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Energy performance assessment of an intelligent energy management system

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Although energy management systems are expected to result in decreased energy consumption, it is important not to overlook the energy used until commissioning (including raw materials acquisition, manufacturing and transportation) and during the usage phase (including operation and maintenance). This paper examines the energy performance of an intelligent energy management system for underground metro stations. The results show that the energy management system has high energy performance in terms of energy payback time and energy return factor, due to its low cumulative energy demand and its potential for energy savings. When we assumed that the lifespan of energy management systems may vary between 5 and 10 years, their cumulative energy demand was found to range between 505,316 and 852,493 MJ_p eq. In all cases, the operating energy was found to far outweigh the embodied energy (68–81%). The energy management system was implemented in a pilot underground station and was found to provide an energy saving of 13.2 ± 1.1% of the total energy consumption of the pilot station. The energy payback time of the energy management system for underground stations was found to range between 40 and 55 days. Consequently, the system pays back between 33 and 91 times the energy invested in it. The results of this research provide valuable information for stakeholders in the energy management systems industry, as they contribute to ascertaining the sustainability of products.

Contents

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1. Introduction

Since buildings are responsible for about 40% of the total primary energy consumption [1], significant research efforts have been recently directed towards energy optimisation [2] through the implementation of automated control systems and intelligent optimisation strategies [3]. Energy management systems have gained popularity as they contribute to continuous energy management of active building systems such as heating, ventilation and air-conditioning [4,5], but their environmental implications have not been researched in depth. While they can be considered almost absolutely eco-friendly during their operational phase, it is important to evaluate the energy consumed until commissioning and usage by the devices in the system, to ascertain their sustainability. In a thorough literature review, we found no relevant studies related to this research area. Only van Dam et al. [6] assessed the life cycle impact of energy management systems. They focused on three domestic energy management systems and concluded that results are highly dependent on the complexity of the system. Gangolells et al. [7] conducted a Life Cycle Analysis of an advanced energy management system developed under the auspices of a European research project entitled "Sustainable Energy Management for Underground Stations" (SEAM4US) [8]. Unlike home energy management system, the SEAM4US energy management system is implemented in a public space and involves multiple systems and equipment, multi-storey underground spaces, and massive flows of people [9]. Even more complexity is added to the system by the fact that it manages a very large environment with multi-faceted thermal behaviour (i.e. intricate air exchange dynamics with the outside, heat conduction with the surrounding soil and high variable internal gains due to travelling passengers and trains) [10], and there are operational restrictions derived from the need to guarantee the reliability of the transport service and the security, safety and comfort of the customers. Results obtained in Gangolells et al. [7] showed that the environmental impact of the SEAM4US system ranged from 1963 (useful life of 5 years) to 3029 Eco-indicator 99 points (useful life of 10 years). The impact on resources was the largest (about 51%), whereas the human health damage category amounted to approximately 35% and the ecosystem quality damage category represented about 14% of the total impact.

The present research focuses on the analysis of the energy performance of the SEAM4US energy management system and its main objective was to evaluate whether direct energy saving achieved by the energy management system is greater than the energy consumed by the system during its manufacturing, assembly, use and maintenance phase. First, we quantified the primary energy requirements of the energy management system by examining the commissioning and usage phases (including raw materials acquisition, manufacturing, transportation, operation and maintenance) and assessing the corresponding contributions. Then, we calculated the time required for the SEAM4US energy management system to save the amount of energy consumed during its initial life cycle stages and how many times the system pays back this energy, taking into account the energy saving provided by the SEAM4US energy management system. Following this introduction, we describe the SEAM4US energy management system and its main functionalities. In Section 3 we describe the methodology. Finally, the results are discussed in Section 4 and conclusions and future work are detailed in Section 5.

