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A breakdown of energy consumption in an underground station

Miquel Casals [a], Marta Gangolells [a*], Núria Forcada [a], Marcel Macarulla [a], Alberto Giretti [b]

[a] Universitat Politècnica de Catalunya, Department of Construction Engineering, Group of Construction Research and Innovation (GRIC), C/ Colom, 11, Ed. TR5, 08222 Terrassa (Barcelona), Spain

[b] Università Politecnica delle Marche, Department of Civil Engineering and Architecture, Via delle Brecce Bianche, 60100 Ancona, Italy.

[*] Corresponding author: Marta Gangolells. Tel: (+34) 93 7398947, Fax: (+34) 93 7398101. E-mail: marta.gangolells@upc.edu

ABSTRACT

Underground transportation systems are big energy consumers and have significant impacts on energy consumption at a regional scale. The literature has revealed that the energy consumption for non-traction purposes may be of the same magnitude as the energy used to move rolling stock, and in some cases even greater. However, most of the research conducted so far has focused on the energy demand of rolling stock. This paper investigates the electricity consumption of an underground metro station using data from on-site surveys and measurements. With an average consumption of 217.64 kWh/ m^2·year, the breakdown revealed that the lighting system dominated the underground station's energy consumption (37%). Illuminated advertising signs were found to be responsible for 14% of the total energy consumption, and ventilation accounted for another 14%. The rest of the energy consumption was attributed to systems such as mobile phone signal antenna (12%), the vertical transportation system (8%) and small power devices (5%). Accurate information on energy consumption for non-traction usage is useful for future implementation of energy conservation measures in underground stations, which could result in a reduction of operating costs in the long run.

Keywords:
energy consumption, energy audit, underground station, metro network

1. INTRODUCTION

An underground metro network is a very complex system that provides a massive public transport service. It involves multiple systems and equipment, multi-storey underground spaces, and massive flows of people. An underground metro network must provide the best possible service to customers and grant access to people with disabilities. High safety and security levels must also be attained. In order to transform underground spaces into efficient, flexible, safe and user-friendly environments, hygiene and comfort requirements must also be met. All these aspects, together with the fact that nearly all the spaces are below ground, make underground metro networks significant energy consumers [1] that have a considerable impact at regional level [2]. By way of example, the London Underground, the largest European metro network in terms of its route length of over 400 km, is the single biggest consumer of electricity in London and one of the top 10 electricity consumers in the United Kingdom [3, 4]. On a lesser scale, the total annual electricity consumption of the Barcelona metro network, which covers 125 km of railroad, is 259,300 MWh. This is enough electricity to power about 65,000 households in one year. Anderson et al. [5] state that energy costs typically represent 5-10% of a European or American metro's operating costs.

According to the literature, between 30% and 50% of the energy consumption in underground metro networks is attributable to non-traction requirements [4, 5 and 6]. Therefore, the energy consumption in stations represents a major proportion of the energy consumed by any subway metro network. Moreover, this percentage is expected to significantly increase over the next few years in response to local government campaigns promoting the use of public transport to meet the established environmental and mobility requirements [7]. At the same time, improvements across the network, such as the introduction of increased services, together with rising standards in consumers' expectations of stations [8], are likely to result in an increase in the installed power demand over the next few years.

However, most of the past research initiatives have been focused on the implementation of strategies to reduce the energy consumption of rolling stock [9, 10, 11 and 12]. In spite of its known importance, less attention has been paid to energy consumption related to the operation of stations. The European research project MALTESE (Management and Assessment of Light Trains for Energy Saving and Efficiency) dealt with energy management and efficiency in light rail transit (a derivative of the traditional tram) [6]. More recently, Fu and Deng [13] investigated the energy consumption of the above-ground Guangzhou Railway Station (China). Even fewer studies have analysed energy consumption at underground metro stations. Fong et al. [14] and Hong and Kim [15] focused their work on an analysis of energy consumption in Korean and Hong Kong subway stations, respectively. The MODURBAN (Modular Urban Guided Rail System) project, funded under the EU FP6 Programme, developed a monitoring system to assess energy consumption, heat rejection and temperature evolution on a daily basis for a complete metro line [16]. Thong and Cheong [17] analysed energy efficiency in Singapore's Rapid Transit System. Liu et al. [18] evaluated the energy saving of a new demand control ventilation strategy for subway platforms. Cao et al. [19] analysed the influence of platform screen doors on the energy consumption of subway stations. Other relevant initiatives to predict electrical consumption in subway stations were led by Ma et al. [20], Liu et al. [21] and Leung and Lee [22]. Ma et al. [20] developed a prediction model to estimate the energy consumption of escalators. Liu et al. [21] developed a model to ensure healthy indoor air quality as well as to minimize energy consumption in a subway ventilation system. Leung and Lee [22] developed an intelligent approach to predict the energy consumption of Hong Kong railway stations, but did not determine the energy consumed by the different subsystems.

Although these results give an insight into the energy demand in underground stations and potential energy-saving strategies, they are directly influenced by contextual factors such as the network's age, the technology of the systems and the climatic characteristics. Most of the existing studies focus on Asian metro networks, which have larger station air conditioning requirements than European or American metro networks. In general, European and American underground facilities tend to be older, and thus it is assumed that they consume more energy [23]. In addition, previous research fails to provide the specific energy consumption of systems and subsystems.

This paper presents an in-depth analysis of the energy consumption of a representative underground station of the Barcelona metro network. We focus in particular on a breakdown of the energy consumption by major subsystems. Accurate information on energy consumption for non-traction usage could help in the implementation of energy conservation measures in underground stations, which may result in a reduction in operating costs in the long run.

2. BARCELONA UNDERGROUND METRO NETWORK

According to the Barcelona metro network operator (Transports Metropolitans de Barcelona, TMB), the electricity required to operate rolling stock amounts to 196,200 MWh, whereas facilities consume 63,100 MWh (2009). The total electricity consumption in the Barcelona metro network increased by around 40% during the 2000-2010 period. This rise is attributable to an increase in service rates and improvements in accessibility and comfort. The energy required to operate the Barcelona metro is provided by 25 electrical substations distributed throughout the network. Taking into account that one electrical substation provides the energy for driving the trains and operating station and tunnel equipment in one or more stations, detailed data related to the energy consumption per metro line or metro station are not available at this moment.

