

Life-cycle Assessment of an Intelligent Lighting System Using a Distributed Wireless Mote Network

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Abstract — This paper describes a life-cycle assessment (LCA) of an efficient lighting system for commercial buildings using a distributed sensor network. This lighting system is controlled by intelligent software that uses miniaturized wireless networked sensors – motes – for sensing and actuation. The mote network is an experimental wireless sensor network that aims to be smaller, more efficient, less expensive and more versatile than other network alternatives. The LCA described in this paper shows the new lighting system has the potential to achieve environmental benefits in comparison to existing systems. The environmental impacts of the proposed intelligent lighting system are 18 to 344 times smaller than those of the conventional lighting system for the different environmental impact categories considered: acidification, global warming potential, carcinogenicity, non-cancer potential, ecotoxicity, photochemical smog, eutrophication, ozone depletion potential, and fossil fuel depletion. This case study also provides insight for design choices in the sensor network, such as what type of battery should be used or which materials should be minimized.

Keywords—Life-cycle assessment; Intelligent lighting; Sensor motes;

INTRODUCTION

The intelligent lighting system (ILS), using a wireless distributed sensor mote network [1] proposed by UC Berkeley's Berkeley Expert Systems Technology (BEST) Lab, was designed to be an efficient lighting solution for commercial buildings. Studies show that the proposed ILS will decrease buildings' lighting electricity consumption by as much as 45% [2]. This is especially significant because approximately 20% of electricity generated in the US goes into lighting [3]. In previous research, it was assumed that this lighting solution was better for the environment because it consumed less electricity than existing lighting systems. An economic study also showed that the system installation and retrofit cost could be recovered in approximately three and a half years [3]. In addition, energy prices could be significantly reduced if widespread implementation of this system was achieved. These energy savings are significant because as little as a 1% load reduction can lead to a 10% reduction in wholesale electricity prices, while a 5% load reduction can cut the wholesale prices in half [5]. Knowing these facts, the

proposed ILS appeared to be an excellent system for saving money and energy.

However, all of the previous analyses of this lighting system neglected to examine the environmental impacts. Since reduced environmental impact is one of the major selling points of the system, an in-depth environmental impact study was initiated.

Life-cycle assessment (LCA) is an approach well-suited for comparing the environmental impacts of the current conventional lighting system to the proposed ILS. It provides a methodology to answer the question, "Is the proposed lighting system better for the environment than the existing system?"

In addition to the analysis, the results of the LCA will be used to gain an understanding of the design trade-offs and their relative environmental impact in order to refine and improve the future design of the proposed ILS.

SCOPE OF STUDY

The LCA includes a cradle-to-grave analysis of five life-cycle stages: raw materials extraction/acquisition, materials processing, product manufacture, product use, and final disposal. Included in the current study are the environmental impacts caused by the transportation needed to deliver the product between stages. The study uses data sources from

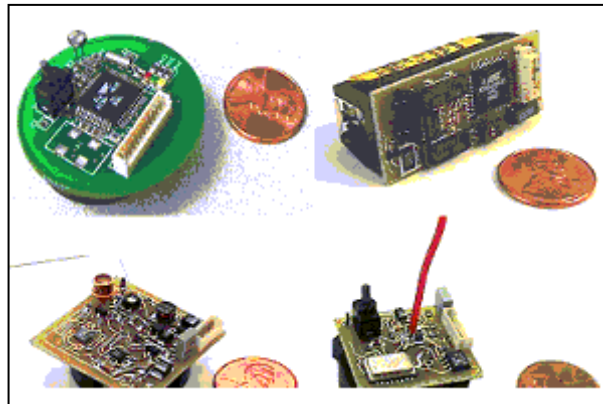


Fig 1. Examples of sensor and actuator motes [4].

1994 to 2002. Appropriate assumptions are made where data cannot be found, provided these assumptions have a relatively small influence on the total environmental impact.

