ISESCO Science and Technology Vision
Volume 4 - Number 6 - November 2008 (43-47)

Economic Feasibility of Solar-powered LED Roadway Lighting

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Abstract

The optical efficacy of light emitting diode (LED) has exceeded 72 lm/W in 2006. This implies that energy can be saved about 75%, as compared to mercury lamps widely used in roadway lighting. In some remote areas where the grid power cannot reach, independent solar-powered lighting using high-power LED provides a promising solution. However, the cost of solar photovoltaic device may cause the application of solar-powered LED roadway lighting to be not economically feasible.

The present study investigates the design of the solar-powered LED roadway lighting using high-power LED luminaire (100W) and estimate the installation cost for a 10 km highway with 2 lanes. LED luminaries are installed on both side of the road with staggered arrangement. The pole distance is 30m. The cost comparison of LED lighting using grid and solar power with the conventional mercury lamps was carried out. It shows that the installation cost is 22 million USD for LED powered by grid power and 26 million USD for solar-powered. The total installation cost of conventional mercury lighting is 18 million USD. The excess cost of LED mainly comes from the cost of LED lamp and solar PV. But, the cost of power generation and electrical transmission line can be greatly reduced since about 75% energy was saved for LED. This permits the use of smaller copper wire and shorter line length for solar-powered system which in turns saves installation cost. The payback time for the excess investment of LED is 2.2 years for LED using grid power and 3.3 years for LED using solar power.

Keywords: *solar LED lighting, roadway lighting; energy saving*

1. Introduction

The conventional roadway lighting utilizing mercury lamps usually consumes electrical power higher than 200W per lamp in order to meet the roadway lighting standard. The optical efficacy of light emitting diode (LED) has exceeded 72 lm/W in 2006. This implies that energy can be saved a great deal, as compared to mercury lamps used in roadway lighting.

In some remote areas where the grid power cannot reach, solar-powered lighting using high-power LED provides a promising solution. However, it is questioned that the high cost of both solar photovoltaic device and high-power LED may cause the application of solar-powered LED roadway lighting not economically feasible.

The solar-powered LED for roadway lighting requires a proper system design with suitable installed capacity of solar PV and battery according to the selected high-power LED[1] in order to meet roadway lighting standard[2]. LED will reduce the power consumption as well as LLP (loss of load power)[3] and thus is the best choice for solar roadway lighting[4].

LED can reduce power consumption in lighting. This implies that the copper wire for electrical transmission line in roadway lighting can be reduced too. For LED roadway lighting powered by solar PV, i.e. stand-alone system, the transmission line installation cost can also be reduced. These two factors may contribute a great deal in economic assessment of LED roadway lighting.

The present study carried out the energy saving analysis of roadway lighting systems using conventional mercury and sodium lamps and the high-power LED. The economic feasibility of the solar-powered roadway lighting using high-power LED luminaires (100W) for 10 km highway with 2 lanes is then studied. The roadway lighting fixtures are installed on both sides of the road with staggered arrangement. The pole distance is 30m. Economic comparison for three kinds of roadway lighting design, namely, LED using grid power or solar power, and conventional mercury lamps, is carried out.

2. Design of high-power LED lighting fixture

A high-power LED lighting system needs to dissipate heat to the ambient in quantity which is several times of the conventional lighting device and keep the LED junction temperature below 80oC to assure reliability and low optical decay[5]. Heat dissipation is thus an important issue in high-power LED lighting technology. In the present study which using a special low-cost heat dissipation device (loop heat pipe, LHP)[6] to develop a fan-less lighting fixture of high-power LED. ***Figure 1*** shows the design of LED fixture using LHP. The evaporator of the LHP is attached on the backside of the LED module through a heat conduction block to absorb the heat generated in the LED lighting module. The absorbed heat evaporates the working fluid inside the LHP to flow through a flexible connecting pipe to the condenser plate which is the housing of the lighting fixture. The vapor is condensed in the condenser from which the heat is dissipated to the ambient. The condensed liquid then returns to the evaporator through the connecting pipe by capillary effect of the wick inside the evaporator.

Since the wick structure inside the evaporator is made at micro pores to induce large capillary force, LHP can transport large amount of heat to a long distance with flexible connecting pipes. ***Figure 2*** shows 100W and 150W LED luminaire which use LHP to transport the heat from LED lighting module to heat dissipation surface.