2. The SEAM4US energy management system

Underground metro stations are major consumers of electricity. However, research on reducing their energy consumption has mostly been focused on improving the energy efficiency of the trains. The infrastructure has been a secondary target, even though electricity consumption in stations can amount to up to 30% of total energy expenditure [9]. Given the huge size of metro networks and the current economic context, it is not feasible to upgrade all equipment for the sole purpose of improving energy efficiency. Thus, improvements in energy management must be sought, although we should take into account that current energy management policies adopted by metro operators consist mainly in on/off schedules that reflect inherited habits more than analysed needs. Along this line, the primary aim of the European research project entitled "Sustainable Energy Management for Underground Stations" [8] is to reduce energy consumption in underground metro stations by developing an intelligent real-time energy management system that can produce significant energy savings in non-traction electricity consumption. Control policies were defined in accordance with the results obtained during the energy audit of the prototype underground station [9]. Taking into account that the metro station was found to be over-illuminated to enhance passenger safety, the lighting subsystem is regulated through logical feed-forward control that varies the illuminance level based on the expected occupancy of the spaces and the visual task of the passengers. A good lighting level is considered necessary in the case of low occupancy, as a lack of lighting in this situation could make passengers feel unsafe. In contrast, the minimum lighting levels required by regulations are considered sufficient to perform the visual task when occupancy is high. Platform ventilation is currently provided by two reversible fans following day–night and seasonal cycles. Fans run at top speed to keep temperature levels as low as possible during the summer. In winter, the speed is reduced, since the main purpose is to control air quality, rather than to provide thermal comfort. In all cases, station fans are switched off during the night. The SEAM4US system regulates the ventilation subsystem by means of an environmental prediction model that considers the actual building's environmental conditions, the prediction of near future disturbance processes (including weather conditions, train arrivals and expected passenger flows) and prediction of the future building status [11]. Finally, the control policy within the vertical transportation subsystem is based on setting the escalators' speeds at lower values than the nominal one when conditions of low traffic are predicted by the occupancy detection subsystem.

These control policies were implemented trough the core, monitoring and control subsystems. The core system provides central processing and storage capacity remotely to the SEAM4US energy management system. It includes a centralized server for hosting the software and databases, and for facilitating access to other SEAM4US devices at stations. The core system also includes shared storage used for periodically storing backups of SEAM4US data. The environmental monitoring network captures the ambient data in the station to model validation and control feedback. The subsystem includes an extensive set of sensor nodes, communication hardware and management and data handling software. Sensor nodes include multiple environmental sensors for measuring air and surface temperature, air flow, air pressure, CO_2, PM10, relative humidity, as well as basic outdoor measurements such as solar radiation and rain accumulation. Some sensor nodes are battery operated, whereas others have batteries only as a backup power source for situations in which wired power supply is temporarily lost. Sensor nodes measure data and transmit it to the gateway node, which in turn forwards data to the WSN gateway (computer hosting local database server software, and providing interfaces to the sensor network's management user interface). The occupancy detection subsystem is used to assess and predict station occupancy. This subsystem relies on 20 existing closed-circuit television (CCTV) cameras distributed throughout the station. The multiple

CCTV video streams are combined in a video recorder and then forwarded to the CCTV gateway (a desktop computer) for further processing. The purpose of the energy consumption monitoring subsystem is to provide detailed energy consumption data on the individual subsystems operating within a metro station. Energy consumption monitoring is carried out using current wired sensors connected to corresponding smart meters. An energy monitoring controller gathers energy measurements from these wireless energy meters and forwards them immediately through a wired Ethernet connection to the core system. Three-phase energy meters with an RS485 serial interface are also used for high accuracy readings. These energy meters need communications gateways to convert serial RS485 to Ethernet. The SEAM4US control subsystem is responsible for transferring commands to existing lighting devices, escalators and fans. Each lighting fixture has been equipped with digital addressable lighting interface (DALI) compatible ballast, connected to a single DALI controller by means of a bi-directional data exchange bus. The controller is also connected to the SEAM4US server via Ethernet. In a similar way, fans and escalators have been equipped with independent programmable logic controllers (PLC). PLCs work in parallel and in collaboration with the existing equipment and they are in charge of transmitting action commands from the SEAM4US server to the device via Ethernet. In order to provide feedback to the control subsystem, each fan is also equipped with an anemometer. For the same purpose, each escalator is equipped with radar.