Barcelona's network consists of seven lines covering more than 100 km of railroad and moving around 370 million passengers per year. The metro is based on an open ticket system with turnstiles. Therefore, the available data only include the number of passengers who enter each station, but not the number of outgoing or transfer passengers. On working days, the service starts at 5 am and ends at 12 pm, except on Fridays, when it finishes at 2 pm. On Saturday mornings, stations open at 5 am and then remain open until Sunday at midnight. One hundred and forty stations are spread around 300 km^2 and include a wide variety of construction and installation solutions, depending on the period during which they were constructed. In order to select a station that was representative of the

Barcelona metro network, we carried out an in-depth analysis of the main characteristics of all 140 underground stations, in terms of annual passengers and main physical and equipment characterization parameters. The statistical analysis revealed one underground station with typical values. In light of its representativeness, this station was used as a case study (Table 1).

Main characteristics	**Barcelona metro network stations**				**Case study**
	Mean	**Standard deviation**	**10^{th} percentile**	**90^{th} percentile**	
Annual passengers [pax]	3,194,871	2,177,060	1,107,012	5,843,863	5,272,835
Number of accesses [ut]	2.34	0.98	1.00	4.00	3.00
Number of halls [ut]	1.54	0.64	1.00	2.00	2.00
Hall floor area [m^2]	243.55	156.07	94.20	451.00	70.00 / 150.00
Platform floor area [m^2]	703.94	175.56	546.00	900.00	650.00
Staff only floor area [m^2]	465.47	237.75	198.80	800.00	380.00
Depth [m]	12.03	8.72	6.61	15.92	10.40
Number of elevators [ut]	4.22	1.91	2.00	6.00	5.00
Number of escalators [ut]	4.26	3.08	1.00	8.00	2.00
Number of fans [ut]	3.11	2.00	1.40	5.00	2.00

Table 1. Selection of a prototype station in the Barcelona metro network.

3. METHODOLOGY

This research used the methodology described in the working draft of ISO 50002, which is now under development [24]. After preliminary contact and a start-up meeting, relevant background information was gathered with the support of the operator's energy management department. In particular, we collected data on the electric distribution network and the characterization of the equipment that uses energy, including the corresponding operating schedules. At a later stage, field work and corresponding metering strategies were designed and implemented by determining the performance metrics, the corresponding metering points and the required frequency. Finally, the daily, weekly, seasonal and annual energy consumption was analysed.

3.1 Background information

The case study focuses on an underground railway and metro station in Barcelona next to an important tourist hub. The station connects six suburban railway lines and three metro lines. The metro station is composed of three underground buildings that were constructed during different periods. The case study focuses on the oldest one, which opened in 1924. With a floor area of 2,810 m^2 and

5,272,835 people entering in 2012, the station has three main accesses from the street, each one equipped with a stairway. The northern accesses lead to the main hall (hall 0), which directly connects to the railway station. This hall houses the station management centre, along with other staff-only spaces such as meeting rooms, locker rooms and rest rooms. The station ventilation equipment is also situated in this area. The southern entrance leads to a secondary hall (hall 1) that is smaller and has only one commercial space. This secondary hall includes an escalator up to street level. In this hall is the entrance to a 250 metre-long corridor that connects three metro lines. The low voltage distribution room, the transformer centre and the signalling room are also situated in the secondary hall. The access door remains hidden behind the main gate during service hours. To connect the halls with the platforms and accesses, the underground station includes corridors, escalators and elevators. Technical rooms, including one for exchanging information between the control centre and the station (communications room) and one containing the mobile phone signal antenna to provide 3G service to underground stations and tunnels, are found at both ends of the platform (Figure 1).

