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Environmental impacts related to the commissioning and usage phase of an intelligent energy management system

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ABSTRACT

This paper presents for the first time the results of a life cycle assessment study for an intelligent energy management system. We considered material acquisition, manufacturing, transportation, assembly, operation and maintenance stages. The results show that the assembly phase had an environmental impact of 897 Eco-indicator 99 points that was mainly due to the monitoring subsystem (87.80%). When the analysis was extended to cover the use phase, the environmental impact ranged from 1,963 (useful life of 5 years) to 3,029 Eco-indicator 99 points (useful life of 10 years). The environmental impact of the use stage was found to represent 54%-70% of the total, whereas the assembly stage represented 46%-30%. The maintenance phase contributed to a very small extent to the total environmental impact (less than 0.5%). In any case, 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.

Keywords:
energy management system, environmental impacts, life cycle assessment, underground station, metro network

1. INTRODUCTION

Many approaches have been found related to life cycle assessment (LCA) within the scope of the broadly defined building industry. According to Ortiz et al. [1], Pajchrowski et al. [2] and Cabeza et al. [3], and within the framework of the top-down approach, the whole building and its entire life cycle are objects of consideration. In the bottom-up approach, the focus is limited to individual materials, components, subsystems or systems. However, to the authors' knowledge, none of the existing initiatives on life cycle analysis address individual systems for managing buildings' energy consumption. Only van Dam et al. [4] explored the effectiveness of home energy management systems taking into account not only the energy savings provided by the system but also the energy needed for its production, use and disposal. Energy management systems have been proved to provide considerable benefits in terms of net energy savings [4] but the full range of environmental impacts related to the whole life cycle of intelligent management systems has not been investigated till now. Although application of information and communication technology (ICT) is often expected to result in decreased environmental impacts [5], several studies focusing on consumer products such computers [6, 7, 8 and 9], monitors [10, 11, 12, 13 and 14], mobile phones [15] and TVs [16] have addressed their negative impacts [17]. Therefore and taking into account the results reported by previous research initiatives within the field of ICT products, it is important to assess the broad spectrum of environmental impacts of devices and components composing intelligent energy management systems during all lifecycle stages. In this sense, life cycle assessment is a widely recognized instrument for assessing the environmental aspects and potential impacts associated with all the stages of a product's life by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts, and interpreting the results [18].

Thus, the main objective of this paper is to contribute to a better understanding of the whole range of environmental impacts related to the commissioning and usage of an intelligent energy management system. The following section describes the energy management system under study. Section 4 presents the methodology used to evaluate its life cycle impacts, which was focused on the material acquisition, manufacturing, transportation, assembly, operation and maintenance stages. This is followed by a discussion of the results and concluding remarks.

2. DESCRIPTION OF THE ENERGY MANAGEMENT SYSTEM

The analysis focuses on an advanced energy management system developed under the auspices of the European research project entitled Sustainable Energy mAnageMent for Underground Stations (SEAM4US) [19]. The SEAM4US energy management system provides smart autonomous control of ventilation, lighting and vertical transportation through the core, monitoring and control subsystems (Figure 1). It has been implemented in a representative underground station of the Barcelona metro network (pilot station) [20].

2.2.1 Core subsystem

The core subsystem remotely manages and supports the monitoring and control subsystems. Due to the strict security policies of public transport operators, the core subsystem cannot be cloud-based and must be located in the operator's control centre. Therefore, a communication infrastructure is needed to integrate the SEAM4US energy management system within the existing operational procedures. The core subsystem is comprised of a centralized server and a backup hard drive disk, holding the central instance of the SEAM4US software.

2.2.2 Monitoring subsystems

The monitoring subsystem creates almost real-time awareness of the station's manageable subsystems. Ventilation control strategies require the monitoring of environmental data, such as surface temperature, relative humidity, air pressure, air speed, pollutants (CO_2 and PM10), outdoor conditions (solar radiation and rain accumulation) and energy consumption, whereas lighting and escalator control requires real-time data on crowd density and energy consumption.