The Product Analyzed: The LCA includes every component that must be created to install the proposed ILS. This includes the wireless sensor mote network, dimmable ballasts, mote housings, and batteries.

Functional Unit: The system is designed to meet the lighting needs of an office building of 5000 square feet for one year.

MODEL DESCRIPTION

In order to quantify the environmental impact of implementing the proposed ILS, the system was broken down into its components. The components modeled in the system are shown in Table I. Examples of sensor motes can be seen in Fig. 1.

Environmental data were gathered for the analysis of each component. The total impact of the ILS was then compared to that of the conventional lighting system. The conventional lighting system total impact is equal to the impact of generating 1.095E6 MJ of electricity in the US. This value was derived from the ILS's projected annual electricity saving [3]. The U.S. electricity model uses a weighted impacts model of coal, natural gas, and oil used for electricity generation.

The LCA of the proposed ILS involves tracking every significant component of the system through its life. This

TABLE I. INTELLIGENT LIGHTING SYSTEM DESCRIPTION

Component	Description
Ballast Housing	The system uses an electronic dimmable ballast. A ballast is a power supply and electronics for florescent light bulbs. The housing is a sheet metal box that houses the electronics.
Ballast Transformer/ Inductor (Cu)	Making up the majority of the weight of the ballast is the transformer and inductor. This component is the copper wire windings of the transformer and inductor.
Ballast Transformer/ Inductor (Si steel)	This component is the silicon steel of the transformer and inductor.
Integrated Circuit (ballast)	The integrated circuit inside the ballast.
Integrated Circuit (mote)	The integrated circuit inside the mote.
Li Battery (mote)	The single lithium AA battery used to power the mote.
Metal Forming (ballast housing)	This is the process of forming the ballast housing sheet metal into a box.
Paint (ballast)	This component is the paint used to coat the ballast housing.
Plastic Casing (mote)	The plastic casing is a small ABS plastic case that houses the mote.
Printed Circuit Board (mote)	The mote uses a printed circuit board to interface with the integrated circuit. The printed circuit board component includes the circuit board itself, the interconnects, solder, capacitors, resistors, and other small common circuit components.
Transportation	Transportation is the process of moving the mote and ballast from the supplier to the site of system installation.

begins with raw material acquisition and finishes with its final disposal. All of the processes involved in implementing the ILS are displayed in the process flow chart in Fig. 2.

LIFE-CYCLE INVENTORY

Life-cycle inventory (LCI) is the quantification of raw material and fuel inputs as well as the solid, liquid, and gaseous emissions from a product system. For the proposed lighting system, this includes the material, energy, and other resource consumption used in raw materials extraction/acquisition, materials processing, product manufacture, transportation, and final disposal. For the conventional lighting system, this includes the energy saved as a result of implementing the ILS. The amount of energy consumed by the ILS in its use phase is not included in either the conventional lighting system or the ILS model because its impact is an order of magnitude greater than any other ILS impact. Since this energy amount is subtracted from both models, the comparison does not change and the ILS impacts are not overwhelmed by electricity used for lighting.

Allocation to the functional unit was performed using Eq. (1).

Mass per functional unit =

$$\frac{\text{Mass of component} \times \text{Number of components}}{\text{Lifetime of component}} \quad (1)$$

LIFE-CYCLE IMPACT ASSESSMENT

Life-cycle impact assessment (LCIA) involves the interpretation of environmental impacts of the environmental emissions identified in the LCI. The goal of the LCIA is to use the data gathered and determine the relative magnitude of contribution to the impact categories for the product system [6]. The impact categories in this assessment include the potentials for acidification, global warming, carcinogenicity, non-cancerous effects, ecotoxicity, photochemical smog, eutrophication, ozone depletion, and fossil fuel depletion.

