Economic Evaluation of Environment-Friendly Streetlights on a University Campus: Using a Field Survey in Korea

Won-Hwa Hong¹, Seung-Hee Cho², Ju-Young Kim³ and Ji-Ae Lee*⁴

¹Professor, School of Architecture and Civil Engineering, Kyungpook National University, South Korea
²Researcher, School of Architecture and Civil Engineering, Kyungpook National University, South Korea
³Patent Examiner, Korean Intellectual Property Office, South Korea
⁴Ph.D. Student, School of Architecture and Civil Engineering, Kyungpook National University, South Korea

Abstract
Nowadays, most illumination sources for streetlights use high intensity discharge (HID) lamps. Global concerns have been raised regarding the amount of atmospheric CO₂ released due to the power consumption of HID lamps. Thus streetlights with LED and solar-energy were analyzed competitively, to evaluate the feasibility of streetlights based on environmentally-friendly products at K University. The results showed that the adoption of a LED based streetlight system and a solar-energy LED system could potentially reduce CO₂ emissions by approximately 120 and 170 tons each year, respectively. While the initial investment cost of LED is higher than HID, the maintenance cost is approximately one quarter of the maintenance cost of HID. However solar-energy LED lights are not appropriate to replace campus lights because of the significantly higher cost. Since the invention of LED, the technology has been continually improving while the prices are quickly decreasing; therefore, the break-even point of investments in environmentally-friendly lights is expected to be reached much earlier than previously anticipated.

Keywords: streetlight; economic evaluation; environment-friendly; LED; photovoltaic streetlight

1. Introduction
The Republic of Korea (South Korea) currently relies on imports for over 90% of its energy needs. In tandem with low-carbon and environmentally friendly green growth policies, the country strives to develop eco-sensitive systems and turn green growth into a part of everyday life in South Korea.

South Korea has set its economy-wide goal of reducing greenhouse gas (GHG) emissions by 30% by 2020 in accordance with a BAU (Business As Usual) scenario. The country's public sector also aims to reduce emissions by 20% by 2015.¹ To these ends, the South Korean government is planning energy reduction in a number of different ways, including the introduction of renewable energy, using energy-efficient equipment.

Renewable energy is a form of energy source that can replace fossil fuels and nuclear energy, and cannot be depleted. Examples of pollution-free energy sources include solar, geothermal, and tidal and wind power.

*Contact Author: Ji-Ae Lee, Ph.D. Student,
No. 304 E2 Kyungpook National University,
80 Daehak-ro, Buk-gu, Daegu, 702-701, Republic of Korea
Tel: +82-53-950-5597  Fax: +82-53-950-6590
E-mail: ize0304@naver.com
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¹The cost of renewable energy is still somewhat higher than that of fossil fuels. However, due to increasingly growing expectations and enthusiasm for renewable energy, technological advancements will be achieved, and the use of renewable energy as an alternative fuel form will increase rapidly in achieving green growth. In the meantime, with the growth of industries related to low-carbon emissions that utilize electricity, hybrid system or hydrogen as fuel, LED and OLED lighting markets have received increasing attention. LED (Light Emitting Diode), the most environmentally friendly lighting source is small in area due to the structural and physical properties of individual light-emitting display. LED technology offers excellent efficiency and long service life and has broadened its unique applications and scope. Recently the advancement of technology has been particularly remarkable and LED applications have rapidly expanded to nearly all industries. The power demand of LED lighting is less than 50% that of fluorescent lighting, yet its service life is 5 times longer. The LED lighting market was expected to grow to KRW 300 billion - 400 billion by 2012. With the governmental policies for increasing the supply of LED lighting in the public sector and the enforcement of mandatory use of LED lighting, as well as increasing participation by non-public sectors, the LED lighting market is expected to exceed the
Another energy issue emerging in South Korean society is the rapid increase in energy consumption across college and university campuses\(^7\). College/university students are considered a demographic to which the largest number of energy-conserving alternatives can be applied. South Korea's Ministry of Environment and the Korea Environmental Corporation (KECO) led the implementation of guidelines for establishing the GHG emissions inventory for higher education institutes in 2011 for the purpose of creating low-carbon green campuses. The said implementation took into consideration the fact that colleges and universities are among the massive emissions sources, and they have tremendous impacts on nearby communities. Establishing the GHG inventory involves providing a list of GHG emissions sources that are generated both directly and indirectly by an organization and the amount of emissions thereof, and can help achieve the country's goals for GHG emissions reduction\(^9\).

