0.3	4.2	0.3	3.7	0.3	0.920	0.001	1.542	0.179
3C-1	Elevators	Elevator 1	-								n/a	n/a
3C-2	Elevators	Elevator 2	-								n/a	n/a

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
2C-1	Others	Sockets. Tunnel to Catalunya	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-2	Others	Sockets. Tunnel to Diagonal	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-3	Air Conditioning	AC Signalling	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
2C-4	Others	Auxiliary services TS/LT rooms	0.6	0.3	0.6	0.3	0.0	0.3	0.540	0.000	0.085	0.088
2C-5	Others	Auxiliary services isolator switch room	0.8	0.3	0.7	0.3	0.0	0.3	0.650	0.000	0.127	0.107
2C-6	Lighting	Auxiliary services switch point	0.3	0.3	-	-	-	-	0.420	0.000	0.028	0.092
2C-7	Others	Auxiliary services station chief	1.7	0.3	-	-	-	-	0.540	0.000	0.202	0.124
2C-8	Others	Auxiliary services communication equipment	2.0	0.3	-	-	-	-	0.360	0.000	0.158	0.084
2C-9	Lighting	Regular lighting staff rooms	4.6	0.3	2.3	0.3	1.4	0.3	0.780	0.000	0.822	0.144
2C-10	Lighting	Regular lighting Circuit 3 Platform 1	2.9	0.3	3.6	0.3	3.4	0.3	0.990	0.001	1.245	0.181
2C-11	Lighting	Regular lighting Circuit 3 Platform 2	3.7	0.3	3.6	0.3	3.4	0.3	0.990	0.001	1.345	0.184
2C-12	Lighting	Regular lighting Circuit 3 Hall 0	5.4	0.4	4.9	0.3	3.1	0.3	0.990	0.001	1.685	0.193
2C-13	Lighting	Regular lighting Circuit 3 Hall 1	5.9	0.4	8.3	0.4	3.1	0.3	0.990	0.001	2.175	0.201
2C-14	Lighting	Regular lighting Circuit 3 Corridor	5.2	0.3	4.6	0.3	5.2	0.3	0.990	0.001	1.886	0.195
2C-15	Lighting	Regular lighting Tunnel 1 to Catalunya	0.0	0.3	0.0	0.3	0.3	0.0	0.000	0.000	0.000	0.000
2C-16	Lighting	Regular lighting Tunnel 2 to Diagonal	0.0	0.3	0.0	0.3	0.3	0.0	0.000	0.000	0.000	0.000
2C-15	Lighting	Regular lighting Tunnel 1 to Catalunya (in the night time)	-	-	-	-	-	-	-	-	2.000	0.000
2C-16	Lighting	Regular lighting Tunnel 2 to Diagonal (in the night time)	-	-	-	-	-	-	-	-	1.680	0.000
2C-17	Validation machines	Validation machines Hall 0	0.7	0.3	1.0	0.3	0.4	0.3	0.8	0.0	0.219	0.136
2C-18	Validation machines	Validation machines Hall 1	0.6	0.3	0.7	0.3	0.6	0.3	0.8	0.0	0.198	0.135
2C-19	Ticket machines	Ticket machines Circuit 1 Hall 0	1.7	0.3	-	-	-	-	0.320	0.000	0.120	0.074
2C-20	Ticket machines	Ticket machines Circuit 2 Hall 0	0.7	0.3	-	-	-	-	0.370	0.000	0.057	0.082