2.2.2.1 Environmental monitoring subsystem

The wireless environmental monitoring network captures ambient data for modelling validation and control feedback. It includes an extensive set of supported sensors (more than 100 units were used in the pilot), communication hardware, as well as management and data handling software. Environmental monitoring is carried out through a dense multihop sensor network, in which network management is optimized and battery replacements are reduced. Wireless deployment also avoids hundreds of meters of cables. In order to monitor outdoor conditions and to predict future behaviour, a weather station is placed outside the station and a weather forecast service is used.

2.2.2.2 Energy monitoring subsystem

The energy consumption monitoring subsystem is aimed at generating energy consumption baselines for the pilot station. It uses detailed energy consumption data from individual subsystems and gives real-time feedback on the energy management system performance. For fairly stable loads such as lighting systems or ventilation, a single smart meter measures multiple power lines. This solution enables the wireless transfer of measurement data (via ZigBee networks), but with reduced monitoring frequency. For highly variable loads such as escalators and elevators, a high performance solution measures few power lines at once, but with high frequency. In this case, measurement data is transferred through RS485 and Modbus/TCP protocols.

2.2.2.3 Occupancy detection subsystem

The occupancy detection subsystem provides an estimation of the crowd density of the spaces in the station with less than 20% error. Unlike all other SEAM4US subsystems, the occupancy monitoring subsystem relies on closed-circuit television (CCTV) infrastructure that is already installed in the station. The use of 20 existing cameras greatly reduces the costs and deployment time, although greater effort is required to create reliable computer vision algorithms. The video processing algorithm and the SEAM4US software interfaces that enable communication with the backend systems are implemented in the CCTV device proxy software. This software runs in the CCTV gateway (desktop computer running Windows 7) at the pilot station and receives the video stream from a dedicated recorder. Algorithm results are sent to the SEAM4US server.

2.2.3 Control subsystem

The control subsystem is responsible for acting on the existing ventilation, lighting and vertical transportation subsystems to reduce the underground station's energy consumption. At the same time, and according to the premises stated by the metro operator, passenger comfort must not be compromised, minimally invasive interventions must be prioritized and the current operator's controllers' tasks must not be modified by SEAM4US actions. This means that the energy management system must be transparent and seamlessly integrated with current operator policies.

The ventilation control system is based on a model predictive control (MPC) approach that considers current building status, the short-term weather forecast, train transit, an occupancy prediction and the estimation of future building status [21]. In order to determine in advance the optimal control policies and anticipate the reaction to external forces [22], the controller includes an optimization algorithm that, at each step, generates a set of candidate control actions, predicts the future status of the building through the embedded model, and selects the optimal action through a scenario analysis. The predictive model is adaptive, as it has learning capabilities and is continuously updated with a feed of actual monitored data life-long. The commands are transferred to the ventilation system through new programmable logic controllers (PLC). PLCs modulate the fans' speed by controlling the corresponding variable frequency drives.

The lighting subsystem is regulated taking into account the two main criteria stated by the metro operator: (1) not to diminish the passenger's feeling of security and (2) to fulfil the minimum lighting levels required by current regulations. In light of the above, it was assumed that a good lighting level is required when there are only a few people in the station, whereas when the occupancy is higher, the minimum lighting level will be enough to perform the visual task. Thus, the lighting control system benefits from real-time crowd density data gathered by the occupancy monitoring subsystem and the user model. These data provide an empirically based prediction of the occupancy of a given space in the station in the near future. Commands are transferred to each lighting fixture through a digital addressable lighting interface (DALI) controller and corresponding compatible ballasts.

The escalators' speed is also modulated between the operational range of 0.2 and 0.5 m/s on the basis of the occupancy monitoring subsystem and the user model. If we assume that the energy consumption decreases at lower speeds, load capability and queue generation are the two main drivers. In other words, the SEAM4US system has to make sure that passengers do not need to wait for longer than strictly necessary and that the escalator motor does not work out of the safety range. Escalators are equipped with programmable logic controllers (PLCs) to interface with the SEAM4US server. In addition, radars are essential to avoid changes in the escalators' speed when users are riding them.