A street lighting system that incorporates solar energy, a form of renewable energy, into LED lighting (the Solar Street Lighting System or SSLS) is not easy for non-public sectors to implement due to their high costs, though schools and other educational institutions can implement the SSLS provided non-governmental organizations make investments and/or the government provides financial assistance. With the said investments and assistance to help implement the SSLS, in which solar energy is captured by solar panels, stored in batteries, and converted into power to light up streetlights, the high efficiency and environmental friendliness of the SSLS can be demonstrated as to just how much and how effectively it helps to reduce energy consumption and carbon emissions.

The aim of this study was to determine the economic feasibility of a SSLS as an alternative to save energy across college/university campuses. The SSLS is a street lighting system combining LED, an eco-friendly lighting source, and solar energy, a form of renewable energy currently receiving increasing attention. For the purpose of determining the economic feasibility, the SSLS was compared with conventional lighting systems, and their respective economic feasibilities were analyzed. Based on the results, the study indicates the economic feasibility of utilizing environmentally friendly energy sources for street lighting and advocates the need for such lighting systems. The results of this study may also be used as a basis for actively introducing SSLS to not only college/university campuses but to a variety of different places both public and private as well provided they require a street lighting system.

2. Overview of Conventional and Eco-Friendly Lighting Systems

2.1 Purpose of and Requirements for Street Lighting Systems

The aim of street lighting is to help improve the visual field of nighttime drivers (vehicles) and pedestrians to ensure their safe and secure transfer. To that end, street lighting systems must secure levels of brightness that will provide comfort for all users, and also must satisfy different requirements, depending on the type of users, such that they can provide a more pleasant and safe environment for nighttime travelers.

The said requirements are clearly stated in the KS (Korean Industrial Standards)\(^5\)\(^,\)^\(^7\). The street lighting requirements for pedestrians are as follows\(^10\):

1. The illumination of the road surface as perceived by the pedestrian shall be sufficient and if possible consistent;
2. The illumination of the road's vertical plane shall be sufficient and shall allow recognition by pedestrians from opposite directions;
3. The brightness of the lighting systems shall be controlled sufficiently so as not to bring discomfort to pedestrians;
4. The color of the lighting source shall be suitable for the environment, and the continuity of the color shall be ensured;
5. The lighting system shall not spoil the view of the road or its surroundings.

2.2 Overview of Environmentally-Friendly Street Lighting

Unlike conventional lighting sources, street lighting systems using LED, an eco-friendly source, are physically small in area and in addition, they are extremely sturdy by not using glass electrodes, filaments or mercury (Hg)\(^6\). LED lighting systems also last longer and are friendly to the environment. LED (Light Emitting Diode), a lighting source utilizing emitted light, has a wide range of applications including signs, signaling, lighting, decoration, disinfection and communications. At the beginning of their development, LEDs had disadvantages such as high price and limited application, and thus were used mostly for light indicators, etc. for space vehicles and machinery where properties such as energy consumption and service life are considered important\(^7\). Since the 1990s, however, the luminance of LEDs has improved significantly, and more colors have become available, which has increased its application greatly. In South Korea, green growth policies have included the LED industry, and the public sector is leading the initiative for replacing conventional lighting systems with LED lighting systems, with a tremendous amount of funds planning to be mobilized. As described above, the country expects to have 30% of the entire lighting system in its public infrastructure replaced with LED lighting by 2015\(^7\).
Solar-powered LED street lighting using solar energy utilizes solar panels to collect solar heat energy and store it in batteries and convert it into power. This lighting system helps improve the visual field of nighttime travelers from sunset to sunrise, and offers longer service life compared to conventional street lighting systems hence energy savings. The said advantages have led to a significant amount of attention being paid to LED lighting amid the worldwide economic slowdowns and energy crisis, and to the development of LED lighting projects. Using solar energy to supply power to streetlights eliminates the need for additional power sources and reduces power bills. It also eliminates the need for power cables, meaning no additional cable work will be needed for installing LED lighting systems, and concerns for installation costs will become unnecessary. This easiness regarding installation offers advantages to isolated areas/regions and islands where supplying power can be challenging. Despite the afore-said benefits of LED lighting systems, the reason why it is difficult to replace numerous streetlights with solar-powered lighting systems is because LED lighting technology and products have not been standardized yet and also because the production costs, as well as the maintenance and repair costs resulting from battery replacement, remain high. Nevertheless, LED lighting technology is advancing rapidly, and at the same time, initiatives for green growth are emerging in the energy market. Hence, the demand for LED for streetlights is expected to grow explosively.