3. Methodology

Fig. 1 summarizes the research method used to assess the energy payback time and the energy return factor of the SEAM4US energy management system.

The energy payback time can be calculated according to the following equation:

$$\mathrm{EPBT} = \frac{\mathrm{CED}}{E_{\mathrm{saved}}} \tag{1}$$

where EPBT is the energy payback time measured in years and represents the time required for the energy management system to save the amount of energy consumed during the manufacturing, assembly, transportation, installation and operational phases; CED is the cumulative energy demand or the primary energy consumed during the manufacturing, assembly, transport, operation and maintenance, expressed in $\mathrm{MJ_p}$; and E_{saved} are the energy savings provided by the energy management system measured in $\mathrm{MJ_p}$.

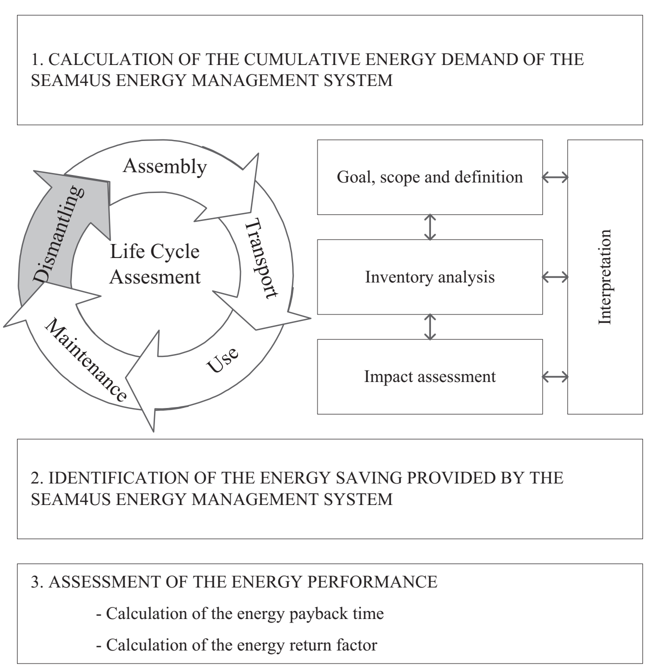

Fig. 1. Research method.

The energy return factor can be obtained by applying Eq. (2):

$$\mathrm{ERF} = \frac{L}{\mathrm{EPBT}} \tag{2}$$

where ERF is the energy return factor and measures how many times the system pays back the energy needed until commissioning and during the usage phase; L stands for the useful life of the energy management system measured in years; and EPBT is the energy payback time of the system measured in years.

3.1. *Calculation of the cumulative energy demand of the SEAM4US energy management system*

The cumulative energy demand of the SEAM4US energy management system was calculated by conducting a life cycle energy assessment (LCEA), in compliance with ISO standards 14040 [12] and 14044 [13]. According to this framework, a life cycle assessment generally involves the following four phases: (1) Goal and scope definition, (2) Life cycle inventory, (3) Life cycle impact assessment and (4) Interpretation of the results.

3.1.1. *Goal and scope definition*

According to ISO 14040, the first step in any LCA study is to clearly define the purpose, scope and system boundaries. The purpose of the present study was to evaluate the cumulative energy demand of the SEAM4US energy management system. The scope was limited to the SEAM4US energy management system, which is described in detail in Section 2. System boundaries include manufacture (including all steps from raw material extraction to the assembly of all the component devices), transport (from production sites to the assembling site located in Finland, and then to the underground station in Barcelona), usage (considering two lifespan scenarios of 5 and 10 years) and maintenance of the SEAM4US system.