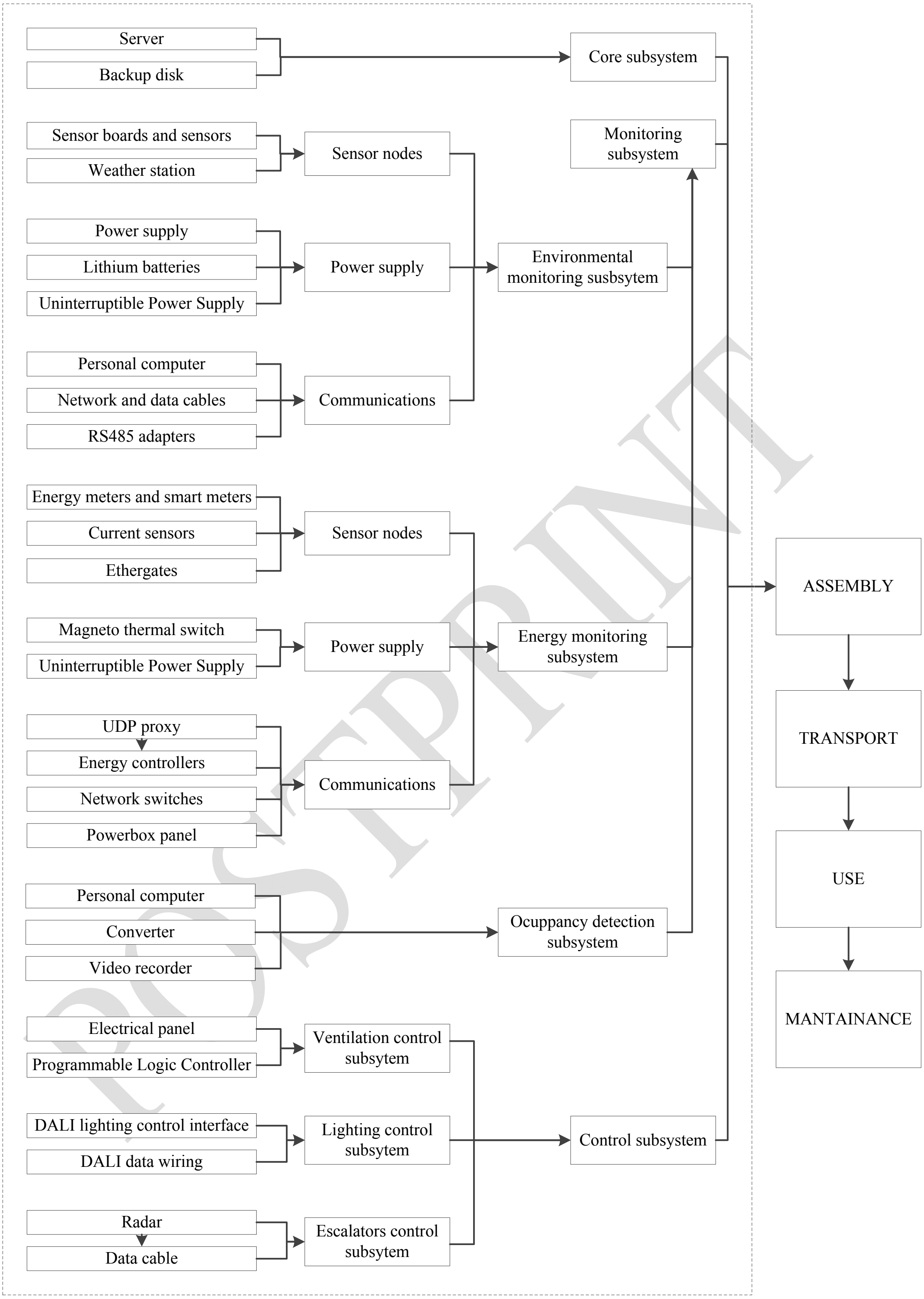

Figure 1. System boundaries.

3. METHODOLOGY

This life cycle assessment study follows the methodology described in ISO 14040 Environmental management – life cycle assessment – principles and framework [18] and ISO 14044 Environmental management – life cycle assessment – requirements and guidelines [23]. Calculations were performed with SimaPRO 7.1 [24] and the Ecoinvent v2.0 database [25]. The Eco-indicator 99 (E) v2.06 method [26] was used to estimate the environmental impacts.