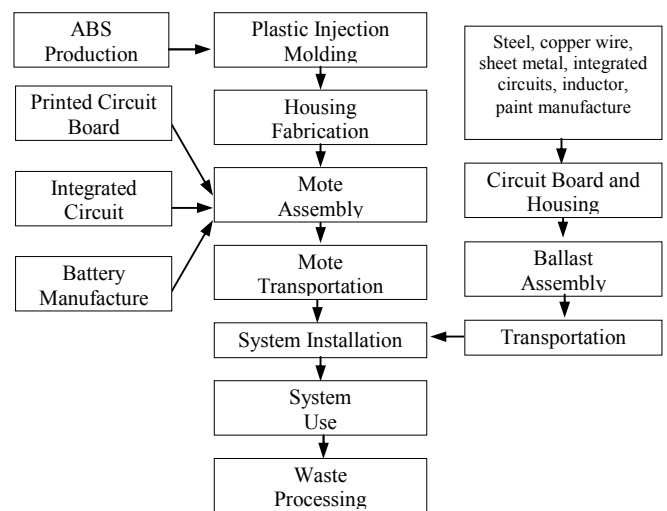


Fig. 2. Simplified process flowchart

The LCI results are translated into the impact categories using emission/resource loadings and equivalency factors. The loading is the inventory amount for each emission/resource. The equivalency factor is a weighting factor that translates a particular emission or resource amount to that which is equivalent to a reference unit. The total contributions to each environmental impact area are calculated using Eq. (2).

$$Total\ Impact = \sum (Loading \times EquivalencyFactor) \quad (2)$$

RESULTS

A. Life-cycle Inventory

The results of the LCI are divided into four categories: emissions to air and water, and consumption of fossil fuels and water. Water use and fossil fuel consumption are shown in Table II. The source of the data for the LCI was [7]. The air and water emissions in the LCI make up an exhaustive list of different substances. (The complete LCI results are found in [8].) A glance at the inventory shows that just about all of the components in the system have emissions such as lead, mercury, ammonia, CFCs, and CO₂ that are commonly recognized to be harmful. The LCIA puts the LCI results into terms that help interpretation and comparability.

Water Use

The total freshwater use of implementing the proposed ILS is nearly 11,000 gallons. The ILS components that require the most water are the integrated circuits of the motes and ballasts, the mote printed circuit boards. The water use of the conventional lighting system is not included as the data bounds and cutoff were not consistent with that of the rest of the model.

B. Life-cycle Impact Assessment

The LCIA results show the relative environmental impacts of the ILS and the conventional lighting system for each

TABLE II. FOSSIL FUEL AND WATER CONSUMPTION

System Component	COAL	NATURAL GAS	OIL	WATER USE
	kg	m ³	MJ	L
Conventional Lighting	118,000	2,434	19,403	-
Ballast Housing	5.6	-	-	12.5
Ballast Transformer and Inductor (cu Wire)	6.6	-	-	2.1
Ballast Transformer and Inductor (si Steel)	10	-	-	22.1
Integrated Circuit (ballast)	181.6	112.6	756	18,254
Integrated Circuit (mote)	90.8	56.3	378	9,127
Li Battery (mote)	56	-	204	1,584
Metal Forming (ballast Housing)	0.162	-		30.9
Paint (ballast)	0.156	-		22.5
Plastic Casing (mote)	1.3	44.1	692	3,460
Printed Circuit Board (mote)	113	58	3,583	8,171
Transportation	-	-	35	-

impact category (Table III). In every impact category, the conventional lighting system yielded a greater impact than the ILS.

C. Acidification

Commonly associated with acid rain, acidification refers to processes that increase the acidity of water or soil. The chief acidifying emissions are sulfur dioxide and nitrogen oxides. Environmental problems resulting from acidification include alteration of alkalinity of lakes and freshwater systems, corrosion of buildings, monuments and historical artifacts, and damage to plants and animals [6]. All acidification-causing chemicals included in the LCA model are expressed in terms of their H⁺ formation potential.

The results of the LCIA show that implementing the ILS would result in reducing the acidification impact by 97%. This reduction, as shown in Table III, is the result of the ILS's electricity savings. As shown in Table IV, the ILS components that are responsible for the greatest acidification impact are the mote battery, the mote printed circuit board, and the copper wire used in the ballast transformer and inductor.