3. Analysis of Current Street Lighting Systems on Campus

Table 1. summarizes an overview of the campus at K University, the target campus of this study located in Buk-gu, Daegu, South Korea (K-University). The said campus consists of 112 buildings, and its gross area is 824,000 m$^2$.

Table 2. lists the supply rates of LED lighting across the K-University campus. As shown in the table, the rate at which conventional lighting systems inside buildings on campus was replaced with LED lighting systems was significantly low, while the rate at which on-campus streetlights were replaced with LED street lighting was 40% or higher.

The supply rate of LED is very low since fluorescent lamps, which used to be the most commonly used interior lamps, have been replaced with LED lamps only in campus remodeling projects. This is because a large number of LED lamps and the related high cost are required for the replacement of LED lamps. Replacement of lamps containing stabilizer and leading lights has been carried out, but it does not meet the government standards applicable to public institutions.
Figs. 2. and 3. show photos of the LED street lighting systems that have replaced the conventional lighting system on campus to evaluate the efficiency of LED street lighting, and photos showing efficiency measurements of the system.

4. Evaluation of Performance and Economic Feasibility of Eco-Friendly Street Lighting Systems

4.1 Evaluation of Performance

Compared with the 250W used by the conventional street lighting system, the SSLS provided light from 90 to 135W with the same effects. In addition, the measurement results show that the SSLS helped save power by 50 - 70%. The photo-energy conversion efficiency was 5% with incandescent lighting, 40% with fluorescent lighting, and 90% with the SSLS which delivers the highest potential efficiency.

As demonstrated by the results, the SSLS, compared to the conventional lighting system, offers advantages such as higher efficiency, lower power consumption, longer service life, and faster response rates. In addition, the SSLS is eco-friendly due to the fact that it does not use mercury.

A SSLS vs. conventional lighting system comparison and analysis were conducted by using 75W lamps as the reference point, due to the SSLS's solar cell modules having limitations in power consumption. The data from the comparison may vary depending on the manufacturer and type of LED products.

Table 3. below summarizes the analysis of the performance of the conventional lighting system to be replaced by the LED lighting system and of the SSLS lighting systems.

4.2 Evaluation of Economic Feasibility

This study has targeted the K-University campus (located in Daegu) and examined the power consumption, initial investments, maintenance and repair costs, and the costs of purchasing carbon emission rights that must be taken into consideration when replacing metal-halide and high-pressure sodium lamps that have been used for the on-campus street lighting system, with the LED lighting system composed of generic LEDs or with a LED lighting system equipped with solar energy modules. Based on the data collected, an evaluation of the economic feasibility was conducted by analyzing the break-even point of each system.

4.2.1 Comparison of Initial Investments

In terms of the initial investments to be made, the same amount of installation costs were incurred by the conventional and LED systems for installing the streetlight poles, excavating and connecting cables. The only difference found was the cost for replacing the lamps in the existing streetlights. The reference point for the comparison was the SUS304 light pole with a metal-halide 250W lamp for the conventional system and the 120W LED light with the SSLS.

SUS304 is the standard for steel used in streetlight installation, which is also widely used in installing stainless heads, flickers, and brackets as well as LED streetlights.

The SSLS in which a light's head, pole, and battery plate are integrated into one component was found to incur costs that correspond to:

The amount of expenses to be incurred from the installation, including excavation and cabling but no foundation anchoring, is USD 250. The initial investments to be made for the 120W LED street lighting system (including lamps and installation work) corresponds to 131% of the expenses for the metal-halide streetlights, including the SMPS (Switching Mode Power Supply).