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	cosφ	$\pm u_{cos\varphi}$	P	$\pm u_P$
2C-21	Ticket machines	Ticket machines Circuit 1 Hall 1	1.0	0.3	-	-	-	-	0.383	0.000	0.084	0.086
2C-22	Ticket machines	Ticket machines Circuit 2 Hall 1	1.7	0.3	-	-	-	-	0.383	0.000	0.143	0.088
2C-23	Lighting	Emergency lighting Circuit 1 Platform 1	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-24	Lighting	Emergency lighting Circuit 2 Platform 1	0.2	0.3	-	-	-	-	0.550	0.000	0.019	0.119
2C-25	Lighting	Emergency lighting Circuit 1 Platform 2	0.2	0.3	-	-	-	-	0.540	0.000	0.020	0.117
2C-26	Lighting	Emergency lighting Circuit 2 Platform 2	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-27	Lighting	Emergency lighting Circuit 1 Hall 0	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-28	Lighting	Emergency lighting Circuit 2 Hall 0	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-29	Lighting	Emergency lighting Circuit 1 Hall 1	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-30	Lighting	Emergency lighting Circuit 2 Hall 1	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-31	Lighting	Emergency lighting Circuit 1 Corridor	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-32	Lighting	Emergency lighting Circuit 2 Corridor	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-33	Lighting	Emergency lighting Staff rooms	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-34	Lighting	Emergency lighting technical rooms	0.2	0.3	-	-	-	-	0.540	0.000	0.018	0.117
2C-35	Lighting	Regular lighting technical rooms	1.0	0.3	1.1	0.3	0.0	0.3	0.970	0.001	0.260	0.161
2C-36	Others	Sockets technical rooms	0.0	0.3	-	-	-	-	0.270	0.000	0.000	0.000
2C-37	Others	Box office	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
2C-38	Others	Auxiliary services new communication chamber	12.3	0.4	-	-	-	-	0.380	0.000	1.028	0.124
2C-39	Air Conditioning	AC new communications chamber	0.0	0.3	-	-	-	-	0.560	0.000	0.000	0.000
2C-40	Others	Fans and Pumps manoeuvre	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-41	Others	Station chief manoeuvre box	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-42	Lighting	Regular lighting parallel tunnel to	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
		Catalunya										
2C-43	Others	Management lighting and Power	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
2C-44	Others	Signalling	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-45	Ticket machines	Ticket machines Circuit 3 Hall 0	1.6	0.3	-	-	-	-	0.470	0.000	0.165	0.108
2C-46	Ticket machines	Ticket machines Circuit 4 Hall 0	1.5	0.3	-	-	-	-	0.370	0.000	0.122	0.085
2C-47	Air Conditioning	AC Signalling	0.0	0.3	-	-	-	-	0.570	0.000	0.000	0.000
2C-48	Air Conditioning	AC Signalling	0.0	0.3	-	-	-	-	0.540	0.000	0.000	0.000
2C-49	Others	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-50	Lighting	Escalator's lighting Hall 1 Access D	1.2	0.3	-	-	-	-	0.780	0.000	0.206	0.176
2C-51	Lighting	Escalator's lighting Hall 1 platform 1	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
2C-52	Others	220 Critic feed	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-53	Lighting	Elevator C1	0.9	0.3	-	-	-	-	0.780	0.000	0.154	0.174
2C-54	Lighting	Elevator C2	1.0	0.3	-	-	-	-	0.780	0.000	0.172	0.175
2C-55	Others	Fire control panel	0.2	0.3	-	-	-	-	0.000	0.000	0.000	0.000
3NC-1	Input	LV 6kV/380V Transformer entry	22.2	0.5	26.5	0.6	19.3	0.5	0.910	0.001	13.576	0.542
3NC-2	Telecommunication system	-	12.4	0.4	17.6	0.5	10.2	0.4	0.900	0.001	7.938	0.408
3NC-3	Escalators	Escalator Hall 1 Access D	-								n/a	n/a
3NC-4	Escalators	Escalator Hall 1 Platform 1	-								n/a	n/a
3NC-5	Others	Critic 380V feed	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2NC-1	Input	LV 6KV/220V Transformer entry	144.0	2.0	143.0	1.9	112.0	1.6	0.970	0.001	49.159	1.399
2NC-2	Ventilation	Station ventilation 1	7.6	0.4	7.5	0.4	6.6	0.4	0.940	0.001	2.591	0.202
2NC-3	Ventilation	Station ventilation 2	8.3	0.4	8.2	0.4	7.4	0.4	0.940	0.001	2.854	0.208
2NC-4	Sub Input	Concession switch board	50.7	0.9	50.3	0.9	43.7	0.8	0.850	0.000	15.622	0.508
2NC-5	Others	Bar 1 Concession	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
2NC-6	Others	Bar 2 Concession	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-7	Others	Reserved	0.2	0.3	0.2	0.3	0.2	0.3	0.950	0.001	0.072	0.154
2NC-8	Others	Reserved	0.3	0.3	0.2	0.3	0.3	0.3	0.950	0.001	0.097	0.154
2NC-9	Others	Septic shaft	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-10	Air Conditioning	Air conditioning station chief	0.0	0.3	-	-	-	-	0.480	0.000	0.000	0.000
2NC-11	Others	Sockets platform 1	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-12	Others	Sockets platform 2	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-13	Others	Sockets Hall 0	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-14	Others	Sockets Hall 1	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-15	Others	Sockets staff rooms	0.0	0.3	0.0	0.3	0.0	0.3	0.710	0.000	0.000	0.000
2NC-16	Lighting	Regular lighting Circuit 2 Platform 1	3.2	0.3	2.8	0.3	2.6	0.3	0.970	0.001	1.060	0.176
2NC-17	Lighting	Regular lighting Circuit 4 Platform 1	2.6	0.3	2.5	0.3	3.4	0.3	0.960	0.001	1.036	0.172
2NC-18	Lighting	Regular lighting Circuit 2 Platform 2	2.6	0.3	2.9	0.3	3.1	0.3	0.970	0.001	1.060	0.174
2NC-19	Lighting	Regular lighting Circuit 4 Platform 2	3.5	0.3	2.2	0.3	4.0	0.3	0.930	0.001	1.146	0.171
2NC-20	Lighting	Regular lighting Circuit 2 Hall 0	4.2	0.3	3.9	0.3	4.3	0.3	0.980	0.001	1.544	0.186
2NC-21	Lighting	Regular lighting Circuit 4 Hall 0	3.2	0.3	2.8	0.3	3.5	0.3	0.960	0.001	1.158	0.175
2NC-22	Lighting	Regular lighting Circuit 2 Hall 1	2.2	0.3	1.8	0.3	1.7	0.3	0.970	0.001	0.702	0.169
2NC-23	Lighting	Regular lighting Circuit 4 Hall 1	1.3	0.3	1.5	0.3	0.3	0.3	0.780	0.000	0.307	0.131
2NC-24	Lighting	Regular lighting Circuit 2 Corridor	5.1	0.3	5.2	0.3	5.1	0.3	0.980	0.001	1.917	0.193
2NC-25	Lighting	Regular lighting Circuit 4 Corridor	6.5	0.4	3.8	0.3	6.0	0.4	0.940	0.001	1.946	0.190
2NC-26	Others	Signalling	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-27	Air Conditioning	Air conditioning L3 management	3.1	0.3	-	-	-	-	0.490	0.000	0.334	0.119
2NC-28	Lighting	Resting room Base Station hall NMO	3.6	0.3	2.9	0.3	0.7	0.3	0.590	0.000	0.540	0.106
-	Backlit advertising panels	-	6.1	0.4	11.9	0.4	14.3	0.5	0.730	0.000	2.995	0.170