D. Ecotoxicity Potential

Ecotoxicity refers to certain toxic substances that pollute soil and water systems. Plants, animals, and other living organisms are all affected by ecotoxicity. The most common emissions that contribute to ecotoxicity include cadmium, chlorobenzene, lead, and mercury. The LCIA quantifies the potential ecological harm of each emission in terms of its ecological toxicity potential. This value is used to sum the ecotoxicity contribution of all emissions [6]. Table III shows that the ILS's ecotoxicity impact is 344 times smaller than that of conventional lighting. This is a result of the ILS' electricity saving. As shown in Table IV, the ILS components that are responsible for the greatest ecotoxicity impact are the mote printed circuit board and the integrated circuits.

E. Eutrophication Potential

"The most common impairment of surface waters in the U.S. is eutrophication caused by excessive inputs of phosphorus and nitrogen" [6]. The impairment refers to water

TABLE III. SYSTEM COMPARISON

Impact Category (Potential)	Unit	Intelligent Lighting	Conventional Lighting
Acidification	moles H ⁺ equiv	4,896	172,333
Ecotoxicity	lb 2,4-D equiv	40	13,766
Eutrophication	kg N	2	114
Fossil fuel depletion	MJ	158,657	25,242,736
Global warming	kg CO ₂ equiv	4,360	535,201
Carcinogenicity	lb C ₆ H ₆ equiv	11	1,879
Non-cancer	lb C ₇ H ₈ equiv	26,568	1,851,071
Ozone depletion	kg CFC-11 equiv	0.00052	0.0478
Photochemical smog	g NO _x equiv	0.676	12

that is not suitable for drinking, irrigation, recreation, fishing, or use by industry. Eutrophication may be a threat to biodiversity by leading to changes in the number of species in ecosystems. The LCIA presents the eutrophication results as the sum of the eutrophication potentials of each nitrogen- or phosphorus-containing emission relative to 1 kg of nitrogen discharged directly to surface freshwater. The results of the LCIA show that implementing the ILS would result in reducing the eutrophication impact by 98%. The significant electricity savings of the ILS are responsible for this impact reduction. As shown in Table IV, the ILS components that are responsible for the greatest eutrophication impact are the integrated circuit, the mote printed circuit board, and the mote battery.

F. Fossil Fuel Depletion Potential

Fossil fuel depletion is the consumption of non-renewable energy resources, including oil, coal, and natural gas. The significance of this environmental impact lies in the fact that fossil fuel resources are limited and might someday be depleted. The LCA presents the fossil fuel depletion results as the sum of the energy production potential of mined fossil fuels in MJ. Table III shows that the ILS is responsible for the consumption of 159 times less fossil fuels than conventional lighting. This is a result of the ILS' electricity saving. As shown in Table IV, the ILS components that are responsible for the greatest fossil fuels consumption are the integrated circuits and the mote printed circuit board.

G. Global Warming Potential

Global warming refers to the increase in average temperature of the Earth. It is believed that global warming is caused by the build-up of greenhouse gases that trap solar energy reflected from the Earth's surface. The major greenhouse gases are CO₂, CH₄, N₂O, and CFCs. Potential effects of global warming include increased droughts, floods, loss of polar ice caps, sea level rise, soil moisture loss, forest loss, change in wind and ocean patterns, changes in agricultural production, decreased biodiversity and increasing occurrences of extreme weather events [6]. Global warming gases are included in the LCA model in terms of their CO₂ equivalency. Table III shows that the ILS' global warming potential impact

is 123 times smaller than that of conventional lighting. This is a result of the ILS' electricity saving. As shown in Table IV, the ILS components that are responsible for the greatest global warming potential are the mote printed circuit board, the integrated circuits, and the mote battery.