3.1 GOAL AND SCOPE OF THE LIFE CYCLE ASSESSMENT

The goal of the study was to estimate the environmental impacts of commissioning and using an intelligent energy management system in an underground metro station (Figure 1). We took into account manufacturing (including all the steps from material extraction up to the assembly of all the component devices), transport (from production sites to the assembly site and on to the pilot station) and functional lifespan (including usage and maintenance). The functional unit was defined as the manufacturing and usage of an energy management system over its lifetime. The lifetime of an energy management system depends on many factors, and thus it is difficult to predict. For this reason, 5-year and 10-year lifetime scenarios were considered.

3.3 LIFE CYCLE INVENTORY, ASSUMPTIONS AND DATA

The following subsections provide an overview of the assumptions made in each lifecycle stage.

3.3.1 Production

The types, quantities and unitary weights of the devices, elements and materials comprising the energy management system were identified according to their technical specifications, the estimated budget and corresponding bill of quantities for deployment in the pilot station, direct observations and expert consultation. All the identified devices and components were linked to respective datasets from Ecoinvent v2.0 [25].

3.3.2 Transport

All the electronic devices in the energy management system were assumed to be transported by sea covering a distance of 6,884 km from the production site (in China) to the assembly site (Oulu, Finland). Average data for transoceanic freight ship transport from Ecoinvent v2.0 were used [25]. Afterwards, the electronic devices as well as other components and materials used in the energy management system were assumed to be transported 3,125 km from the assembly site (Oulu, Finland) to the pilot station (Barcelona, Spain). In this case, average data for European aircraft freight transport were used from Ecoinvent v2.0 [25].

3.3.3 Use and maintenance

In accordance with current operating schedules of the Barcelona metro network, the SEAM4US energy management system is assumed to work 24 hours per day, 365 days a year, using the Spanish electricity mix, low voltage level, from Ecoinvent v2.0 [25]. The energy used during the operational phase was estimated at 20,435.33 MJ per year. Two lifespan scenarios were considered: 5 years and 10 years. The maintenance phase included battery replacement activities. The replacement interval depends on the battery capacity and interval in which the data is sent to the backend systems. Assuming a 180-second interval and 2900 mAh battery capacity, the batteries must be changed every 2 years.

3.4 IMPACT ASSESSMENT

According to the results, the environmental impact related to the assembly phase of the intelligent energy management system amounted to 897.02 Eco-indicator 99 points. The energy management system mostly contributed to the resource damage (51.50%) and human health (29.88%) categories, followed by damage to ecosystem quality (18.62%). The main environmental impact was found to be fossil fuel depletion (35.21%). Respiratory effects caused by inorganic pollutants were in second position (17.03%), whereas mineral depletion was ranked third (16.29%). The impact of ecotoxicity accounted for 12.07% and carcinogenic substances represented 8.55% of the overall environmental impact. The rest of the environmental impact was attributed to climate change (4.14%), land use (4.09%), acidification / eutrophication (2.46%), radiation (0.11%), respiratory effects caused by organic pollutants (0.02%) and ozone layer depletion (0.02%) (Table 1).

Impact category [Eco-indicator'99 points]	SEAM4US system		SEAM4US subsystems										
			Core subsystem		Environmental monitoring subsystem		Energy monitoring subsystem		Occupancy detection subsystem		Control subsystem	
Carcinogens	76.65	8.55%	2.25	8.32%	50.23	9.33%	16.73	7.72%	2.82	8.70%	4.62	5.61%
Respiratory effects (organics)	0.20	0.02%	0.01	0.03%	0.12	0.02%	0.04	0.02%	0.01	0.03%	0.02	0.03%
Respiratory effects (inorganics)	152.80	17.03%	5.32	19.63%	92.01	17.09%	35.72	16.48%	6.23	19.19%	13.52	16.42%
Climate change	37.17	4.14%	1.32	4.86%	22.67	4.21%	7.68	3.54%	1.46	4.50%	4.04	4.91%
Radiation	1.03	0.11%	0.05	0.20%	0.63	0.12%	0.18	0.08%	0.06	0.18%	0.11	0.13%
Ozone layer	0.17	0.02%	0.00	0.00%	0.11	0.02%	0.05	0.02%	0.00	0.00%	0.00	0.00%
Ecotoxicity	108.27	12.07%	2.63	9.69%	62.52	11.61%	32.64	15.06%	3.45	10.62%	7.04	8.55%
Acidification / eutrophication	22.06	2.46%	0.70	2.58%	13.49	2.51%	4.76	2.20%	0.81	2.49%	2.31	2.80%
Land use	36.70	4.09%	1.37	5.05%	23.71	4.40%	7.18	3.31%	1.59	4.91%	2.85	3.46%
Minerals	146.14	16.29%	3.71	13.68%	83.06	15.43%	44.10	20.35%	4.96	15.28%	10.32	12.54%
Fossil fuels	315.82	35.21%	9.75	35.98%	189.89	35.27%	67.64	31.21%	11.06	34.10%	37.48	45.53%
Total	897.02	100.00%	27.11	100.00%	538.44	100.00%	216.71	100.00%	32.44	100.00%	82.31	100.00%