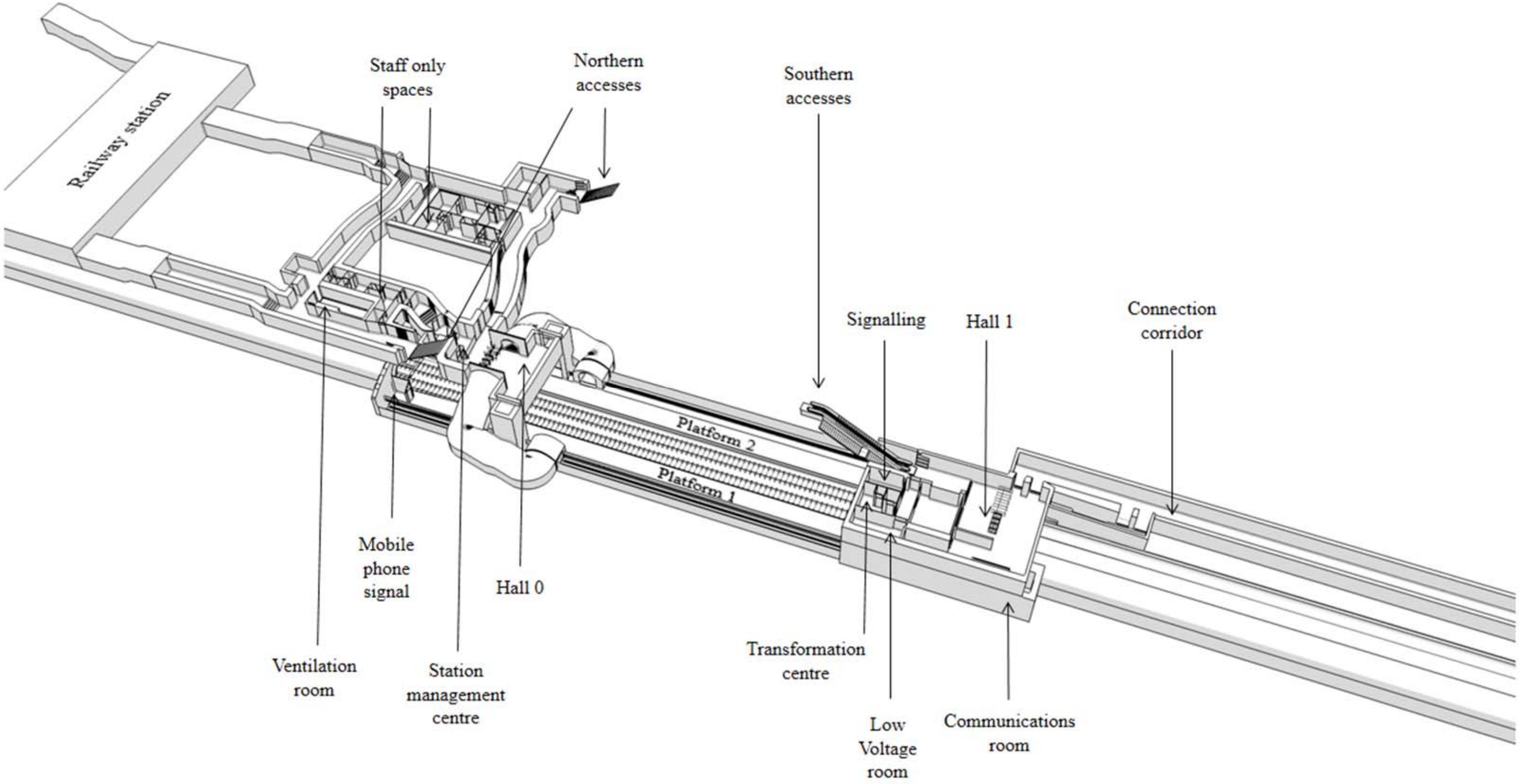

Figure 1. Main areas of the case study station.

3.1.1 Power distribution

The high voltage AC energy received at the substation is converted into both DC high voltage (1500 V) and a subtransport network at 6000 V AC. DC 1.5 kV is used for traction purposes, whereas AC 6 kV delivers the energy to each station's step-down transformer. Transformers feed the station's three-phase devices, such as ventilation and vertical transport equipment at 380 V and single-phase devices including the rest of the equipment, such as lighting and computer systems at 220 V. This equipment is connected between live wires (L_1L_2, L_2L_3, L_1L_3), so there is no need for a neutral wire. The station's essential supply is granted by means of a secondary connection (at 220 V) to the electricity company network (electrical provider). In normal conditions, this auxiliary feed only provides current to a limited number of circuits, yet it is designed to be able to supply electricity to some other circuits if necessary. The low voltage auxiliary feed is a three-phase system that is also connected between live wires (Figure 2).

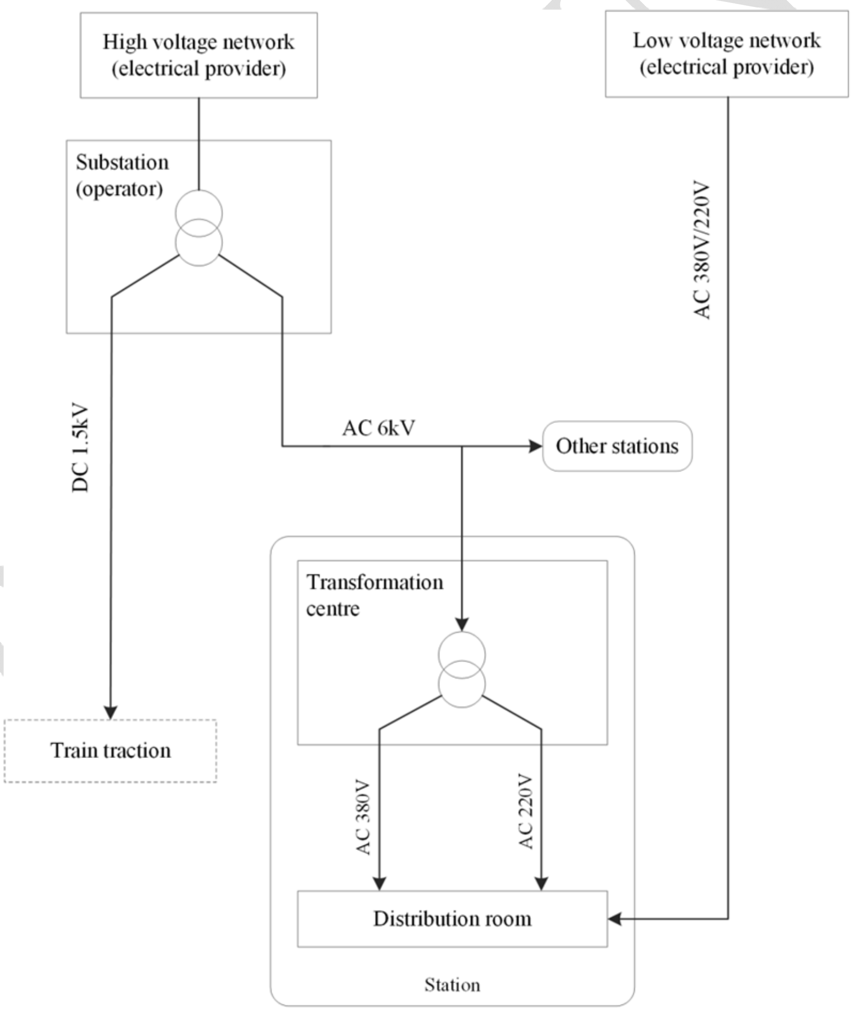

Figure 2. Power distribution in the Barcelona metro network. Source: adapted from TMB.

The low voltage distribution network hosts 55 critical circuits (C), 28 non-critical circuits (NC) and 8 auxiliary circuits (A) through 10 distribution switchboards. Critical circuits comprise all the essential circuits to operate the station reliably. Equipment such as the elevators, the air conditioning in the signalling spaces, some auxiliary services, sockets in tunnels, emergency lights, the fire alarm control panel, ticket validation and ticket selling machines, etc. are included in these critical circuits. Half of the circuits devoted to regular lighting are also considered to be critical, due to the uninterrupted nature of the transport service. Non-critical circuits are those that are not vital to the correct operation of the station, such as the rest of the regular lighting, air conditioning of staff offices, platform sockets and commercial concessions. Auxiliary circuits are mainly fed by the electricity company connection and they basically provide continuous lighting and, to a lesser extent, signalling.

3.1.2 Major equipment or service systems

Part of the equipment in underground stations is required for the operation of the metro network, whereas other equipment is aimed at improving access conditions and customer comfort. The main electricity consumers in the station are described below.