3.1.2. *Life cycle inventory*

The second stage of an LCA study involves the collection of data to quantify the material and energy inputs and outputs of a system. The various components of the energy management system and their respective quantification (mainly in terms of number and unitary weight) were identified using the technical specifications of the advanced energy management system and the estimated budget for its deployment in the pilot station. In a second stage and when necessary, the design team was contacted to further detail the composition of some parts of the SEAM4US energy management system. Table 1 shows the inventory for the SEAM4US management system. Finally, in the third and last stage, all the identified devices and components were linked to life cycle inventory data within the Ecoinvent v2.0 database [14]. Although this database contains specific data for some electronic components, electric materials and products, some devices had to be modelled using unspecific, generic data. Table 2 summarizes the key characteristics and assumptions used in this LCA study.

3.1.3. *Life cycle energy assessment*

In the third stage, life cycle inventory data is used to calculate the significance of the energy consumption related to the product or the process being analysed. In this case, calculations were performed with SimaPRO 7.1 [15]. According to the aim of the research, the cumulative energy demand method [16] was used.

Table 1
Main components of the SEAM4US energy management system.

System	Description	Unit	Amount
Core system	Server	ut.	1
	Backup disk	ut.	1
Environmental monitoring	**Sensor nodes**		
	Sensor board	ut.	42
	Fan sensor	ut.	2
	Absolute pressure sensor	ut.	28
	Air temperature sensor	ut.	27
	High speed anemometer	ut.	12
	Low speed anemometer	ut.	2
	Relative humidity sensor	ut.	1
	CO_2 sensor	ut.	3
	PM10 sensor	ut.	3
	Differential pressure sensor	ut.	2
	Pyranometer	ut.	1
	Nitriletube	m	100
	Weather station and corresponding mounting kit	ut.	1
	Power supply		
	Power supply	ut.	3
	Lithium battery	ut.	101
	Uninterruptible power supply (UPS)	ut.	2
	Communications		
	Personal computer	ut.	3
	Rack	ut.	1
	Network cable	m	4
	Data cable	m	450
	Rack tray	ut.	2
	Tray	m	110
	Galvanised steel wiring duct	m	15
	Corrugated shielded wiring duct	m	10
	RS485 adaptor	ut.	3
Occupancy detection	Three-conductor cable	m	2
	Personal computer	ut.	1
	Converter	ut.	1
	RJ45 data cable	m	5
	Video recorder	ut.	1
Energy monitoring	**Sensor nodes**		
	Energy metre	ut.	3
	Smart metre	ut.	15
	Current sensor	ut.	120
	Ethergate	ut.	3
	Shielded cable	m	120
	Power		
	Magneto-thermal switch	ut.	1
	Uninterruptible Power Supply (UPS)	ut.	1
	Low smoke, zero halogen, flame retardant cable	m	60
	Communications		
	UDP proxy	ut.	1
	Energy controller	ut.	2
	Network switch	ut.	2
	Powerbox panel for UPS supply	ut.	1
	Wiring duct	m	10
	Rack	ut.	1
	Rack tray	ut.	1
	Data transmission cable	m	4
Control	**Ventilation**		
	Electrical panel	ut.	2
	Programmable logic controller (PLC)	ut.	2
	Lighting		
	DALI lighting control interface	ut.	2
	DALI data wiring	m	450
	Escalator		
	Radar	ut.	1
	Data cable	m	2

Table 3 shows the cumulative energy demand related to the assembly phase of the SEAM4US energy management system by subsystem. Table 4 illustrates results related to the energy consumption of the SEAM4US energy management system during the assembly, transport, use and maintenance phases. The initial embodied energy is defined as the total primary energy required by the devices in the system, including the extraction of raw materials, manufacturing and transportation to the station (cradle to site). Similarly, the recurring embodied energy is defined as the total primary energy used during maintenance activities. Finally, the operational energy corresponds to the primary energy consumed during the useful life of the system.

3.1.4. *Interpretation of the results*

The last stage of an LCEA involves interpreting the results, which is done in Section 4.