Table 1. Environmental impacts caused by the manufacturing of the various SEAM4US subsytems.

Table 2 also shows the environmental impacts caused by the manufacturing of the various SEAM4US subsytems. The results revealed that the environmental impact related to the assembly phase of the SEAM4US energy management system was mainly caused by the monitoring subsystem (87.80%). The control subsystem was found to represent the second largest source of pollution, as it accounted for 9.18% of the overall impact. Finally, the core subsystem was found to be responsible for 3.02% of the total impact. According to the results, the impact of the monitoring subsystem can be mostly attributed to the environmental monitoring subsystem (60.03%), followed by the energy monitoring subsystem (24.16%) and the occupancy detection subsystem (3.62%) (Table 2).

SEAM4US system	**Environmental impact** [Eco-indicator'99 points]	
Core subsystem	27.11	3.02%
Environmental monitoring subsystem	538.44	60.03%
Energy monitoring subsystem	216.71	24.16%
Occupancy detection subsystem	32.44	3.62%
Control subsystem	82.31	9.18%
Total	897.02	100.00%

Table 2. Environmental impact caused by the manufacturing of the various SEAM4US subsytems.

According to the impact assessment, the SEAM4US system results in an overall impact of 1963.10 Eco-indicator 99 points if the commissioning stage (including raw materials acquisition, manufacturing and transportation) and a 5-year usage phase (including operation and maintenance) are taken into account (Table 3). The category with the highest percentage was resource damage (51.35%), followed by human health damage (34.93%) and ecosystem quality damage (13.72%). As shown in Table 3, the environmental impact was clearly dominated by fossil fuel extraction (42.88%). Respiratory effects on humans caused by inorganic substances (23.94%), mineral extraction (8.47%), ecotoxicity (7.73%), climate change (5.43%) and carcinogenic effects on humans (5.28%) were also found to contribute significantly to the environmental impact. According to the results, acidification and eutrophication accounted for 3.36% of the overall impact, whereas land use represented 2.63%. Other environmental impacts such as ionizing radiation (0.25%), respiratory effects caused by organic substances (0.01%) and ozone layer depletion (0.01%) were found to be of less importance. According to Table 4, more than half of the environmental impact related to the SEAM4US system, including material acquisition, manufacturing, transportation, assembly, 5-year operation and maintenance stages, could be attributed to the use phase (53.93%). The assembly phase was found to represent 45.69%, whereas the maintenance phase, including battery replacement, was found to involve only 0.37% of the impact (Table 4).

Impact category [Eco-indicator'99 points]	Total		Assembly phase		Operational phase (5 years)		Maintenance phase	
Carcinogens	103.65	5.28%	76.65	8.55%	26.99	2.55%	0.02	0.22%
Respiratory effects (organics)	0.29	0.01%	0.20	0.02%	0.08	0.01%	0.00	0.02%
Respiratory effects (inorganics)	469.91	23.94%	152.80	17.03%	314.46	29.70%	2.65	36.21%
Climate change	106.66	5.43%	37.17	4.14%	69.20	6.54%	0.29	3.91%
Radiation	4.93	0.25%	1.03	0.11%	3.90	0.37%	0.00	0.03%
Ozone layer	0.19	0.01%	0.17	0.02%	0.02	0.00%	0.00	0.00%
Ecotoxicity	151.70	7.73%	108.27	12.07%	43.40	4.10%	0.03	0.44%
Acidification / eutrophication	65.94	3.36%	22.06	2.46%	43.54	4.11%	0.33	4.51%
Land use	51.69	2.63%	36.70	4.09%	14.71	1.39%	0.28	3.79%
Minerals	166.33	8.47%	146.14	16.29%	18.94	1.79%	1.25	17.01%
Fossil fuels	841.81	42.88%	315.82	35.21%	523.51	49.45%	2.48	33.86%
Total	1,963.10	100.00%	897.02	100.00%	1,058.75	100.00%	7.33	100.00%

Table 3. Environmental impacts caused by the SEAM4US system until commissioning (including raw materials acquisition, manufacturing and transportation) and during the usage phase (including operation and maintenance) considering a useful life of 5 years.