Table 3. Analysis of Conventional and Environmentally-Friendly Streetlights

| Lamp       | Streetlights with HID lamps | Environmentally-friendly streetlights | Photovoltaic LED |
|------------|-----------------------------|--------------------------------------|------------------|
| Wattage    | 250W                        | 90W (Type A)                         | 120W (Type A)    |
| Electric Power | 220V                      | 220V                                 | 220V (Type B)    |
| Illumination(6m) | 36lx                    | 30lx                                 | 45lx             |
| Power Consumption | 253W                    | 253W                                 | 85.8W            |
| Life       | 12,000Hr                    | 9,000Hr                              | 120W             |
| Color rendering | 28Ra                     | 65Ra                                 | 75W              |
| Hydrgyrum  | 35mg                        | 30mg                                 | None             |
|            |                             |                                      | 80-90Ra          |
The SSLS wherein the head, pole and battery plate are integrated into one was found to incur costs that correspond to 306% of the costs incurred by the conventional system, excluding cabling costs. Table 4. lists the comparisons of the initial investment costs that are expected to be generated by each lighting system.

LED price includes the amount calculated in additional cost (lamp, bracket, etc.). There are a variety of LED standards, and in general, the price of HID-Metal halide lamps ranges from USD 45 to USD 65 and LED streetlights from USD 267 to USD 446 approximately. It was identified that the installation cost spent on the streetlights in the national university; the research subject, did not deviate from the average installation cost.

4.2.2 Comparison of Power Bills

Table 5. lists the comparison and analysis of power bills for on-campus street lighting, between the conventional lighting system, the generic LED lighting system, and the SSLS. Based on the analysis and a scenario of using daily (1) the 250 W metal-halide system, (2) the 120 W LED lighting system (Company B), and (3) the 75 W solar-powered LED system for 10 hours on average, the LED street lighting systems were found to consume only 44% of the power that would be consumed by the conventional street lighting system for the duration of 1 year, saving 56% of the annual power bills. Although there can be differences in power consumption with the SSLS depending on the weather, it was assumed for the purpose of this study that the system does not contribute to any power bills due to its internal power generation capability.

The costs were calculated by the equation below, and were based on a 10-hour-daily-use scenario. The unit price of KEPCO (Korea Electric Power Corporation) used for the calculation was the average price for 2011 and did not include the basic rate⁹.)

\[
\text{Total energy cost (Electricity consumption)} = W \times N \times T \times C \times 365 \text{ (kWh/yr)}
\]

W: Electricity consumption (kWh)
N: Number of streetlight
T: Using time (10 h/day)
C: Standard Price of Electricity

4.2.3 Comparison of Maintenance and Repair Costs

Table 6. shows the maintenance and repair costs of the street lighting systems. The said costs for the conventional system were found to be USD 89 for each pole per year. With the LED street lighting system, the maintenance and repair costs for lamp replacement were excluded since this system eliminates the need for replacing lamps for 13 years provided the lights are used for 10 hours per day⁹). However, for the duration of 10 years, 3 SMPS replacements are expected, during which the cost of USD 214 will be generated per pole. Therefore, the cost of approximately USD 21.4 will be incurred for each pole per year, which will decrease cost by about 76%.

The SSLS was found to generate costs for 3 battery replacements for the duration of 10 years, which corresponds to USD 3,214 (75 W) for each pole (100 AH x 4 EA x 3 times). The figure translates into about USD 321/1 EA in annual maintenance and repair, which is equivalent to 360% of the maintenance and repair costs with the conventional street lighting system.

| Type                | Cost (USD) | Cost deviation | Percent |
|---------------------|------------|----------------|---------|
| HID                 | 313        | 0              | 100%    |
| Pole (SUS304)       | 1,339      |                |         |
| Installation costs  | 250        |                |         |
| LED                 | 893        | +580           | 131%    |
| +SMPS               |            |                |         |
| Pole (SUS304)       | 1,339      |                |         |
| Installation costs  | 250        |                |         |
| Photovoltaic LED    | 7,722      | +5,821         | 306%    |

Table 4. Comparison of Required Initial Investment (1 USD=1,120 KRW)

| Type                | Cost (USD) | Cost deviation | Percent |
|---------------------|------------|----------------|---------|
| HID                 | 89.3       | 0              | 100%    |
| LED                 | 21.4       | -68            | 24%     |
| Photovoltaic        | 321.4      | +232           | 360%    |

Table 5. Comparison of the Power Bills for On-Campus Street Lighting (1 USD =1,120 KRW)

Table 6. Comparison of the Maintenance Cost (1 USD = 1,120 KRW)
4.2.4 Comparison of Carbon-Emission Right Costs

The Kyoto Protocol on Climate Change (the Kyoto Protocol), which has been in effect since 2005, enforces mandatory GHG emissions reduction on 38 developed countries\(^{16}\); the Kyoto Protocol also has introduced the emissions trading system to encourage flexible implementation. Emissions trading is, put simply, a system that allows countries to buy and sell the right to emit GHG emissions.