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	cosφ	$\pm u_{cos\varphi}$	P	$\pm u_P$
-	Backlit advertising panels	-	0.0	0.3	3.7	0.3	3.7	0.3	0.610	0.000	0.573	0.105
-	Backlit advertising panels /Vending machines	Concessionaires Platform 1	10.0	0.4	9.2	0.4	4.8	0.3	0.720	0.000	2.195	0.162
-	Backlit advertising panels /Vending machines	Concessionaires halls	3.4	0.3	5.4	0.4	4.5	0.3	0.640	0.000	1.081	0.121
-	Backlit advertising panels /Vending machines	Concessionaires halls	11.0	0.4	14.2	0.5	9.7	0.4	0.780	0.000	3.458	0.195
-	Others	Concessionaires Platform 2	8.8	0.4	2.9	0.3	7.9	0.4	0.710	0.000	1.768	0.152
-	Photo booths	-	1.4	0.3	-	-	-	-	0.500	0.000	0.154	0.114
-	Televisions	PC news	0.6	0.3	-	-	-	-	0.490	0.000	0.065	0.108
-	Televisions	AD news	3.8	0.3	-	-	-	-	0.500	0.000	0.418	0.124
-	Others	-	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
-	Others	-	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000
-	Others	-	0.0	0.3	-	-	-	-	0.000	0.000	0.000	0.000

Table 18. Summer survey measurement and power calculation.

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	cosφ	$\pm u_{cos\varphi}$	P	$\pm u_P$
2A-1	Input	Low voltage (220 V) company connection	21.5	0.5	20.5	0.5	21.0	0.5	0.990	0.001	7.922	0.332
2A-2	Others	Signalling	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
2A-3	Lighting	Night-watch lighting Circuit 1 Platform 1	3.4	0.3	3.8	0.3	4.0	0.3	0.990	0.001	1.408	0.184
2A-4	Lighting	Night-watch lighting Circuit 1 Platform 2	5.1	0.3	4.7	0.3	2.9	0.3	0.960	0.001	1.549	0.185