Environmental impact [Eco-indicator'99 points]	**Lifetime scenarios**			
	5 years		**10 years**	
Assembly phase	897.02	45.69%	897.02	29.61%
Operational phase	1,058.75	53.93%	2117.50	69.90%
Maintenance phase	7.33	0.37%	14.66	0.48%
Total	1,963.10	100.00%	3029.18	100.00%

Table 4. Environmental impact caused by the SEAM4US system until commissioning (including raw materials acquisition, manufacturing and transportation) and during the usage phase (including operation and maintenance) considering a useful life of 5 and 10 years.

When the analysis was extended to cover a 10-year use phase, the environmental impact of the energy management system for underground stations was found to amount to 3029.18 Eco-indicator 99 points (Table 5). However, the damage categories were found to have similar percentages. The category with the highest percentage was still resource damage (51.31%), whereas human health damage amounted to 36.42% and ecosystem quality damage represented 12.27% of the impact. In this case, the environmental impact was also dominated by fossil fuel extraction (45.15%) and respiratory effects caused by inorganic pollutants (25.98%). Other environmental impacts such as ecotoxicity (6.44%), mineral extraction (6.16%) and climate change (5.82%) also contributed significantly. Finally, minor environmental impacts were found to be carcinogen effects (4.31%), acidification / eutrophication (3.63%), land use (2.20%), radiation (0.29%), respiratory effects caused by organic pollutants (0.01%) and ozone layer depletion (0.01%) (Table 5). In this case, the impact of the usage phase of the SEAM4US system rose to 69.90%, whereas the impact of the assembly phase diminished to 29.61%, and the maintenance phase accounted for 0.48% of the overall impact (Table 4).

Impact category [Eco-indicator'99 points]	Total		Assembly phase		Operational phase (10 years)		Maintenance phase	
Carcinogens	130.66	4.31%	76.65	8.55%	53.97	2.55%	0.03	0.22%
Respiratory effects (organics)	0.37	0.01%	0.20	0.02%	0.16	0.01%	0.00	0.02%
Respiratory effects (inorganics)	787.03	25.98%	152.80	17.03%	628.93	29.70%	5.31	36.21%
Climate change	176.15	5.82%	37.17	4.14%	138.41	6.54%	0.57	3.91%
Radiation	8.83	0.29%	1.03	0.11%	7.79	0.37%	0.00	0.03%
Ozone layer	0.21	0.01%	0.17	0.02%	0.04	0.00%	0.00	0.00%
Ecotoxicity	195.13	6.44%	108.27	12.07%	86.80	4.10%	0.06	0.44%
Acidification / eutrophication	109.81	3.63%	22.06	2.46%	87.08	4.11%	0.66	4.51%
Land use	66.68	2.20%	36.70	4.09%	29.42	1.39%	0.56	3.79%
Minerals	186.52	6.16%	146.14	16.29%	37.88	1.79%	2.49	17.01%
Fossil fuels	1367.81	45.15%	315.82	35.21%	1047.02	49.45%	4.96	33.86%
Total	3029.18	100.00%	897.02	100.00%	2117.50	100.00%	14.66	100.00%

Table 5. Environmental impacts caused by the SEAM4US system until commissioning (including raw materials acquisition, manufacturing and transportation) and during the usage phase (including operation and maintenance) considering a useful life of 10 years.

In both cases, the impact of the use phase was dominated by fossil fuels (49.45%), respiratory inorganics (29.70%) and climate change (6.54%) due to the system's electricity consumption. Other minor impacts were acidification / eutrophication (4.11%), ecotoxicity (4.10%), carcinogens (2.55%), minerals (1.79%), land use (1.39%), radiation (0.37%) and respiratory organics (0.01%) (Table 3 and 5). Similarly, the highest environmental impact related to the maintenance phase was found to be respiratory effects caused by inorganic pollutants (36.21%), followed by fossil fuel extraction (33.86%) and mineral extraction (17.01%) (Table 3 and 5).