3.2. *Identification of the energy saving provided by the SEAM4US energy management system*

The SEAM4US energy management system was implemented in a prototype underground station and energy savings were verified according to the International Performance Measurement and Verification Protocol [17]. Energy savings achieved with the lighting control system were determined by partial field measurement. The ventilation control system's performance was assessed trough calibrated simulation because of the multiplicity of external influencing factors (including temperature, wind speed and direction, and indoor temperature). However and in order to get further evidence, on-site measured performance data was recorded during two months. Because of the constraints imposed by the pilot, savings obtained with the escalator's control system were estimated by simulating the model with the real data recorded by the occupancy network. Results showed potential yearly energy savings ranging between 74,336 and 87,339 kWh (Table 5).

3.3. *Assessment of the energy performance of the SEAM4US energy management system*

Table 6 shows the energy payback time and the energy return factor of the SEAM4US energy management system for the two lifespan scenarios. The results were obtained taking into account the primary conversion factor of 2.461 MJ_p/MJ_f set by the Spanish Institute for Energy Diversification and Saving [18], which is along the lines of that suggested by the European Directive 2012/27/EC (2.5 MJ_p/MJ_f) [19].

Table 2
Assumptions for the process steps considered in this study.

Process step	Assumptions		Data source
Production	Composition of the system: Technical specifications + budget		Ecoinvent v2.0 [14]
	Non-electronic devices:	No transport	–
	Electronic devices:	Transport of 6884 km from the production site (in China) to the assembling site (Oulu, Finland)	Transoceanic freight ship transport from Ecoinvent v2.0 [14]
Transport	Transport of 3125 km from the assembling site (Oulu, Finland) to the use site (Barcelona, Spain)		European aircraft freight transport from Ecoinvent v2.0 [14]
Use	Operation: 24 h per day, 365 days a year, for 5/10 years (in accordance with current operating schedules of the Barcelona metro network)		Spanish electricity mix, at a low voltage level, from Ecoinvent v2.0 [14]
Maintenance	Change of batteries: every 2 years (assuming 2900 mAh battery capacity and 180 s transmission interval)		AA cell battery (Li-ion) from Ecoinvent v2.0 [14]

Table 3
Cumulative energy demand of the SEAM4US energy management system during the assembly phase.

SEAM4US energy management subsystem	Cumulative energy demand [MJ_p eq]
Core system	5636.48
Environmental monitoring system	95,586.50
Occupancy detection	6308.77
Energy monitoring system	32,463.53
Control	18,144.29
Total	158,139.57

Table 4
Cumulative energy demand of the SEAM4US energy management system during the assembly, transport, use and maintenance phases, depending on the assumed lifespan.

	Cumulative energy demand [MJ_p eq]	
	5-year lifespan	10-year lifespan
Initial embodied energy	158,139.57	158,139.57
Operational energy	346,005.38	692,010.76
Recurring embodied energy	1171.42	2342.85
Total	505,316.37	852,493.17

Table 5
Energy saving provided by the SEAM4US system.

Subsystems	Energy consumption baseline [MJ_f]	Percentage of saving (%)
Lighting (only public spaces)	214,878.99	24.1 ± 1.9
Ventilation	84,193.19	30.6 ± 2.0
Escalators	38,693.2	8.5 ± 1.9
Others	273,806.61	–
Total	611,571.99	13.2 ± 1.1

Table 6
Energy payback time and energy return factor depending on the assumed lifespan.

	5-year lifespan		10-year lifespan	
	Minimum	Maximum	Minimum	Maximum
Energy payback time [years]	0.15	0.13	0.13	0.11
Energy return factor [–]	32.58	38.28	77.25	90.77

4. Discussion of the results

The assembly phase of the SEAM4US energy management system was found to involve a cumulative energy demand of 158,139.57 MJ_p eq. The results show that the environmental monitoring subsystem dominates the energy consumption (60.44%). The energy monitoring subsystem was found to be responsible for 20.53% of total energy consumption, and the control subsystem accounted for another 11.47%. According to the results, the occupancy detection subsystem represents 3.99% of the energy consumed, mainly because it relies on existing infrastructure. The rest of the energy consumption can be attributed to the core system (3.56%) (Table 3).