- **Ventilation**
  As the stations are underground, special equipment is needed to guarantee the air quality and to ensure an optimal oxygen level. In addition to air renewal, ventilation systems are used to control the internal temperature of metro stations and tunnels and to extract smoke in case of fire. The ventilation of the Barcelona metro network is based on a double air extraction system in the interstation (which handles flow rates of up to nearly 150,000 m^3/h) and an air blowing system in the stations (where 80% is forced, and the remaining 20% is blown by depression across the access points). Ventilation units have an automatic control system in the form of programmable logic control. Each ventilation unit is provided with sound-proofing elements to minimise its noise level in the street. In the case study, two reversible identical fans with corresponding variable frequency drives provide ventilation to the platform. The ventilation system works at different rates in summer and winter. With a flow rate of 62,500 m^3/h, fans run at top speed (1,500 rpm) to keep temperature levels as low as possible during the warmer period. In winter, the power of the fans is reduced, since the main purpose during this period is to control air quality, rather than to provide thermal comfort. Fans also have different running modes depending on the time of day (day-night). Table 2 shows the main electric characteristics of the fans. In addition to the general ventilation of the station, some air conditioning devices are installed in technical rooms such as the communications rooms. Air conditioning devices are also situated in staff areas.

— **Vertical transportation**

The underground nature of metro stations requires vertical transportation. Two hydraulic, low consumption electric lifts connect the main hall with both platforms. They travel a distance of 6.30 m at a speed of 1 m/s. Installed in 2009, the elevators are powered by electric motors and are operated by a variable frequency drive, with a starting current of 20 A. Each elevator can accommodate 13 people at the same time (maximum load of 1,000 kg). In addition, two escalators connect Platform 1 with the secondary hall (4.22 m high), and the secondary hall with the street (6.27 m high) at a speed ranging from 0.2 to 0.5 m/s. Besides using a variable frequency drive, they belong to the "intelligent generation" of escalators, and include features such as reverse direction (up/down), automatic starting and stopping, operation recovery after checking whether there is anyone on the escalator using photocells, and remote control activations. Installed in 2009, each escalator can transport 6,000 passengers per hour. The main electrical characteristics of the elevators and escalators are summarized in Table 2.

	Fans	**Elevators**	**Escalators**	
			Hall 1 – Street Southern access	**Platform 1 – Hall 1**
Power [kW]	13.60	7.40	12.00	9.00
Tension [V]	220	380 / 220	380 / 220	380 / 220
$I_{nominal}$ [A]	42.70	16.00	21.65	16.40

Table 2. Main characteristics of the station's fans, elevators and escalators.

— **Lighting**

The lighting load in metro stations is rather large, as the underground spaces cannot take advantage of natural lighting. Proper lighting serves different purposes, as it is an investment in safety, security and aesthetics. In this case, the underground station is illuminated by 425 luminaires (Table 3). In general, public spaces are illuminated by fixtures including two 36 W T8 fluorescent lamps with standard electronic ballasts (models 1, 2 and 3 in Table 3). Private spaces are also illuminated by fluorescent lamps, but there is greater variability in the fixtures in terms of the number of lamps per fixture and the power per lamp (models 1, 4 and 5 in Table 3). A total of 110 emergency lights are also spread homogeneously across the station. The station has a total of 39 circuits for 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 into auxiliary (5), critical (12) and non-critical (10) circuits.

	Lighting fixtures				
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Number of fixtures	209	181	16	6	3
Number of lamps per fixture	2	2	3	1	2
Power per lamp [W]	36	36	18	18	54
Type of diffuser	Louver	Wrap-around	n.a.	n.a.	n.a.
Location	Platforms Hall 0 Hall 1 Office WC Ventilation room	Hall 0 Hall 1 Corridors	Dressing room Office	WC Storage room	Office Ventilation room

Table 3. Main characteristics of the station's lighting fixtures.

— **Ticket sale and validation**

The Barcelona metro ticket system is based on credit-card shaped cardboard tickets with a magnetic coded strip. In the case study station, tickets are controlled by 9 automatic validating machines (5 in the main hall and 4 in the other hall), which allow passengers to access the metro network through turnstiles. Tickets are sold in 5 automatic ticketing machines located in the main hall and 2 more in the secondary hall.

— **Safety and security**

Companies providing collective passenger transport services must guarantee a safe, secure, fast method of transportation, taking into account all of the potential hazards involved in the operation (safety) and the threats from the outside in terms of crime (security). Safety systems in the station under study include fire protection systems and emergency exits, among others. The security system is equipped with 33 cameras, interphone systems (one in each ticketing machine and one on each platform), and other elements.

— **Information**

One of the greatest challenges to companies providing underground collective passenger transport services is to keep customers constantly informed of everything that happens in the network. For this reason, the station has four LED panels showing train arrival information (two per platform) and 4 LCD monitors connected to the operator's station TV broadcast.

— **Communication**

The daily management operations of modern metro networks are run from a control centre, which is usually located in the operating company's headquarters. All the technological equipment necessary to exchange information between the control centre and the station (i.e. train arrivals or departures, automatic information displays, system monitoring, etc.) is housed in the communications room and includes some servers and a UPS. The communications room is also equipped with an air conditioning system.

3.2 Design and implementation of the metering strategy

In accordance with the Energy Performance of Buildings Directive [25], performance metrics were determined for the entire station's electricity use, measured in kWh/m^2·year, and the corresponding CO_2 rating, measured in kg eq. CO_2/m^2·year. In order to allow station benchmarking by normalizing consumption, the electricity use per entering passenger was also considered important for the purpose of this research. The data required to build the performance metrics are shown in Table 4.

Performance metrics	**Static data**	**Dynamic data**	**Survey frequency**
Total station electricity use [kWh/m^2·year]	Floor area of the station [m^2]	Electricity consumption of the entire station [kWh]	Winter / Summer
Total station CO_2 rating [kg eq CO_2/m^2·year]	Floor area of the station [m^2] Electric mix [kg CO_2/ kWh of electricity]	Electricity consumption of the entire station [kWh]	-
Electricity use in public spaces [kWh /m^2·year]	Floor area of public spaces in the station [m^2]	Electricity consumption of systems in public spaces [kWh]	Winter / Summer
Electricity use in private spaces [kWh /m^2·year]	Floor area of private spaces in the station [m^2]	Electricity consumption of systems in private spaces [kWh]	Winter / Summer
Electricity use for subsystem [kWh /m^2·year]	Floor area of the station [m^2]	Electricity consumption of subsystems [kWh]	Winter / Summer
Total station electricity use per entering passenger [kWh/year·passenger]	Number of annual entering passengers [pax]	Electricity consumption of the entire station [kWh]	Winter / Summer

Table 4. Determination of associated performance metrics.