4. RESULTS DISCUSSION

Although a broad variety of LCA studies dealing with different ICT devices have been published, none of them focus on the environmental impact related to energy management systems. However, major power generation technologies have been covered by several studies and they conclude that fossil fuel based technologies can never compete with renewable technologies. According to Rashedi et al. [27], photovoltaic, biomass plants, nuclear plants and wind farms and hydro-kinetic power technologies are sequentially better than the fossil fuel technologies. Desideri et al. [28] examined the life cycle impact of a ground-mounted photovoltaic plant with a useful life of 25 years. The environmental impact was found to range between 0.0073 and 0.0078 Eco-indicator 99 points for 1 KWh of produced energy depending on the end of life scenario. Desideri et al. [29] analysed a concentrated solar thermal power plant with parabolic trough collectors with a technical lifetime of 30 years. In this case, the environmental impact was found to amount to 0.0023 Eco-indicator 99 points per kWh of produced energy. Rashedi et al. [27] focused on the analysis of the eco-profile of onshore vertical and horizontal axis wind turbines and concluded that it ranges from 0.0007 to 0.0012 Eco-indicator 99 points per kWh of produced energy.

According to the SEAM4US project [29], the energy management system is planned to save at least 5% of the energy consumed in an underground station. Taking into account the energy consumed in a representative underground station of the Barcelona metro network [20] and the primary conversion factor of 2.461 MJp/MJf set by the Spanish Institute for Energy Diversification and Saving [30], the eco-profile of each kWh of primary energy saved by the intelligent energy management system ranges between 0.0039 and 0.0040 Eco-indicator 99 points. Thus and in light of the obtained results, energy management systems become a competitive alternative for turning metro stations into more sustainable spaces, especially when taking into account the constraints posed by their underground and urban character.

Taking into account that 1 Eco-indicator 99 point represents one thousandth of the yearly environmental load of an average citizen in Europe [26], the environmental impact related to the assembly of the SEAM4US energy management system (897.02 Eco-indicator 99 points) is comparable to the environmental load of an average European citizen during no more than 9 years. This environmental impact was found to be clearly dominated by the monitoring subsystem (87.80%). However, this percentage would have been higher if the occupancy detection subsystem did not rely on existing cameras distributed throughout the station.

Results revealed that the environmental impact was mostly caused by the usage phase of the SEAM4US energy management system (53.93% in a 5-year lifetime scenario and 69.90% in a 10-year life time scenario) mainly because the system is always on. If the efficiency of the system needs to be improved, the technological progress must focus on getting more energy efficient ICT devices and sensors. In this sense, the frequency of reading transmissions could be optimized. The environmental impact related to the usage phase of the SEAM4US energy management system would also be diminished by using environmentally friendly energy sources. Taking into account that the environmental impacts are expected to be increasingly related to raw material extraction and production, it is advisable to get smaller ICT devices and to use the system for as long as possible.

The end-of-life phase was not considered within this study, mainly because of the uncertainty in the final disposal of information and communication technology (ICT) products. Related data is unobservable and reliable quantitative data on treated e-waste flows is not available. In addition, a significant number of electronic devices are processed informally at the end of life [17, 31 and 32]. Some studies such as Duan et al. [9], Hischier and Baudin [13] and Bitencourt de Oliveira [33] mention that proper end-of-life disposal potentially reduces the environmental impact [17] mainly in terms of energy usage. Taking into account that this paper is the first step in modelling all the life cycle impacts of an intelligent energy management system, future studies should address end of life scenarios. This is even more important if we take into account the speed of technological progress and obsolescence in the ICT sector.

Modelling of information and communication technology products reveals numerous problems with data availability and quality. Furthermore, an insurmountable challenge in producing a rigorous LCA of an ICT product is the presence of hundreds of components inside any device with hundreds, and perhaps thousands, of contractors and sub-contractors responsible for different aspects of it [34]. In addition, standardized life cycle impact (LCI) databases do not include enough specific electronic components, and thus LCA studies must rely on proxy data. Better coverage of electric and electronic components, devices and products and improved quantification of their inputs and outputs in LCI databases would enhance the usefulness of LCA studies within this industry.