The cost of emitting 1 ton of CO\(_2\) emissions is set at USD 13. Based on this, Table 7. analyzes the costs of carbon emissions rights. Depending on the emissions coefficient, the amount of carbon emissions is 0.424 kg/kW\(^{10,12}\). In the case where the 250 W metal-halide lamp is used for the entire on-campus street lighting, and the trading right cost for CO\(_2\) emissions is assumed to be 100%, the amount of CO\(_2\) produced from the LED lighting system and the cost thereof correspond to 48% of the figure with the conventional system, which is equivalent to a 52% reduction in costs. With the use of the SSLS, the figures correspond to 30% and 70%, respectively.

Table 7. Comparison of the Expenses of the Carbon Emissions Rights

| CO\(_2\) Emission (Ton) | Cost (USD) | Cost variation (USD) | Percent |
|------------------------|-----------|----------------------|---------|
| HID                    | 240       | 3404                 | 0       | 100%    |
| LED                    | 115       | 1631                 | -1773   | 48%     |
| Photovoltaic           | 72        | 1021                 | -2383   | 30%     |

5. Economic Evaluation and Discussion

According to the results of this study, the initial investments to be made for the conventional and LED street lighting systems under the same installation conditions are not the same: the LED systems demand 44% more in terms of cost than the conventional system. However, in 8 years, when the break-even point is reached, the LED systems will incur lower costs than conventional street lighting, as the analytical data suggest. Fig.4. lists the graphs showing, with each system, all costs anticipated for each streetlight (pole), i.e., the aggregated sum of initial investments, power bills, maintenance and repair costs, and emissions trading costs.

In addition, since the conventional lighting system uses 250 W lamps while the LED systems use 120 W lamps, there is no need to install additional power cables for the LED systems; only the lamp heads need to be replaced. The SSLS requires an exorbitant amount of initial investment, which corresponds to more than 3 times the costs required by the conventional street lighting system. Furthermore, the SSLS requires a significant amount of maintenance and repair costs as necessitated by battery replacement; therefore, so far, it is not the most recommended system in terms of cost consideration. The target campus in particular has a large number of trees, which poses difficulties in meeting the installation requirements. The 5 LED streetlights (poles) installed on campus of the target university were provided by a BTL project, and they do not offer significant benefits in terms of the power bills and energy conservation. Hence, based on the said analyses, replacing the existing street lighting system on campus with the SSLS is considered impractical.

Fig.5. shows that, when excluding the initial investments, the power bills, maintenance and repair costs associated with the conventional lighting system increase significantly year after year. On the contrary, when replacing the conventional lamps with LED heads, the power bills, maintenance and repair costs show only a moderate annual increase, which, in 12 years, translates to less cost in total compared with the conventional system. Hence, the results of this have demonstrated the economic feasibility of replacing conventional lamps with LED heads, which is much better than continuing to use the conventional lighting system.

Installing LED streetlights should be given priority over non-LED ones, since it takes at least 8 years for streetlights to reach the breakeven point and bring economic effects. However, simply replacing the heads of the existing streetlights with LED heads is possible provided they have 250W bulbs. It is considered far more economical since it does not require extra wiring or power supply. Presently, in Korea, the government's support for boosting the supply rate of LED lamps is on the rise as part of its environment-friendly policy.
6. Conclusion

The aim of this study was to examine the economic feasibility of street lighting systems using an environmentally friendly lighting source. Streetlights installed on the campus of K-University, a national university located in Buk-gu, Daegu, South Korea, were compared and analyzed against a LED street lighting system and a solar-powered LED street lighting system (the SSLS) to examine their respective initial costs, power bills, maintenance and repair costs and emissions trading costs. By using break-even point analysis, the economic feasibility of each system was evaluated.