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
2A-5	Lighting	Night-watch lighting Circuit 1 Hall 0	4.6	0.3	4.8	0.3	5.1	0.3	0.990	0.001	1.823	0.193
2A-6	Lighting	Night-watch lighting Circuit 1 Hall 1	2.1	0.3	2.3	0.3	1.4	0.3	0.950	0.001	0.700	0.165
2A-7	Lighting	Night-watch lighting Circuit 1 Corridor	5.0	0.3	5.1	0.3	5.6	0.4	0.970	0.001	1.934	0.192
2A-8	Others	New transformer feed	5.5	0.4	4.1	0.3	3.8	0.3	0.920	0.001	1.566	0.179
3C-1	Elevators	Elevator 1	widely variable								0.448[19]	0.009
3C-2	Elevators	Elevator 2	widely variable								0.448[20]	0.009
2C-1	Others	Sockets. Tunnel to Catalunya	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-2	Others	Sockets. Tunnel to Diagonal	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-3	Air Conditioning	AC Signalling	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
2C-4	Others	Auxiliary services TS/LT rooms	3.3	0.3	3.0	0.3	2.7	0.3	0.540	0.000	0.617	0.098
2C-5	Others	Auxiliary services isolator switch room	0.8	0.3	0.7	0.3	0.0	0.3	0.650	0.000	0.124	0.107
2C-6	Lighting	Auxiliary services switch point	0.4	0.3	-	0.0	-	0.0	0.420	0.000	0.037	0.092
2C-7	Others	Auxiliary services station chief	1.2	0.3	-	0.0	-	0.0	0.540	0.000	0.143	0.122
2C-8	Others	Auxiliary services communication equipment	2.2	0.3	-	0.0	-	0.0	0.360	0.000	0.174	0.084
2C-9	Lighting	Regular lighting staff rooms	3.7	0.3	1.5	0.3	4.6	0.3	0.780	0.000	0.971	0.144
2C-10	Lighting	Regular lighting Circuit 3 Platform 1	3.9	0.3	3.6	0.3	4.1	0.3	0.990	0.001	1.459	0.186
2C-11	Lighting	Regular lighting Circuit 3 Platform 2	3.5	0.3	3.4	0.3	4.5	0.3	0.990	0.001	1.434	0.185
2C-12	Lighting	Regular lighting Circuit 3 Hall 0	4.8	0.3	4.3	0.3	3.1	0.3	0.990	0.001	1.534	0.189
2C-13	Lighting	Regular lighting Circuit 3 Hall 1	6.4	0.4	8.4	0.4	3.0	0.3	0.990	0.001	2.238	0.203
2C-14	Lighting	Regular lighting Circuit 3 Corridor	6.3	0.4	4.3	0.3	4.3	0.3	0.990	0.001	1.874	0.198
2C-15	Lighting	Regular lighting Tunnel 1 to Catalunya	0.0	0.3	0.0	0.3	0.3	0.0	0.000	0.000	0.000	0.000

[19] Average value; it was assumed to be the same as the average power measured on circuit 3C-1.
[20] Average value in the period of measurement (that was from the 2:30 pm to midnight in a day of the summer survey).

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	cosφ	$\pm u_{cos\varphi}$	P	$\pm u_P$
2C-16	Lighting	Regular lighting Tunnel 2 to Diagonal	0.0	0.3	0.0	0.3	0.3	0.0	0.000	0.000	0.000	0.000
2C-15	Lighting	Regular lighting Tunnel 1 to Catalunya (in the night time)	-	-	-	-	-	-	-	-	2.000	0.000
2C-16	Lighting	Regular lighting Tunnel 2 to Diagonal (in the night time)	-	-	-	-	-	-	-	-	1.680	0.000
2C-17	Validation machines	Validation machines Hall 0	0.7	0.3	0.8	0.3	0.7	0.3	0.8	0.0	0.229	0.136
2C-18	Validation machines	Validation machines Hall 1	0.7	0.3	0.8	0.3	0.7	0.3	0.8	0.0	0.229	0.136
2C-19	Ticket machines	Ticket machines Circuit 1 Hall 0	1.0	0.3	-	0.0	-	0.0	0.320	0.000	0.070	0.072
2C-20	Ticket machines	Ticket machines Circuit 2 Hall 0	0.8	0.3	-	0.0	-	0.0	0.370	0.000	0.065	0.082
2C-21	Ticket machines	Ticket machines Circuit 1 Hall 1	1.0	0.3	-	0.0	-	0.0	0.383	0.000	0.084	0.086
2C-22	Ticket machines	Ticket machines Circuit 2 Hall 1	0.6	0.3	-	0.0	-	0.0	0.383	0.000	0.050	0.084
2C-23	Lighting	Emergency lighting Circuit 1 Platform 1	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-24	Lighting	Emergency lighting Circuit 2 Platform 1	0.2	0.3	-	0.0	-	0.0	0.550	0.000	0.024	0.120
2C-25	Lighting	Emergency lighting Circuit 1 Platform 2	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-26	Lighting	Emergency lighting Circuit 2 Platform 2	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-27	Lighting	Emergency lighting Circuit 1 Hall 0	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-28	Lighting	Emergency lighting Circuit 2 Hall 0	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-29	Lighting	Emergency lighting Circuit 1 Hall 1	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-30	Lighting	Emergency lighting Circuit 2 Hall 1	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-31	Lighting	Emergency lighting Circuit 1 Corridor	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-32	Lighting	Emergency lighting Circuit 2 Corridor	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-33	Lighting	Emergency lighting Staff rooms	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117
2C-34	Lighting	Emergency lighting technical rooms	0.1	0.3	-	0.0	-	0.0	0.540	0.000	0.012	0.117