Taking into account that obsolescence risks may go beyond the devices' useful physical life span, the useful life of an energy management system is highly difficult to predict and this may involve a high variability of results. Moreover, it must be taken into account that the electricity mix can change during a system's lifespan.

Another aspect that is difficult to address in LCA studies on ICT products is spatial variation and local environmental uniqueness [34]. In this paper, overall data sets were used for the manufacturing stage. The nature of ICT supply chains could not be modelled because it would be resource-intensive, if not impossible, due to the complexity of the system under consideration. However, a distinction was made, in terms of transport, between electronic products, electric devices and other components and materials in the energy management system. Electronic products were assumed to be manufactured in China, whereas electric devices and other components and materials were assumed to be manufactured near the assembly site (Oulu, Finland). The usage phase was modelled at regional level, using the Spanish electric mix.

5. CONCLUSIONS

The results of this research provide for the first time an insight into the environmental impact caused by the commissioning and usage phases of an intelligent energy management system using the life cycle assessment methodology. System boundaries included manufacturing (including all the steps from material extraction up to the assembly of all the component devices), transport (from production sites to the assembly site and on to the pilot station), assembly, usage (considering two lifespan scenarios of 5 and 10 years) and maintenance. Life cycle impacts were calculated with SimaPRO 7.1 [24] using the Eco-indicator 99 (E) v2.06 method [26] and the information contained within the Ecoinvent v2.0 database [25]. The key contributions of this study are summarized below:

- The environmental impact related to each kWh of primary energy saved by means of the intelligent energy management system ranges between 0.0039 and 0.0040 Eco-indicator 99 points, competing remarkably with renewable power generation sources.
- The assembly phase of the SEAM4US energy management system has an environmental impact of 897 Eco-indicator 99 points. The monitoring subsystem dominates the environmental impact (87.80%), followed by the control subsystem (9.18%) and the core subsystem (3.02%). The main environmental impacts related to the assembly phase of the energy management system are fossil fuel depletion (35.21%), respiratory effects caused by inorganic pollutants (17.03%), mineral depletion (16.29%) and ecotoxicity (12.07%).
- When considering the use phase, the environmental impact of the energy management system for underground stations ranges between 1,963 Eco-indicator 99 points (useful life of 5 years) and 3,029 Eco-indicator 99 points (useful life of 10 years). The greatest impact is on resources (about 51%), and there is also a major impact on human health (35%-36%). The least impact is on ecosystem quality (12%-14%). Fossil fuel depletion (43%-45%) and respiratory effects caused by inorganic pollutants (24-26%) are the main environmental impacts.
- The use stage has a greater environmental impact than the assembly stage, ranging between 54% (useful life of 5 years) and 70% (useful life of 10

years), whereas the assembly stage represents between 46% and 30% of the total environmental impact, respectively. In both cases, the impact of the use phase is dominated by fossil fuels (49.45%), respiratory inorganics (29.70%) and climate change (6.54%).

- The maintenance phase contributes slightly to the total (0.37% in the 5-year scenario and 0.48% in the 10-year scenario). In this case, the impact is dominated by respiratory effects caused by inorganic pollutants (36.21%), fossil fuel extraction (33.86%) and mineral extraction (17.01%).

Taking into account that direct environmental effects should not detract from the environmental benefits in terms of energy saving, this paper is useful for a range of stakeholders –including the electronics industry, building energy managers, building owners and policy makers – as it provides the grounds future environmental improvements. Considering the huge increase and expected future growth of intelligent energy management systems, manufacturers should be able to identify future optimization opportunities. For example and taking into account that the main environmental impacts arising from the intelligent energy management system were directly related to energy usage, priority areas of action include improving the energy efficiency of the system. The transition to environmentally friendly energy sources would also contribute to reducing the environmental impact of the SEAM4US system. It is also advisable to use the system for as long as possible to diminish the environmental impact of the assembly phase. This paper also sets the basis for environmental benchmarking among competing technologies.

Further research is needed to analyse the environmental impact related to end of life. Improved LCI databases are needed, as data quality and availability is a serious challenge in life cycle assessment studies of ICT products.

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