Due to the operation mode of the station (mainly in aspects related to ventilation and air conditioning), we had to distinguish between summer and winter seasons. Accordingly, recorded voltage and electrical current measurements were collected during a representative day in the winter season and a representative day in the summer season. Instant currents absorbed by all the low voltage circuits and empirical power factor values were measured with an electrical network analyser. Metering points were determined according to the existing electrical architecture and wiring. All measures were made in the main switchboard. Restrictions due to operating conditions had to be taken into account in the determination of metering points. Although direct metering was always prioritized, eventually two direct meters were used to determine a third measurement by difference. Elevators and escalators are variable loads, so instant measures did not allow us to model their energy consumption reliably. For this reason, a twelve-hour continuous measurement (every second) was performed, covering periods when the station was open and closed. This provided an acceptable estimation of the energy consumption of vertical transport means.

3.3 Analysis of the energy consumption of the underground station

Although current and voltage can vary slightly during the day in a three-phase system without a neutral, we assumed that these currents remain constant while the circuit is on. Thus, the apparent power (S_i) and the real power (P_i) were calculated for a three-phase load configuration (three lives wires without a neutral), in which all three voltages are considered equal. The apparent power and the real power were also calculated for single-phase loads (two live wires).

The electricity consumed by operational constant loads was obtained according to Equation 1.

$$E_{t\,i} = \sum_{i=0}^{n} P_i \cdot t_i \qquad (1)$$

Where:

$E_{t\,i}$ represents the electricity consumed during a period of time t by the load i, P_i denotes the real power measured in W for the load i, and t is the period of time the load i is on. As the devices do not all work simultaneously, an hourly usage map was drawn up for each circuit, taking into account the type of day and the time of year. Figure 3 depicts the state of a circuit for a given hour and profile. Table 5 shows the profile considered for each subsystem, depending on the type of day (weekday, Saturday or Sunday).

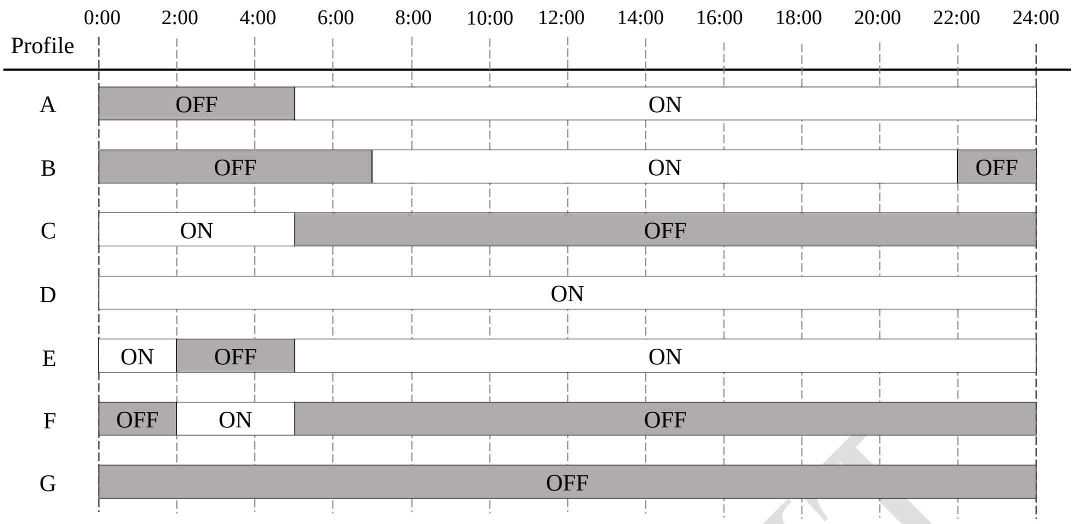

Figure 3. Hourly usage profiles.

Subsystem	Profile		
	Weekday	**Saturday**	**Sunday**
Lighting	A	E	D
Nightwatch lighting	D	D	D
Tunnel lighting	C	F	G
Ventilation	B	B	B
Escalators	A	E	D
Elevators	A	E	D
Illuminated advertising signs	D	D	D
Vending machines	D	D	D
Mobile phone signal antenna	D	D	D
Air conditioning	A	E	D
Air conditioning - technical rooms	D	D	D
Validation machines	D	D	D
Ticketing machines	D	D	D
LCD monitors	D	D	D
Small power	Broken down for each device.		

Table 5. Subsystem's profile per type of day.

In case of operational variable loads (escalators and elevators), the energy consumption during 12 hours was directly read from the electric network analyser and then transformed according to the corresponding hourly usage profiles.

The weekly electricity consumption of the underground station was calculated according to Equation 2. This equation includes a seasonal perspective, because of the varying profile of the station during the year.

$$E_{w\,S,W} = 5 \cdot E_{wd\,S,W} + E_{Sat\,S,W} + E_{Sun\,S,W} \qquad (2)$$

Where:

$E_{w\,S,W}$ represents the electricity consumed by the station during a week in summer (S) or winter (W) measured in kWh, $E_{wd\,S,W}$ denotes the energy consumed by the station during a working day in summer (S) or winter (W) measured in kWh, $E_{Sat\,S,W}$ represents the energy consumed by the station on Saturdays in summer (S) or winter (W) measured in kWh, and $E_{Sun\,S,W}$ stands for the energy consumed by the station on Sundays in summer (S) or winter (W) measured in kWh.

The annual electricity consumption was calculated according to Equation 3, taking into account that, according to the metro operator, both the winter and the summer seasons usually last 26 weeks.

$$E_y = E_{w\,S} \cdot 26 + E_{w\,W} \cdot 26 \qquad (3)$$

Where:

E_y is the energy consumed annually by the underground station measured in kWh, $E_{w\,S}$ is the energy consumed weekly during the summer measured in kWh, and $E_{w\,W}$ is the energy consumed weekly during the winter measured in kWh.

4. RESULTS

4.1 Survey raw data

The average active power absorbed by each of the 91 electrical circuits in the underground metro station was measured using an electrical network analyser during two on-site surveys, which were representative of the winter and the summer seasons. Individual power factors were also measured.
Table 6 shows these empirical values grouped according to the main electrical subsystems in the underground station.