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
2C-35	Lighting	Regular lighting technical rooms	2.0	0.3	2.0	0.3	0.0	0.3	0.970	0.001	0.493	0.166
2C-36	Others	Sockets technical rooms	0.3	0.3	-	0.0	-	0.0	0.270	0.000	0.018	0.059
2C-37	Others	Box office	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
2C-38	Others	Auxiliary services new communication chamber	12.0	0.4	-	0.0	-	0.0	0.380	0.000	1.003	0.121
2C-39	Air Conditioning	AC new communications chamber	9.2	0.4	-	0.0	-	0.0	0.560	0.000	1.133	0.165
2C-40	Others	Fans and Pumps manoeuvre	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-41	Others	Station chief manoeuvre box	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-42	Lighting	Regular lighting parallel tunnel to Catalunya	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2C-43	Others	Management lighting and Power	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
2C-44	Others	Signalling	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-45	Ticket machines	Ticket machines Circuit 3 Hall 0	0.7	0.3	-	0.0	-	0.0	0.470	0.000	0.072	0.104
2C-46	Ticket machines	Ticket machines Circuit 4 Hall 0	1.5	0.3	-	0.0	-	0.0	0.370	0.000	0.122	0.085
2C-47	Air Conditioning	AC Signalling	19.8	0.5	-	0.0	-	0.0	0.570	0.000	2.483	0.220
2C-48	Air Conditioning	AC Signalling	0.2	0.3	-	0.0	-	0.0	0.540	0.000	0.024	0.117
2C-49	Others	-	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2C-50	Lighting	Escalator's lighting Hall 1 Access D	1.2	0.3	-	0.0	-	0.0	0.780	0.000	0.206	0.176
2C-51	Lighting	Escalator's lighting Hall 1 platform 1	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
2C-52	Others	220 Critic feed	1.8	0.3	1.0	0.3	1.0	0.3	0.820	0.000	0.396	0.140
2C-53	Lighting	Elevator C1	0.9	0.3	-	0.0	-	0.0	0.780	0.000	0.154	0.174
2C-54	Lighting	Elevator C2	1.0	0.3	-	0.0	-	0.0	0.780	0.000	0.172	0.175
2C-55	Others	Fire control panel	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
3NC-1	Input	LV 6kV/380V Transformer entry	26.0	0.6	32.0	0.7	16.3	0.5	0.910	0.001	14.834	0.579
3NC-2	Telecommunication system	-	15.6	0.5	20.6	0.5	9.6	0.4	0.900	0.001	9.043	0.438

