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TECHNO-ECONOMIC ANALYSIS OF OFF-GRID PV LED ROAD LIGHTING SYSTEMS FOR ANTALYA PROVINCE OF TURKEY

A. Can Duman and Önder Güler

Istanbul Technical University, Istanbul, Turkey
E-mail: dumanan@itu.edu.tr; onder.guler@itu.edu.tr

ABSTRACT

In this study, a techno-economic analysis of off-grid PV LED road lighting systems is made for Antalya province of Turkey. DIALux software is used for road lighting calculations and HOMER software is used in modelling, sizing, and optimization of the energy systems. Calculations are made to determine whether maximum or minimum pole spacing options for both twin-bracket central and opposite lighting arrangements provide the optimal system design for off-grid PV LED road lighting systems under the *M3* lighting class in Antalya. The techno-economic analysis of the energy system in case of dimming LED luminaires after midnight is made. Since the payback periods of the systems are found to be above the system lifetime (20 years) with and without dimming, in addition to the current case, future projections, in which electricity unit prices increase and cost of PV system component and battery costs decrease, are examined.

Keywords: LED, road lighting, PV system, techno-economic analysis, dimming

1. INTRODUCTION

Renewable energy systems without giving rise to any greenhouse gas emissions unlike conventional energy sources have gained widespread support by governments, businesses and consumers in recent years. Photovoltaic (PV) and wind turbine technologies are among the most competitive renewable technologies, which provide a clean source of electricity and can replace traditional fossil sources by reducing CO_2 emissions. One of the sectors that consume energy is road lighting, and in recent years, the subject of meeting electricity energy demand of road lighting installations via off-grid renewable energy systems has gained an interest. Many studies have been evaluated in this area including the techno-economic feasibility of PV based lighting installations [1–5]. Under current economic conditions, off-grid lighting systems are feasible only in the rural areas, where electricity does not reach and new transmission lines are required to be installed. However, owing to the declining trend in LED luminaire and PV system component prices, the systems have a potential to become attractive in the rest of the world [6].

In the last seven years, PV costs reduced by more than 70 % due to the developments in the material technology and reached from 1.34 $/W to under 0.5 $/W [7, 8]. Beside the decreasing trend of PV prices, recent developments in LED technology have made it possible to switch from traditional lighting to energy efficient LED lighting. Apart from their cost benefit, LED luminaires with lower power requirements made it available to use smaller sized and thus cheaper PV panels and batteries, which led to investments in off-grid PV lighting installations at lower costs.

In this study, a techno-economic analysis of off-grid PV LED road lighting systems is made for Antalya, the fifth most populous province and tourism centre of Turkey being located at the south of the country with high solar irradiation and sunshine duration levels. DIALux software is used for road lighting calculations and HOMER software is

Table 1. Road Lighting Criteria for Selected Road Lighting Classes

Road Lighting Class	L_{avg} (cd/m²)	U_o	U_l	*TI* (%)	SR
M3	≥1.0	≥0.4	≥0.5	≤15	≥0.5

used in modelling, sizing and optimization of the PV energy systems. In the first part of the study, calculations are made to determine whether maximum or minimum pole spacing options for both twin-bracket central and opposite lighting arrangements provide the optimal system design in off-grid PV LED road lighting systems under the *M3* lighting class in Antalya. In case of meeting lighting criteria using maximum pole spacing, more durable, higher, and thus more expensive lighting poles mounted with higher capacity and costly PV system components and LED luminaires are required per kilometre. However, the number of poles to be built is lesser. On the contrary, in case of using minimum pole spacing, a higher number of lighting poles is required per kilometre whereas size, capacity and cost of the system components and length of the lighting pole decrease. In the second part of the study, a techno-economic analysis in case of dimming LED luminaires after midnight is made over the optimal design determined in the first part. Lighting calculations and energy system optimization is carried out once again over the optimal design. In addition to the current case, payback periods of the systems were calculated considering future scenarios for cases of 25 % increase in electricity tariffs, 25 % decrease in PV system component and battery costs, 50 % decrease in PV system component and battery costs, and 25 % increase in electricity tariffs with 50 % decrease in PV system component and battery costs.