Subsystems	Active power [kW]		Power factor
	Winter	Summer	
Lighting	29.74	29.93	0.95
Ventilation	5.44	25.40	0.94
Illuminated advertising signs	10.30	9.90	0.70
Vending machines	1.92	2.67	0.60
Mobile phone signal antenna	7.94	9.04	0.90

Air conditioning	0.33	5.49	0.53
Validation machines	0.42	0.46	0.82
Ticketing machines	0.69	0.46	0.46
LCD monitors	0.48	0.46	0.50
Small power	3.14	4.92	0.58

Table 6. Average active power and power factors for each electrical subsystem in the underground metro station.

The total average active power absorbed by the main electrical subsystems varied considerably. The variation can be attributed to the seasonal operational profile of the underground station (i.e. ventilation and air conditioning). In addition, most of the electrical subsystems of the underground station showed high power factors. The total weighted power factor, including all the subsystems of the underground station, was found to be 0.98.

Elevators and escalators are operational variable loads. Thus, their average active power and power factors are not constant over time [26, 27]. In order to find load variations, elevators and escalators were monitored continuously over 12 hours to cover periods that were considered relevant due to their usage profile. Figure 4 and 5 show the instant energy consumption for an elevator and an escalator during a 10 minute period, respectively.

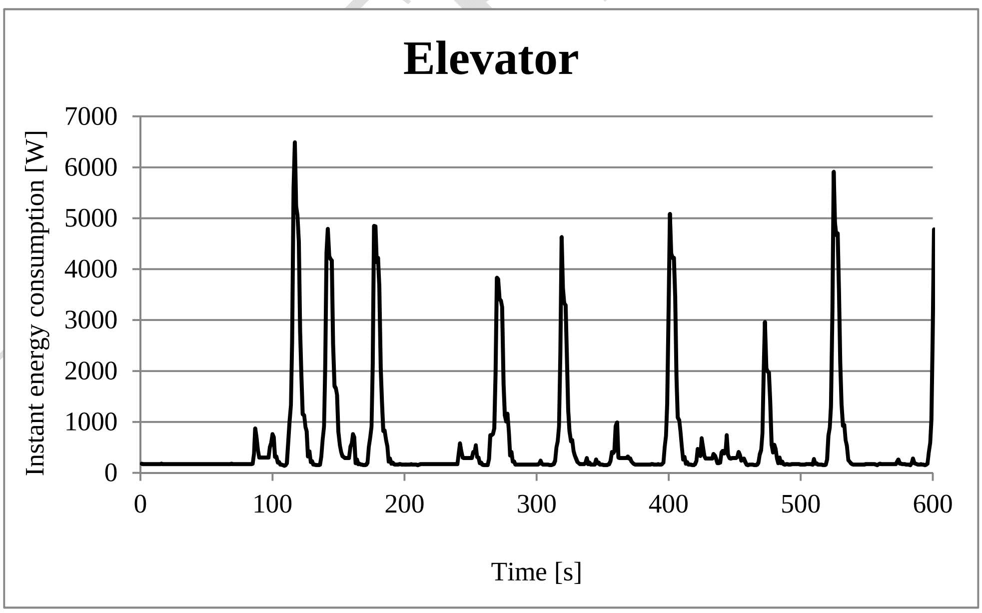

Figure 4. Instant energy consumption for an elevator during a 10 minute period.

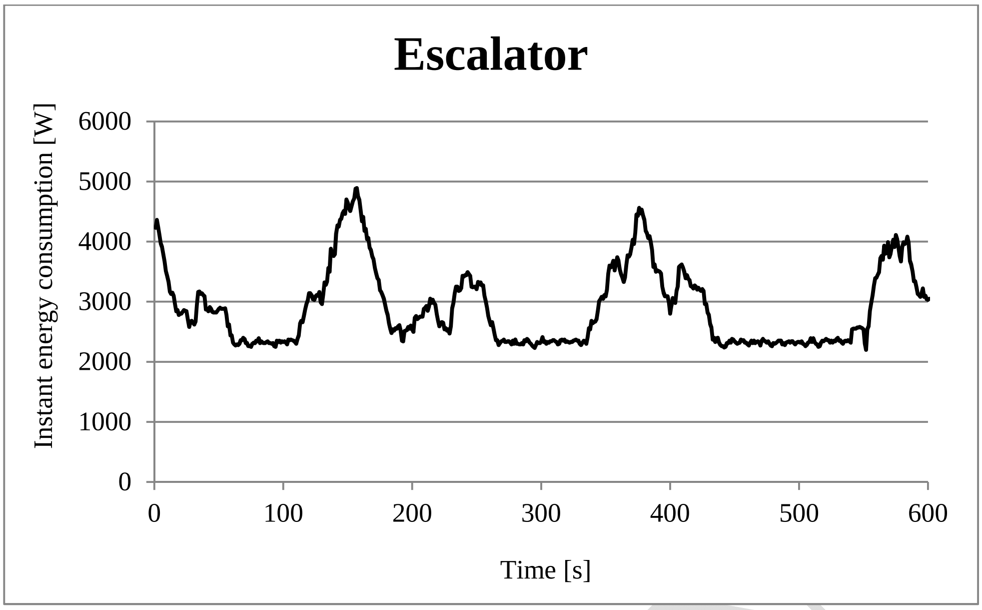

Figure 5. Instant energy consumption for an escalator running at 0.5 m/s during a 10 minute period.

4.2 Energy consumption

The daily, weekly and annual energy consumption of the underground station were calculated according to Equations 1, 2 and 3. Table 7 shows the daily and annual energy consumption by electrical subsystem, type of space, type of day and season.

Subsystems	Energy consumption [kWh]						
	Summer			Winter			Year
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	
Private							
Lighting	42.27	45.38	50.05	32.77	35.50	39.58	14,188.18
Mobile phone signal antenna	217.04	217.04	217.04	190.50	190.50	190.50	74,173.12
Air conditioning	122.55	126.25	131.81	6.35	7.02	8.02	23,857.59
Small power	108.01	112.09	118.21	74.00	74.58	75.44	33,549.90
Public							
Lighting	566.99	607.55	668.39	573.17	613.60	674.24	214,878.99
Ventilation	380.93	380.93	380.93	81.67	81.67	81.67	84,193.19
Escalators	101.27	111.93	127.92	100.70	111.30	127.20	38,693.20
Elevators	19.95	22.05	25.20	18.51	20.45	23.38	7,367.36
Illuminated advertising signs	237.68	237.68	237.68	247.25	247.25	247.25	88,257.59
Vending machines	64.25	64.25	64.25	46.12	46.12	46.12	20,087.06
Validation machines	11.00	11.00	11.00	10.96	10.96	10.96	3,996.25
Ticketing machines	8.83	9.76	11.15	13.14	14.52	16.59	4,208.00
LCD monitors	11.06	11.06	11.06	11.58	11.58	11.58	4,121.56
Total	1,891.11	1,956.18	2,053.78	1,407.44	1,465.68	1,553.44	611,572.00

Table 7. Daily and yearly energy consumption of the underground station by electrical subsystem, type of space, type of day and season.