H. Carcinogenicity and Non-cancer Potential

Exposure to toxic substances through the air, water, and soil may cause cancer and other human health problems. Exposure can also be magnified through the food chain. The LCA model calculates the relative toxicological concern of each emission based on its Human Toxicity Potential [6]. The Human Toxicity Potential for each chemical is then compared to baseline values for benzene (for carcinogens) and toluene (for non-carcinogens). Potent emissions in this category include acrylonitrile, benzene, cadmium, chromium VI, lead, and mercury. Table III shows that the ILS' carcinogenicity impact is 171 times smaller than that of conventional lighting. This is a result of the ILS' electricity saving. The non-cancer potential impact is 70 times smaller. As shown in Table IV, the ILS' components that are responsible for the carcinogenicity and non-cancer impacts are the mote printed circuit board, the integrated circuits, the mote battery, and the silicon steel from the ballast transformer and inductor.

I. Ozone Depletion Potential

Ozone depletion refers to the reduction in the amount of ozone in the stratosphere. Depletion of the ozone layer is caused by emissions of CFCs and halons. This depletion is formidable because stratospheric ozone protects the Earth from UVB radiation. Increased exposure to UVB radiation may cause skin cancer and cataracts. UVB radiation can also have harmful effects on crops, materials, and marine life [6]. The LCIA provides ozone depletion potential results as the sum of the ozone depletion potentials of each emission relative to CFC-11. The results of the LCIA show that implementing the ILS would result in reducing the ozone depletion potential impact by 99%. This is a result of the ILS's electricity saving. As shown in Table IV, the ILS components that are responsible for the greatest ozone depletion potential impact are the mote battery, the mote printed circuit board, ballast housing paint.

TABLE IV. TOP CONTRIBUTORS FOR EACH IMPACT CATEGORY

Impact Category	Highest Contributor		Second Highest Contributor		Third Highest Contributor	
	Contributor	Percentage	Contributor	Percentage	Contributor	Percentage
Acidification	Li Battery (mote)	37.8%	Printed Circuit Board (mote)	32.8%	Ballast Transformer/Inductor (Cu)	25.7%
Ecotoxicity	Printed Circuit Board (mote)	82.8%	Integrated Circuit (mote)	7.9%	Integrated Circuit (ballast)	4.0%
Eutrophication	Integrated Circuit (mote)	32.4%	Printed Circuit Board (mote)	25.7%	Li Battery (mote)	25.2%
Fossil fuel depletion	Integrated Circuit (mote)	49.1%	Integrated Circuit (ballast)	24.6%	Printed Circuit Board (mote)	15.6%
Global warming	Printed Circuit Board (mote)	29.7%	Integrated Circuit (mote)	27.2%	Li Battery (mote)	18.0%
Carcinogenicity	Printed Circuit Board (mote)	40.7%	Li Battery (mote)	28.8%	Integrated Circuit (mote)	18.7%
Non-carcinogenicity	Printed Circuit Board (mote)	87.6%	Integrated Circuit (mote)	3.7%	Ballast Transformer/Inductor (Si steel)	2.4%
Ozone depletion	Li Battery (mote)	94.3%	Printed Circuit Board (mote)	2.8%	Paint (ballast)	1.8%
Photochemical smog	Printed Circuit Board (mote)	70.8%	Li Battery (mote)	13.0%	Integrated Circuit (mote)	6.4%

J. Photochemical Smog Creation Potential

Photochemical smog is excessive ozone pollution in the troposphere. Ozone pollution is caused by emissions of nitrogen oxides and volatile organic compounds that react in the presence of UV light from the sun. Photochemical smog leads to detrimental impacts on human health and ecosystems [6]. The photochemical smog impact result given by the LCIA is the sum of all the emissions impacts in terms of their NO_x equivalent. The results of the LCIA show that implementing the ILS would result in reducing the photochemical smog impact by 94%. This is a result of the ILS' electricity saving.

As shown in Table IV, the ILS components that contribute the most to the ozone depletion potential impact are the mote printed circuit board, the mote battery, and the integrated circuit.