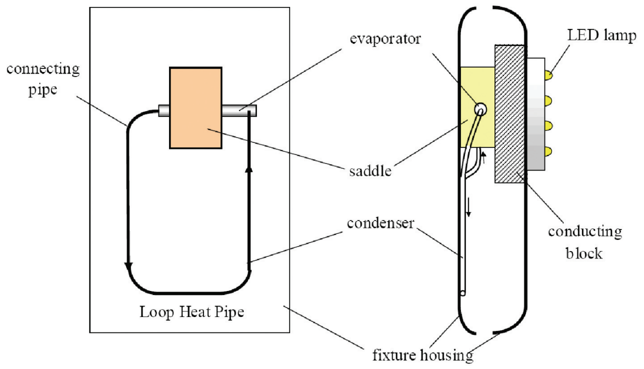

Figure 1. *Design of LED fixture using loop heat pipe.*

3. Field test of high-power LED lighting fixture

A 100W LED lighting fixture was developed in August, 2005, using a LHP and LED lamps with efficacy 45 lumen/W. The total luminous flux of the luminaire is 3,600 lm. This luminaire was installed in a city alley (7m wide) with lamp tilted angle 30 degrees and lamp height 5.5m. The demonstration and monitoring of the LED light in the city alley started right after the installation on September 18, 2005. This 100W LED luminaire was powered by using constant voltage input. Therefore, the input power will float with ambient temperature and affect the output luminous flux. In the present study we use the specific luminous flux (Is), the ratio of luminous intensity to electrical power input (Lux/W), as an operating index. ***Figure 3*** shows the monitored results of Is for over 20 months which shows no significant change. This reveals no light decay. In 2006, we replace the LED lamps of the luminaire with efficacy 72 lumen/W and obtain a total luminous flux 6,000 lm at 100W input power which is to be used in the study of roadway lighting.

In June, 2006, we built a 200m LED lighting roadway in the campus of National Taiwan University for experiment and demonstration, as shown in ***Figure 4***. The 150W LED luminaries with 8,000 lm were installed on the road at 5.2m high.

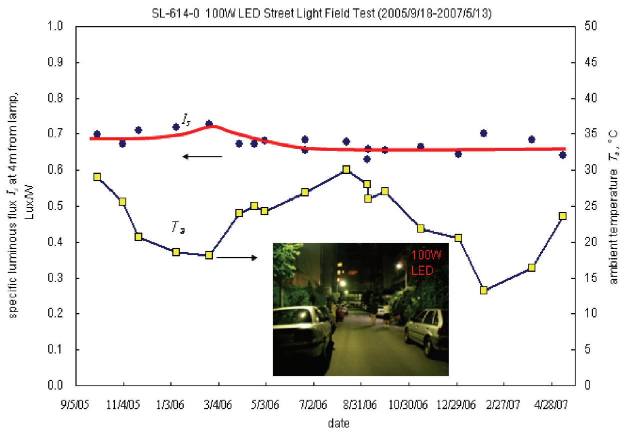

Figure 3. *Long-term road test of LED street light (100W).*

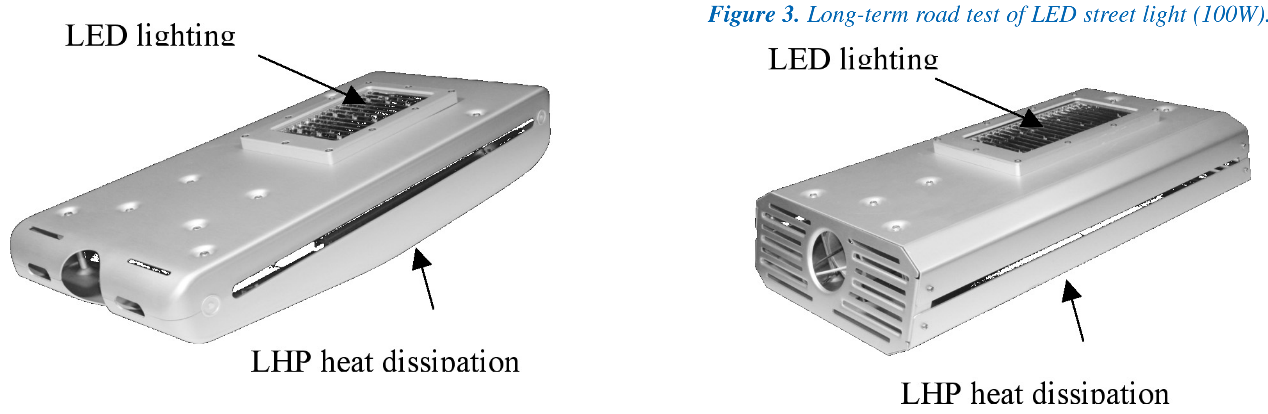

Figure 2. *100W(left) and 150W(right) LED lighting fixture using LHP.*

Figure 4. 200m roadway LED lighting field test in NTU.

4. Energy saving analysis of LED lighting

We use the experiences obtained from the field tests of *Figures 3* and *4* to estimate the energy saving of LED. The present (2007) optical efficacy of LED light sources is about the same as that of mercury lamps (~70 lm/W). However, the light directedness of LED can effectively make the output light to hit on the road surface. *Figure 5* shows that more than 85% light output from the LED lamps can hit the road surface. For conventional lighting fixture, only about 40 to 50% light output from the lamp can hit the road surface. A great energy saving is thus possible for LED. In addition, the roadway lighting system can pass the IESNA standard.