5. DISCUSSION OF RESULTS

According to the results, the total energy consumption of the underground station amounts to 611,572.00 kWh/year. The average usage of electrical power in the underground station was found to be about 217.64 kWh/ m^2·year. Accordingly, the CO_2 rating for the entire station is 65.29 kg eq CO_2/m^2·year. As shown in Table 7, private spaces account for 23.84% of the annual electricity consumption, whereas public spaces represent 76.16%. The entire station's electricity use per entering passenger was found to be 0.12 KWh/passenger·year.

According to the results, the seasonal energy consumption for the underground station varies between 261,468.31 kWh in winter (42.75%) and up to 350,102.89 kWh in summer (57.24%). From a weekly perspective, the lowest energy consumption is for winter weekdays with an average consumption of 1,407.44 kWh, whereas the highest energy consumption is for summer Sundays with an average consumption of 2,053.78 kWh. In general, about 68.08% of the electricity is consumed during the weekdays, whereas the rest (31.92%) is consumed over the weekend.

With an annual consumption of 229,067.17 kWh, the lighting system was found to be the station's biggest energy consumer (37.46%). Fortunately, enormous improvements can be made in energy consumption for lighting. A few examples of energy saving measures are (1) replacement of lamps with more efficient models, (2) replacement of fixtures to use different types of lamps, (3) deployment of a smart network to adapt illumination to the operator's needs, (4) field illuminance testing to ensure that current values do not exceed the minimum requirements stated by current legislation, (5) checking of the performance of the installed lighting system [28] and (6) use of occupancy sensors in staff rooms. Preliminary estimations show that savings could range from 10% to over 40% when some of the abovementioned measures are combined.

Surprisingly, illuminated advertising signs were found to be the second largest consumer of electricity in the underground station, with a share of 14.43%. Part of this electricity consumption (88,257.59 kWh/year) can be attributed to the fact that illuminated advertising signs are outside of the operator's management and are usually left on after service hours. Therefore, this unnecessary energy usage could be eliminated by just switching off the lights of the advertising signs, which would achieve an estimated saving of 16.67% (14,709.60 kWh/year).

The electricity consumption related to the ventilation system represents about 13.77% of the underground station's consumption (84,193.19 kWh/year). The ventilation system was initially designed to give high enough ventilation rates in static conditions, without taking into account the operation of the trains. However, the air moved by circulating trains could be harnessed to reduce the ventilation load that fans must provide, which would decrease the electricity consumption. The new system should also take into account key inputs such as indoor air quality [29, 30] and temperature readings. Preliminary studies show that a saving of up to 30% could be achieved. However, detailed simulations are needed to obtain a more accurate estimation.

According to the results, the electricity consumption related to the mobile phone signal antenna amounts to 74,173.12 kWh/year, which represents 12.13% of the underground station's total electricity consumption. In order to reduce this consumption, current equipment could be replaced by more efficient devices. However, agreement on this energy-saving measure would have to be reached with the concessionaire.

In this case study, the vertical transportation systems accounted for 7.53% of the station's total electricity consumption. Escalators were found to have an annual electricity consumption of 19,346.60 kWh each. However, there is little room for improvement here, as the equipment already uses top-of-the-range technology. Measures to reduce standby consumption are already in place, and lighting is switched off without reducing the service quality. Elevators were found to have an individual annual electricity consumption of 3,683.68 kWh. This value could be reduced by implementing some energy-saving measures. On the usage side, the current inverter could be replaced with a regenerative one, which could provide an estimated energy saving of 25%. On the standby side, switching off the lights when no one is using the elevator could also lead to energy saving, whose magnitude would depend on the usage pattern.

Small power devices account for 5.49% of the electricity consumed in the station, which equals 33,549.90 kWh/year. This category includes plug-in equipment, signalling and auxiliary services, among others. Due to the large number, diversity, transient nature and low individual power of these items, energy conservation measures are difficult to plan in this initial stage.

The air conditioning system in staff and technical rooms consumed 3.90% of the total electricity consumption of the underground station (23,857.59 kWh/year). In this case, electricity could be saved by installing occupancy-sensors in staff rooms, to interact with the occupancy loads.

The annual electricity consumption attributable to the vending machines was 20,087.06 kWh, which represents a share of 3.26%. As this equipment depends on the concessionaires, it is difficult for the metro operator to plan and implement energy conservation measures.

Finally, the percentage breakdown also showed other minor sources of electricity consumption. Ticketing and validation machines accounted for 0.69% and 0.65% of the total electricity consumption, respectively. There is little room for improvement here, as the individual consumption of ticketing machines is not more than the consumption of a regular computer. Validation machines located in station entrances have even lower individual energy consumption. LCD monitors used to provide timely information to passengers were found to consume 4,121.56 kWh/year (0.67%). As in the case of illuminated advertising signs, LCD monitors remain on after service hours. Turning off this equipment would lead to an estimated energy saving of 686.93 kWh/year.

6. CONCLUSIONS

In spite of its importance, studies on the energy consumption of metro stations have been very scarce in comparison to those on rolling stock, and tend to include more qualitative than empirical data. To change this situation and to understand the main components of the overall energy balance of an underground metro station, we conducted an energy audit of a highly representative station of the Barcelona underground metro network.

According to the results, the annual energy consumption of the underground station is 611,572 kWh (or 217.64 kWh/ m^2·year). The lighting system has the highest electricity consumption of all the systems, and accounts for almost four tenths of the total. Illuminated advertising signs, ventilation devices and the mobile phone signal antenna account for one tenth each, and the rest of the energy is consumed by other systems such as escalators and elevators, small power devices, air conditioning in staff and technical rooms, vending machines, ticketing and validation machines and LCD monitors. Taking into account that even a small fraction of non-traction energy saving in underground transportation scenarios will produce a relevant energy-saving figure in absolute terms, we outlined some energy-saving measures to be implemented in the underground station.