TOP CONTRIBUTORS

Table IV shows the relative impact contributions of the top three contributors in each impact category. The most prevalent components in this table are the mote printed circuit board, the mote integrated circuit, and the lithium battery. Besides these three components, only the ballast paint as well as the silicon steel and copper in the ballast transformer and inductor were included in the top three contributors for any of the categories.

UNCERTAINTY

When examining the results of an LCA, it is important to understand the degree of uncertainty associated with the results. Given the LCI and LCIA limitations stated above, the uncertainty of the results is fairly high. Two of the largest sources of uncertainty in the LCA are:

- The data for manufacturing of each mote component were taken from European companies and applied to our model, which is for the US.
- The LCA impacts of the integrated circuit and printed circuit board were determined from data referring to the impacts averaged from all the integrated circuit and printed circuit board manufacturers. The impacts of the specific manufacturers of these mote components may vary from the average significantly.

The LCA results yielded impacts from the proposed ILS that were an order of magnitude smaller than that of the conventional lighting system. With this in mind, the uncertainty of the LCA is likely not large enough to change the overall result that the proposed ILS is better for the environment than the conventional lighting system.

DESIGN INSIGHT

The LCIA results show that only a few components are responsible for the majority of the system's environmental impact. Future mote designs should minimize or eliminate the components with the highest environmental impact. The battery, a major contributor to the system impact, could be eliminated and replaced with a connection to the ballast. The ballast converts the building AC electricity to DC and steps

down the voltage. Since there is one mote per ballast and the motes are connected to the ballasts for actuation, this solution appears to be feasible.

The two other components that make up the majority of the system impact are the printed circuit board and the integrated circuit. Both of these components are essential, but work can be done to minimize their size. Reducing the integrated circuit and printed circuit board size can be achieved by redesigning them such that they only have the minimum functions and structures needed for this application. Other design considerations for reduced system impact include the minimization or elimination of the ballast paint and minimization of the plastic used in the mote housing.

FUTURE WORK

The future of the proposed ILS holds many changes and advancements. The biggest changes will occur with the progression of mote technology. This LCA assumed a relatively short life for the mote of 5 years. As the mote technology improves, the lifetime will increase, thus spreading out the mote impact over a longer period of time. Several research institutes are currently studying centimeter-scale distributed sensor networks [10]. The UC Berkeley Wireless Research Center (BMRC) group is working on the fabrication of a radio on a CMOS substrate. In addition, the UCLA WINS (Wireless Integrated Network Sensors) group is developing low-power wireless MEMS (microelectronic mechanical systems) [10]. The biggest change in terms of cost and environmental impact for the future will come when the motes become micrometer size devices based on MEMS technology. The batch fabrication and small size of the MEMS motes should yield much smaller costs and environmental impact [9].

One obstacle for MEMS motes is the battery size. Although MEMS technology has shrunk mechanical systems down to the microscale, battery energy density has not improved significantly [4]. Fortunately, power alternatives are being developed. Amirtharajah et al. fabricated a MEMS system that extracts electric energy from vibrations [12]. It is thought that vibrations in the building could provide power for the motes, eliminating the need for a battery. Alternatively, MEMS motes could use photovoltaics for power as well. The Berkeley Sensor and Actuator Center has demonstrated that solar power is feasible for some MEMS mote applications [13].

CONCLUSION

The LCA proved to be an effective tool for evaluating the environmental impacts associated with implementing the proposed ILS. It was shown that the impacts of the proposed ILS were 18–344 times smaller than those of the conventional lighting system for the different environmental impact categories considered. This study supports the claim that the proposed ILS has environmental advantages. Furthermore, the future of the mote network lies in making them smaller and not dependent on batteries. Future changes may further decrease the environmental impact of the mote network, thus making the proposed ILS an even “greener” lighting solution.

The proposed ILS becomes an even more attractive lighting solution in terms of cost and environmental impact when it shares the mote network with other systems. The mote network could be shared with an HVAC (heating, ventilation, and air conditioning) control system, a fire detection and fighting system, and a security system.

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