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	$\cos\varphi$	$\pm u_{\cos\varphi}$	P	$\pm u_P$
3NC-3	Escalators	Escalator Hall 1 Access D	widely variable								2.723[21]	0.004
3NC-4	Escalators	Escalator Hall 1 Platform 1	widely variable								1.847[22]	0.031
3NC-5	Others	Critic 380V feed	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2NC-1	Input	LV 6KV/220V Transformer entry	220.0	2.8	218.0	2.8	167.0	2.2	0.970	0.001	74.540	2.068
2NC-2	Ventilation	Station ventilation 1	34.7	0.7	33.0	0.7	34.0	0.7	0.940	0.001	12.143	0.430
2NC-3	Ventilation	Station ventilation 2	38.0	0.7	37.0	0.7	36.0	0.7	0.940	0.001	13.253	0.458
2NC-4	Sub Input	Concession switch board	48.0	0.8	46.0	0.8	40.6	0.8	0.850	0.000	14.532	0.482
2NC-5	Others	Bar 1 Concession	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-6	Others	Bar 2 Concession	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-7	Others	Reserved	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-8	Others	Reserved	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-9	Others	Septic shaft	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-10	Air Conditioning	Air conditioning station chief	5.9	0.4	-	0.0	-	0.0	0.480	0.000	0.623	0.128
2NC-11	Others	Sockets platform 1	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-12	Others	Sockets platform 2	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-13	Others	Sockets Hall 0	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-14	Others	Sockets Hall 1	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-15	Others	Sockets staff rooms	7.2	0.4	0.0	0.3	7.0	0.4	0.710	0.000	1.281	0.143
2NC-16	Lighting	Regular lighting Circuit 2 Platform 1	3.2	0.3	2.9	0.3	2.4	0.3	0.970	0.001	1.047	0.176
2NC-17	Lighting	Regular lighting Circuit 4 Platform 1	2.8	0.3	2.4	0.3	3.5	0.3	0.960	0.001	1.061	0.173
2NC-18	Lighting	Regular lighting Circuit 2 Platform 2	2.8	0.3	2.9	0.3	3.5	0.3	0.970	0.001	1.134	0.176
2NC-19	Lighting	Regular lighting Circuit 4 Platform 2	3.4	0.3	2.0	0.3	4.1	0.3	0.930	0.001	1.122	0.170

[21] Average value in the period of measurement (that was about one day during the opening time of the station).
[22] Average value in the period of measurement (that was about one day during the opening time of the station).

Circuit code	Load category	Circuit description	Phase current (A)						Power factor		Active power (kW)	
			I_1	$\pm u_{I_1}$	I_2	$\pm u_{I_2}$	I_3	$\pm u_{I_3}$	cosφ	$\pm u_{cos\varphi}$	P	$\pm u_P$
2NC-20	Lighting	Regular lighting Circuit 2 Hall 0	4.5	0.3	3.5	0.3	3.7	0.3	0.980	0.001	1.456	0.186
2NC-21	Lighting	Regular lighting Circuit 4 Hall 0	3.3	0.3	3.0	0.3	3.5	0.3	0.960	0.001	1.195	0.176
2NC-22	Lighting	Regular lighting Circuit 2 Hall 1	2.3	0.3	1.7	0.3	1.7	0.3	0.970	0.001	0.702	0.169
2NC-23	Lighting	Regular lighting Circuit 4 Hall 1	1.3	0.3	1.5	0.3	0.3	0.3	0.780	0.000	0.307	0.131
2NC-24	Lighting	Regular lighting Circuit 2 Corridor	5.0	0.3	5.0	0.3	4.9	0.3	0.980	0.001	1.855	0.192
2NC-25	Lighting	Regular lighting Circuit 4 Corridor	6.2	0.4	3.5	0.3	5.9	0.4	0.940	0.001	1.863	0.189
2NC-26	Others	Signalling	0.0	0.3	0.0	0.3	0.0	0.3	0.000	0.000	0.000	0.000
2NC-27	Air Conditioning	Air conditioning L3 management	11.4	0.4	-	0.0	-	0.0	0.490	0.000	1.229	0.154
2NC-28	Lighting	Resting room Base Station hall NMO	3.4	0.3	3.2	0.3	1.2	0.3	0.590	0.000	0.585	0.107
-	Backlit advertising panels	-	7.6	0.4	13.0	0.4	15.2	0.5	0.730	0.000	3.319	0.178
-	Backlit advertising panels	-	0.0	0.3	4.0	0.3	4.0	0.3	0.610	0.000	0.620	0.105
-	Backlit advertising panels /Vending machines	Concessionaires Platform 1	5.6	0.4	13.4	0.4	14.1	0.5	0.720	0.000	3.027	0.169
-	Backlit advertising panels /Vending machines	Concessionaires halls	2.4	0.3	4.7	0.3	4.9	0.3	0.640	0.000	0.975	0.118
-	Backlit advertising panels /Vending machines	Concessionaires halls	5.2	0.3	8.0	0.4	6.6	0.4	0.780	0.000	1.962	0.160
-	Others	Concessionaires Platform 2	12.8	0.4	3.5	0.3	11.8	0.4	0.710	0.000	2.534	0.171
-	Photo booths	-	1.3	0.3	-	0.0	-	0.0	0.500	0.000	0.143	0.113
-	Televisions	PC news	0.5	0.3	-	0.0	-	0.0	0.490	0.000	0.054	0.108
-	Televisions	AD news	3.7	0.3	-	0.0	-	0.0	0.500	0.000	0.407	0.124
-	Others	-	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
-	Others	-	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000
-	Others	-	0.0	0.3	-	0.0	-	0.0	0.000	0.000	0.000	0.000