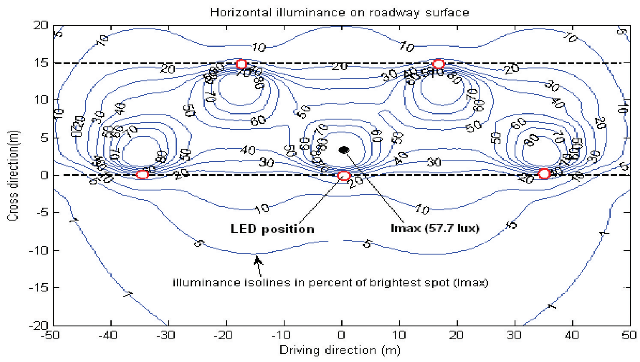

Figure 5. Illuminance distribution on the road surface.

Table 1 shows the energy saving analysis of LED lighting compare to sodium lamp and mercury lamp. The major cause that LED can reduce the energy consumption is its lighting-to-target effectiveness and low light decay in lifetime. The LED have about 110° light emission angle, while the conventional lamps usually have 360° and needs a reflector to direct the light beam to the target. Therefore, the LED can have highly lighting-to-target efficiency.

Based on the power consumption per net illuminance to target, $p_o=1/e_o$(W/lm), LED can save 35.4% and 65.0% energy consumption compared to sodium lamp and mercury lamp respectively in brand new performance, as shown in *Table 1*. The LED also have longer lifetime of 50,000 hours at 30% light decay, if the heat dissipation is resolved properly. Hence, the lifetime performance can save about 53.5% energy and 74.8% compared to sodium and mercury lamps, respectively.

TABLE 1. Energy saving, LED vs. Sodium and Mercury lamp

Brand new performance	Sodium	LED	Mercury	LED
1. Lamp efficacy,η_L(lm/W)	120	72	65	72
2. Luminaire efficiency,η_F=η_2xη_p	0.595	0.72	0.595	0.72
- secondary optics efficiency,η_2	0.7	0.85	0.7	0.85
- power supply efficiencyη_p	0.85	0.85	0.85	0.85
3. Lighting-to-target effectiveness, η_R	0.4	0.85	0.4	0.85
4. overall lighting efficiency for brand new luminaire, e_o=η_L xη_Fxη_ R(lm/W)	28.6	44.2	15.5	44.2
- power consumption per net illuminance to target, p_o=1/e_o(W/lm)	0.035	0.023	0.065	0.023
Energy saving= [p_o(HID)-p_o(LED)]/p_o(HID)	-	**35.4%**	-	**65.0%**
Lifetime performance				
5. luminaire maintenance factor, Cm	0.7	0.8	0.7	0.8
6. Lifetime decayed illuminance,η_D	0.4	0.7	0.4	0.7
- life time, yr	3	10	3	10
- lifetime-average light decay, η_Da=η_D+(1-η_D)/2	0.7	0.85	0.7	0.85
7. Lifetime-average overall lighting efficiency, e_LCYC=e_ox—Cmx—η_Da(lm/W)	14.0	30.1	7.6	30.1
- lifetime-average power consumption per net illuminance to target, p_e=1/e_LCYC(W/lm)	0.071	0.033	0.132	0.033
Lifetime energy saving = [p_e(HID)-p_e(LED)]/p_e(HID)	-	**53.5%**	-	**74.8%**

5. Economic Analysis of LED and solar-powered LED

LED can reduce power consumption in lighting. This implies that the copper wire for electrical transmission line in roadway lighting can be reduced too. For LED roadway lighting powered by solar PV, i.e. stand-alone system, the transmission line installation cost can also be reduced. These two factors may contribute a great deal in economic assessment of LED roadway lighting.

The present paper studied the economic feasibility of the solar-powered roadway lighting using high-power LED luminaires (100W) for 10 km highway with 2 lanes. The roadway lighting fixtures are installed on both sides of the road with staggered arrangement. The pole distance is 30m. Economic comparison for three kinds of roadway lighting design, namely, LED using grid power or solar power, and conventional mercury lamps, is carried out.

Table 2 shows the 10km roadway lighting installation cost of grid-powered LED system, solar-powered LED system, and grid-powered mercury lamp. Each unit of solar-powered roadway LED lighting system includes a 400Wp PV module, a 100Ah-24V battery, and 100W LED lighting fixture.