Based on the results of the analysis, both of the LED systems were found to reduce significantly the energy consumption and carbon emissions, thereby demonstrating the efficacies advocated by the low-carbon green growth initiatives. The LED street lighting system in particular requires initial investments that exceed 131% of that of the initial costs required by the conventional lighting system. However, the LED system helps reduce energy bills by 56% and 76% in maintenance and repair costs, demonstrating it can offer significant financial benefits. On the contrary, SSLS contributed to a 30% increase in the initial costs, excluding cabling, thereby making it difficult to invest in the installation of SSLS in public buildings. Furthermore, after the costly installation, funds will still be required to replace the batteries, i.e., 3 times in 10 years, which translates to a 360% rise in maintenance and repair costs compared with the figure by the conventional lighting system. Therefore, it was concluded that the SSLS is not suitable as an alternative to replace the conventional on-campus street lighting system.

Despite the aforesaid findings, LED technology has led to a consistently increasing demand since its development, and development of the technology has been under way, with significant progress being made. In the meantime, costs have decreased, which is contributing to the rapid distribution of technology. Therefore, the break-even point of the conventional street lighting system and LED street lighting system is expected to be pushed forward more significantly than originally anticipated. With further technological advancement and stabilization of initial costs achieved in the future, it is recommended that eco-friendly lighting sources be actively introduced to street lighting to help reduce energy waste by streetlights, and to comply with the green-growth initiative that aims to create a low-carbon eco-friendly environment and to develop more eco-sensitive systems. Efforts should also be made and emphasized in operating systems by turning green growth into a part of everyday life.

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References

1) Korea Energy Economics Institute. The 5th report of energy use rationalization act. 2010.
2) C.J. Lee. Domestic and Foreign tendency of recent LED lighting market, Korea Photonics Industry Association, The Optical Journal. 2011 Dec pp.33-41.
3) Korea Environment Corporation. Final Report on the Development of Guidelines for Reducing Greenhouse Gas Emissions and Creating Green Campuses. 2011.
4) H.J. Kim, I.H. Yu, J.T. Kim. Improvement of luminous environment by changing light source in urban street. KIIEEE. 2005 May.
5) Recommended levels of illumination, KSA 3011.
6) Y. Aoyama, T. Yachi. An LED module array system designed for streetlight use. IEEE 2008.
7) X. Long, R. Liao, J. Zhou. Development of street lighting system-based novel high-brightness LED modules. IET. 2009; 3: 40-46.
8) Kyungpook National University. Statistical Yearbook of Kyungpook National University, 2011.
9) Korea Electric Power Corporation, Statistics of electric power in Korea, 2011; 81.
10) M.S Pak. A study on the EU Emissions Trading Schemes. The international association of area studies. 2008 Jun; 12(2): 297-324.
11) http://www.europeanclimateexchange.com.
12) Mickinsey & Company and Ecofys. EU ETS Review: Report on International Competitiveness. European Commission Directorate General for Environment. 2006 Dec.
13) Kim JY, Hong WH, LEE JH. A Study on Economic Evaluation of Building Integrated Photovoltaic, Journal of the Architectural Institute of Korea, Vol. 22, No. 5, 1229-6163 KCI, 2006.
14) A. N. Sperber et al., Performance evaluation of energy efficient lighting associated with renewable energy applications, Renewable Energy 44(2012), pp.423-430.
15) Huang BJ, Wu MS, Hsu PC, Chen JW, Chen KY. Development of high-performance solar LED lighting system, Energy Conversion and Management 2009; 51(8); 1660-75.
16) Yuan Su, Hiroto Takaguchi, Junwei Yan, Analysis of Energy Consumption Structure Of A Science And Engineering University Campus In Southern China, Journal of Environmental Engineering (Transactions of AIJ), Vol. 77 (2012) No. 675, pp.399-407.
17) Won-Hwa Hong Ju-Young Kim Choun-Mi Lee, Gyu-Yeob Jeon, Energy Consumption and the Power Saving Potential of a University in Korea. Using a Field Survey, Journal of Asian Architecture and Building Engineering Vol. 10 (2011) No. 2, pp.445-452.
18) Jung-Tang Chu, Chih-Chiang Kao, Hung-Wen Huang, Wen-Deng Liang, Chen-Fu Chu, Tien-Chang Lu, Hao-Chung Kuo, Shing-Chung Wang, Effects of Different n-Electrode Patterns on Optical Characteristics of Large-Area p-Side-Down InGaN Light-Emitting Diodes Fabricated by Laser Lift-Off, Japanese Journal of Applied Physics, Vol. 44-Part 1 (2005) No. 11, pp.7910-7912.