B.2. Energy consumption calculations

Table 19 shows the calculation of daily, weekly and seasonal consumption for each load according to the operating hours and calculation assumption illustrated in section 4.

Table 19. Calculation of daily, weekly and seasonal consumption for each load category

Load category	Winter					Summer				
	daily (kWh)			weekly (kWh)	seasonal (MWh)	daily (kWh)			weekly (kWh)	seasonal (MWh)
	working day	Saturday	Sunday			working day	Saturday	Sunday		
lighting system	639.5±19.1	674.3±20.9	726.6±23.8	4,598.2±100.6	137.9±3.0	643.5±19.1	678.6±20.9	731.2±23.8	4,627.1±100.70	101.8±2.2
ventilation system	81.7±4.3			571.7±30.4	17.2±0.9	380.9±9.4			2,666.5±65.9	58.7±1.5
escalators[23]	102.7±0.1			718.7±1.0	21.6±0.1	102.7±0.1			718.7±1.0	15.8±0.1
elevators[24]	17.0±0.3			118.9±1.8	3.6±0.1	17.0±0.3			118.9±1.8	2.6±0.1
air conditioning	8.0±1.8			56.1±12.3	1.7±0.4	131.8±5.3			922.7±37.2	20.3±0.8
backlit advertising panels and vending machines	247.2±5.1			1,730.7±35.6	51.9±1.1	237.7±4.9			1,663.8±34.4	36.6±0.8
telecommunication system	190.5±6.0			1,333.5±42.1	40.0±1.3	217.0±6.5			1,519.3±45.58	33.4±1.0
validation machines	7.9±3.6	8.7±4.0	10.0±4.6	58.3±19.2	1.7±0.6	8.7±3.6	9.6±4.0	11.0±4.6	64.2±19.2	1.4±0.4

[23] Daily consumption was evaluated on the basis of the measurement carried out with the analyzer Fluke 435-II during the summer survey on the circuit 3NC-3 from the 5:00 am to the 10:00 pm.

[24] Daily consumption was evaluated on the basis of the measurement carried out with the analyser Fluke 435-II during the summer survey on the circuit 3C-2 from the 2:30 pm to midnight.

Load category	Winter					Summer				
	daily (kWh)			weekly (kWh)	seasonal (MWh)	daily (kWh)			weekly (kWh)	seasonal (MWh)
	working day	Saturday	Sunday			working day	Saturday	Sunday		
ticket machines	13.1±4.1	14.5±4.5	16.6±5.2	96.8±21.5	2.9±0.6	8.8±4.0	9.8±4.4	11.2±5.1	65.0±21.1	1.4±0.5
photo booths	2.9±2.2	3.2±2.4	3.7±2.7	21.6±11.4	0.6±0.3	2.7±2.2	3.0±2.4	3.4±2.7	20.0±11.4	0.4±0.3
televisions	9.2±3.1	10.1±3.5	11.6±4.0	67.6±16.5	2.0±0.5	8.8±3.1	9.7±3.4	11.1±3.9	64.5±16.4	1.4±0.4
others	96.5±7.6	106.7±8.4	121.9±9.6	711.2±40.1	21.3±1.2	149.3±7.7	165.0±8.5	188.5±9.7	1,099.7±40.4	24.2±0.9

APPENDIX C. EVALUATION OF MEASUREMENT UNCERTAINTY

The uncertainties of the electrical parameters, i.e. currents, voltages, power factors and powers, was evaluated according to the JCGM 100:2008 – Guide to the expression of Uncertainty in Measurement (GUM).

The Type B evaluation of uncertainty defined in the GUM was considered for the measures collected during the winter and summer surveys described in section 4, so the measurement uncertainties were calculated considering the instrument data specifications, i.e. the accuracy and resolution. The accuracy of phase current and line voltage is specified in the manual of the clamp meter Fluke 376 as follow:

- For AC current:
    - accuracy = 2% of reading + 5 digit;
    - resolution = 0.1 A.
- For AC voltage:
    - accuracy = 1.5% of reading + 5 digit;
    - resolution = 0.1 V.