It shows that the installation cost is 22.48 million USD for LED lighting powered by grid and 30.91 million USD for solar-powered. The total installation cost of conventional mercury lighting is 18.82 million USD. The excess cost of LED mainly comes from the cost of LED lamp and solar PV. But, the cost of electrical power generation and electrical transmission line can be greatly reduced since about 75% energy was saved for LED. This permits the use of smaller copper wire and shorter line length for solar-powered system which in turns saves installation cost. *Table 3* shows that the payback time for the excess investment of LED is 1.2 years for LED using grid power and 3.3 years for LED using solar power. This result shows the solar-powered roadway LED lighting is economically feasible.

TABLE 2. Installation cost comparison of 10km roadway lighting

Roadway distance(km) / Number of lamps installed	10 / 667	30m apart in two staggered rows				
Type of lighting design	Grid-powered LED		Mercury lamp		Solar-powered LED	
	Unit price, $	Subtotal	Unit price, $	Subtotal	Unit price, $	Subtotal
Lamp cost, $	1,000	666,667	60	40,000	1,000	666,667
Power generator cost, $	$400/kW	30,651	$400/kW	93,333	0	0
Power line cost, $		448,000		608,000		100,000
PVC pipe cost, $		180,000		180,000		40,179
Transformer station cost, $	11,000	29,700	11,000	59,400	0	0
Light pole, $	300	200,000	300	200,000	300	200,000
Solar PV per W LED, Wp		-		-		2.5
Total solar PV installation, kWp		-		-		167
Solar PV price, $/Wp		-		-		5
Total solar PV module cost, $		-		-		833,333
Battery cost, $		-		-	300	200,000
Controller cost, $		-		-	500	333,333
PV module poles, $		-		-	300	200,000
Civil construction and installation, $	1,000	666,667	1,000	666,667	700	466,667
Other, 2%	2%	17,767	2%	22,815	2%	34,137
Freight, 1%	1%	8,844	1%	11,407	1%	16,667
Total installation cost, USD	2,248,335		1,881,622		3,090,982	

TABLE 3: Cost/effectiveness comparison of 10km roadway lighting

Roadway distance(km) / Number of lamps installed	10 / 667	30m apart in two staggered rows	
Type of lighting design	Grid-powered LED	Mercury lamp	Solar-powered LED
Lighting power per lamp, W	100	400	100
Total power consumption, kW	77	267	67
Total installation cost, USD	2,248,335	1,881,622	3,090,982
Maintenance and lamp replacement saving			
Maintenance cost per year, $/yr	3% 47,450	3% 55,249	3% 72,735
Lamp replacement time, yr	10	2	10
Lamp replacement cost, $/yr	0	36,667	0
Net maintenance saving, $/yr	44,465	-	19,181
Overall cost/effectiveness			
Power saving, kW	190	-	267
Lighting hours, hr/day		12	
Electricity price, $/kWh	0.3 (fixed price)		(in remote island)
Yearly total energy saving, kWh/yr	832,368	-	1,168,000
Yearly total energy saving, $/yr	249,710	-	350,400
Net maintenance saving, $/yr	44,465	-	19,181
Additional investment for LED, $	366,713	Base	1,209,360
Payback time(LED additional investment/ total yearly saving), yr	1.2	-	3.3
Side benefit of LED lighting			
CO_2 emission reduction, kg/yr	549,363	-	770,880

Conclusion

Solar lighting using PV has been commercialized for quite a long time. The performance of solar lighting device however has many defects in lighting capability and reliability. The optical efficacy of LED has exceeded 72 lm/W in 2006. This implies that the lighting energy can be saved about 75% compared to the mercury lamp and LED is suitable for solar lighting.

The present study investigates the design of the solar-powered LED roadway lighting using high-power LED luminaire (100W). This solar-powered LED roadway lighting system can save 75% lighting energy as compared to the mercury lamp. The payback time for the excess investment of the whole lighting system is 2.2 years for LED using grid power and 3.3 years for LED using solar-powered. Since the heat dissipation problem of LED fixture has been solved by using LHP. The LED fixture lifetime can exceed 10 years. Therefore, the roadway lighting using high-power LED either by gird power or solar power is economically feasible in considering the payback time and the lifetime.

Acknowledgement

The present study was supported by Advanced Thermal Devices, Inc., and Energy Bureau, Ministry of Economic Affairs, Taiwan.

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Nomenclatures

Ta	Ambient temperature, °C
Is	Specific luminous flux, lux/W
η_L	Lamp efficacy, lm/W
η_F	Luminaire efficiency
η_2	Secondary optics efficiency
η_p	Power supply efficiency
η_R	Lighting-to-target effectiveness
e_o	Overall lighting efficiency for brand new luminaire, lm/W
p_o	Power consumption per net illuminance to target, W/lm
Cm	Luminaire maintenance factor
η_D	Lifetime decayed illuminance
η_Da	Lifetime-average light decay
e_LCYC	Lifetime-average overall lighting efficiency, lm/W
p_e	Lifetime-average power consumption per net illuminance to target, W/lm