Assuming a lifespan of 5 years, the cumulative energy demand of the energy management system for underground stations amounts to 505,316.37 MJ_p eq (Table 4). The operational energy was found to be about 68.47%, whereas the initial embodied energy accounted for 31.30%. The recurring embodied energy was found to represent only 0.23% of the total energy consumption. As shown in Table 4 and assuming a lifespan of 10 years, the cumulative energy demand of the advanced energy management system was found to be 852,493.17 MJ_p eq. In this case, the operational energy rose to 81.17% of the total electricity consumption, whereas the initial embodied energy amounted to 18.55% and the recurring embodied energy represented 0.27%. Although the impact from the use phase varies depending on the electricity mix of the country where the system is installed, it can be stated that after any significant lifespan, operating effects far outweigh embodied effects, mainly because the system is always on. Strategies that directly or indirectly reduce the operating energy of an energy management system should be the first priority if reducing the total energy of the system is a concern. Further developments of the system should lead to more energy efficient devices and sensors and the optimisation of the frequency of reading transmissions. As the operating energy of the system decreases, it will be increasingly important to reduce its embodied energy. The main opportunities for improvement are associated with the environmental monitoring subsystem, which had by far the highest embodied energy of the SEAM4US system.

The energy payback time for the SEAM4US energy management system was found to range between 47 and 55 days when a useful life of 5 years was considered (Table 6). In the case of a 10-year lifespan, this value was found to be even smaller, between 40 and 47 days (Table 6). Thus, it can be stated that the time required for the energy management system to save the amount of energy consumed during the manufacturing, assembly, transportation, installation and operational phases is almost insignificant compared with its useful life. In this sense, it is important to highlight that the energy management system has much better energy performance than photovoltaic devices, with energy payback times ranging from 0.7 to 3.5 years [20], or building retrofit actions such as installing a high-efficient boiler in residential buildings (4.7 years) [21], or walls insulation in public buildings (26.5 years) [22]. The advanced energy management system was found to save from 32.58 to 90.77 times the energy consumed during the initial phases, depending on the useful life (Table 6).

5. Conclusions

The results of this research provide valuable information for stakeholders in the energy management systems industry, as they contribute to ascertaining the sustainability of products. From the results, we can conclude that advanced energy management systems for underground stations have very high energy performance, even when we consider the energy they consume during raw materials acquisition, manufacturing, transportation, operation and maintenance phases. The system needs to work for less than two months to save the energy needed to compensate for the energy consumed until commissioning and during the usage phase. Thus, the energy management system pays back between 33 and 91 times the energy invested in it.

The assembly phase of the SEAM4US energy management system was found to involve a cumulative energy demand of 158,139.57 MJ_p eq. The results show that the environmental monitoring subsystem dominates energy consumption (60.44%). The cumulative energy demand of the energy management system for underground stations was found to range between 505,316.37 MJ_p eq (useful life of 5 years) and 852,493.17 MJ_p eq (useful life of 10 years). In any case, the operational energy has been found to represent the largest share of the energy consumption (68.47–81.17%).

Many factors may affect the estimation of the cumulative energy demand, the energy payback time, and the energy return factor. Rapid technological development may be a source of variability of results, and have an impact on the production processes as well as the content and energy performance of the actual devices. The system lifespan can be highly variable and difficult to predict. In addition, there is a reasonable risk of obsoleteness before the end of the lifespan. It has been widely argued that energy use must be quantified in primary terms, since this incorporates not only the final energy consumption but also the energy used to produce and deliver it, and thus provides a more global vision of the corresponding environmental impact. However, it must be taken into account that the technology and electricity mix can change during a system's lifespan. Improved databases are needed to increase the potential of LCA studies in the electric and electronic industries. A concerted effort is required to quantify the inputs and outputs of the numerous electric and electronic components, devices and products. Further steps should cover the analysis of the dismantling phase, to evaluate its influence on the energy analysis. Although end of life impacts are expected to be limited, it is also important to model actual e-waste management and to assess alternative waste scenarios, covering informal management when relevant.

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