Accuracy of power factor is specified in the manual of the analyzer Fluke 435-II as follow:

- accuracy = 0.1% of reading;
- resolution = 0.001 A.

The Type B standard uncertainty u was calculated for the phase currents, the voltage and the power factors assuming a uniform distribution, so it was evaluated according the following relation:

$$u = \frac{accuracy}{\sqrt{3}}$$

The combined uncertainty of the active power u_P was calculated according to the low of error propagation. The active power P has the following expression:

$$P = U \cdot \frac{I_1 + I_2 + I_3}{\sqrt{3}} \cdot \cos\varphi$$

$\mathrm{I_1, I_2, I_3}$ current in each of the phases;
U line voltage;
$\cos\varphi$ power factor.

Therefore, the combined uncertainty of the active power is calculated as follows:

$$u_P = P \cdot \sqrt{\left(\frac{u_U}{U}\right)^2 + \left(\frac{u_{\cos\varphi}}{\cos\varphi}\right)^2 + \frac{u_{I1}^2 + u_{I2}^2 + u_{I3}^2}{(I_1 + I_2 + I_3)^2}}$$

u_U Type B standard uncertainty of line voltage;
$u_{\cos\varphi}$ Type B standard uncertainty of power factor;
u_{Ii} Type B standard uncertainty of phase currents.

The expanded uncertainty of the active power U_P is calculated assuming the Student's t-distribution and a level of confidence of 95%, so assuming a coverage factor equal to 1.96.

$$U_P = k \cdot u_P$$

Concerning the measurement performed with the energy monitoring network installed in PdG-L3, the uncertainty was calculated considering the Type A evaluation defined in the GUM. For each single measure x_i of a group of measurement, the uncertainty $u(x_i)$ is calculated through the following relation:

$$u(x_i) = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}}$$

where N is the number of measurement and $\bar{x}$ is the average value of the measures, defined as follows:

$$\bar{x} = \frac{\sum x_i}{N}$$

The Type A uncertainty of the average value $\bar{x}$ is defined by the following relation:

$$u_{\bar{x}} = \frac{u_{x_i}}{\sqrt{N}}$$

The expanded uncertainty is then calculated assuming the Student's t-distribution and a level of confidence, e.g. 95%:

$$U_{\bar{x}} = k \cdot u_{\bar{x}}$$

$$k = Student's\ t\ distribution\ (degree\ of\ freedom, level\ of\ confidence)$$

GLOSSARY AND ABBREVIATIONS

- **Backend equipment**: it is all the hardware that the SEAM4US System requires except sensors and actuators.
- **Baseline**: the status-quo condition of PdG-L3 station, prior SEAM4US implementation.
- **CCIF**: the software interface used by OCC operators to manage and control station and tunnel devices.
- **CCTV**: Closed Circuit TV.
- **Control Subsystem**: it refers to all the components needed for controlling the pilot: Controllers, Prediction Models, Device Proxies (software) and Actuators (hardware)
- **Core System**: basic hardware parts of the system (Server and Back-up HDD).
- **GUM**: Guide to the expression of Uncertainty in Measurement.
- **JCGM:** Joint Committee for Guides in Metrology.
- **LinkSmart Middleware**: the platform on which the SEAM4US System is based. It provides the components Network Manager, Device Manager, Event Manager, Data Storage, History Acquisition.
- **Monitoring Subsystem**: it refers to all the components needed for monitoring the pilot: Monitoring Models, Device Proxies (software) and Sensors (hardware)
- **OCC**: Operation Control Center
- **PdG-L3**: Passeig de Gracia - Line 3 (pilot station).
- **PLC**: Programmable Logic Controller.
- **SEAM4US**: Sustainable Energy mAnageMent for Underground Stations.
- **SEAM4US Simulator**: is the overall simulator for predicting the performance of the SEAM4US Control. It has a ‘Model In the Loop’ (MIL) Architecture, and it is composed by a number of components (models and controllers).
- **SEAM4US System**: is the whole system, including all the components included in the SEAM4US System Architecture (User Interfaces, Controllers, Models, Device Proxies, System Supervision, LinkSmart Middleware, Sensors, Actuators).
- **VFD**: variable frequency drive.