The strength of this research lies in the fact that it provides the first published quantitative basis for guiding the implementation of energy conservation measures in ageing European and American underground metro stations. However, further research should be conducted to achieve a higher level of accuracy in the results, and especially to understand the prevalence, usage patterns and energy information of small power devices. As pumping shafts are often used to prevent underground water from filtering into underground metro stations, further research should be conducted to estimate the contribution of pumps to the total energy consumption. In addition, energy conservation recommendations should be further explored. Specific efficiency improvement recommendations for each main electric subsystem should be analysed in depth. Consequently, advanced modelling techniques are needed to simulate the complex dynamics of the ventilation of underground spaces. The development and implementation of middleware platforms and multi-agent control systems for the optimization of the use of energy in subway stations should also be further explored. A detailed financial analysis of each recommendation should be carried out, to prioritize low cost measures that could lead to significant energy savings.

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8. REFERENCES

[1] R. Ansuini, R. Larghetti, M. Vaccarini, A. Carbonari, A. Giretti, S. Ruffini, H. Guo, S.L. Lau, Hybrid modelling for energy saving in subway stations, in: J. Wright, M. Cook (Eds.), Proceedings of the 2012 Building Simulation and Optimization Conference, Loughborough, 2012, pp. 425-432.

[2] A. Giretti, M. Lemma, M. Vaccarini, R. Ansuini, R. Larghetti, S. Ruffini, Environmental modelling for the optimal energy control of subway stations, Gerontechnology 11 (2012) 168-175.

[3] Transport for London, London Underground Environment Strategy 2008-2013, Mayor of London, 2011.

[4] Transport for London, LU Carbon Footprint report 2008, Mayor of London, 2009.

[5] R. Anderson, R. Maxwell, N. G. Harris, Maximizing the potential for metros to reduce energy consumption and deliver low-carbon transportation in cities, CoMET and NOVA Groups, Imperial College London, London, 2009.

[6] MALTESE. Management and assessment of light trains for energy saving and efficiency. EU funded project. Contract number: XVII/4.1031/96-138, 1997.

[7] A. Fuertes, M. Casals, M. Gangolells, O. Puigdollers, Overcoming challenges for energy management in underground railway stations. The SEAM4US project, eWork and eBusiness in Architecture, Engineering and Construction, ECPPM 2012, pp. 123–129.

[8] F. Ampofo, G. Maidment, J. Missenden, Underground railway environment in the UK. Part 1: Review of thermal comfort, Applied Thermal Engineering 24 (2004), 611-631.

[9] ELECRAIL. Analysis of energy consumption on metropolitan railways, commuter railways and high speed lines. Spanish funded project. Contract number : PT-2007-038-20IAPM, 2007.

[10] RAILENERGY. Innovative integrated energy efficiency solution for railway rolling stock, rail infrastructure and train operation. EU funded project. Contract number: FP-3SUSTDEV 31485, 2006.

[11] Underground timetable design for optimizing energy transfer during regenerative braking process. Spanish funded project. Contract number: CIT-370400-2007-9, 2007.

[12] HEMBOT. High efficiency motor bogie for trains. EU funded project. Contract number: BRPR-CT97-0454, 1997.

[13] K. Fu, Z. Deng, Current situation of energy consumption in Guangzhou Railway Station and analysis on the potential of energy conservation, Journal of Sustainable Development 2 (2009) 117-120.

[14] K.F. Fong, V.I. Hanby, T.T. Chow, Optimization of MVAC systems for energy management by evolutionary algorithm, Facilities 21 (2003) 223 – 232.

[15] W. Hong, S. Kim, A study on the energy consumption unit of subway stations in Korea, Building and Environment 39 (2004) 1497-1503.

[16] MODURBAN. Modular Urban Guided Rail System. EU funded project. Contract number: TIP4-CT-2005-516380, 2005.

[17] M. Thong, A. Cheong, Energy efficiency in Singapore's Rapid Transit System, Journeys, 2012.

[18] J. Liu, X. Deng, Y. Wang, Numerical evaluation of energy consumption and indoor environment in subway island platform with DCV system, in: Eleventh International IBPSA Conference Proceedings, Glasgow, 2009, pp. 1894-1898.

[19] R.G. Cao, S.J. You, S.Y. Dong, Energy consumption analysis and reconstruction of subway platform screen doors in northern cities for energy-saving, Journal of Chongqing University 32 (2009) pp. 218 - 222.

[20] W.W. Ma, X.Y. Liu, L. Li, X. Shi, C.Q. Zhou, Research on the waiting time of passengers and escalator energy consumption at the railway station, Energy and Buildings 41 (2009) 1313–1318.

[21] H. Liu, S. Lee, M. Kim, H. Shi, J. T. Kim, K. L. Wasewar, C. Yoo, Multi-objective optimization of indoor air quality control and energy consumption minimization in a subway ventilation system, Energy and Buildings 66 (2013) 553-561.

[22] P.C.M. Leung, E.W.M. Lee, Estimation of electrical power consumption in subway station design by intelligent approach. Applied Energy Volume 101 (2013) 634–643.

[23] Imperial College London, Research: Railway and Transport Strategy Center. [Online] 2012. [Cited: 17 03 2012.] http://rtsc.org.uk/.

[24] International Standard Organisation. ISO 15002 Energy audits (under development).

[25] European Union (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

[26] S. S. Ahmed, A. Iqbal, R. Sarwar, Md. S. Salam, Modeling the energy consumption of a lift. Energy and Buildings 71 (2014) 61-67.

[27] C. Carrillo, E. Díaz-Dorado, J. Cidrás, M. Silva-Ucha, A methodology for energy analysis of escalators, Energy and Buildings 61 (2013) 21-30.

[28] S. Kocabey, N. Ekren, A new approach for examination of performance of interior lighting systems, Energy and Buildings 74 (2014) 1-7.

[29] M. Kim, B. SankaraRao, O.Y. Kang, J. Kim, C. Yoo, Monitoring and prediction of indoor air quality (IAQ) in subway or metro systems using season dependent models, Energy and Buildings 46 (2012) 48-55.

[30] S. Lee, H. Liu, M. Kim, J. T. Kim, C. Yoo, Online monitoring and interpretation of periodic diurnal and seasonal variations of indoor air pollutants in a subway station using parallel factor analysis (PARAFAC), Energy and Buildings 68 (2014) 87-98.