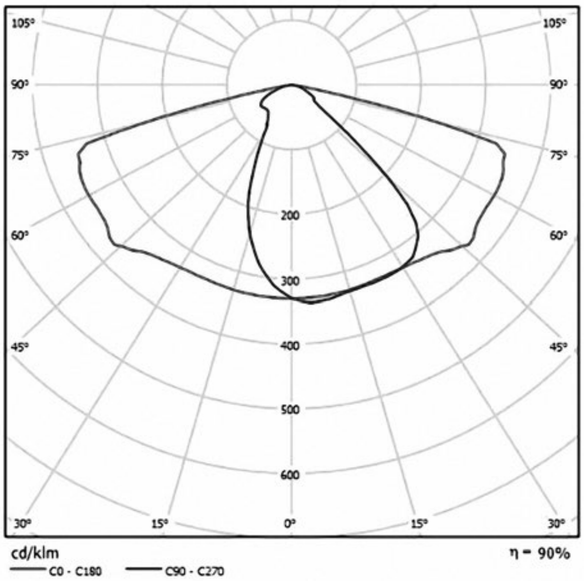


Fig. 1. The luminous intensity diagram of the luminaires

2. ROAD LIGHTING CALCULATIONS

Today, road lighting criteria are determined by the International Commission on Illumination (CIE) and the European Committee for Standardization (CEN) [9, 10]. Turkish Electricity Distribution Co. (TEDAŞ) holds the responsibility for the installation and maintenance of approximately 5 million lighting poles located in cities and rural areas in Turkey [11]. In 2016, according to Turkish Statistical Institute (TÜİK) data, electricity consumption in general lighting was 4161 GWh, which is 1.8 % of the total 231,204 GWh electricity consumption of Turkey [12].

In the study the *M3* road lighting class is selected, where relatively high-powered luminaires could be used without exceeding limited PV battery capacity that can be mounted on a lighting pole. Road lighting calculations are made for the twin-bracket central and opposite arrangements for a 4-lane road with a width of 14 meters. Median length is taken as 2 meters.

The road lighting calculations are performed according to TEDAŞ Technical Specification for LED Road Lighting Luminaires, Procedures, and Principles on the Usage of LED Luminaires in the General Lighting Scope, TS EN13201–3 and Technical Specifications for Road Lighting Luminaires TEDAŞ MYD-95–009.B [13–16]. The road lighting criteria need to be followed for the *M3* road lighting class are given in Table 1. The maintenance factor is set as 0.89 for the protection class of *IP66* that is guaranteed according to CIE154:2003 [17]. Road surface class is assumed to be *R3*.

The luminous intensity diagram of the luminaires used in the study is given in Fig. 1.

According to the TEDAŞ Technical Specifications for LED Road Lighting Luminaires, minimum pole spacings to be provided in the *M3* road lighting class are 30 m and 28 m for the twin-bracket central and opposite arrangements respectively [13]. There-

Table 2. Road Lighting Calculations for *M3* Road Lighting Class

Parameter	Arrangement			
	Opposite		Twin-bracket central	
Spacing (m)	28	51	30	49
Luminaire luminous flux (lm)	4641	9270	5642	9270
Luminaire power (W)	39	73	46	73
Luminous efficacy of luminaire (lm/W)	119	127	123	127
Height (m)	7	10	8	9.5
Boom length (m)	1	1	1.5	0.5
L_{avg} (cd/m^2)	1.01	1.00	1.09	1.02
U_o	0.47	0.42	0.53	0.40
U_l	0.76	0.53	0.78	0.51
TI (%)	10	13	10	14
SR	0.61	0.85	0.76	0.89

Table 3. Average Lighting Times and Durations for Antalya

Month	Daily average lighting time, h: min	Daily average lighting duration, h: min	Monthly average lighting duration, h
Jan	06:41 / 17:33	13:08	407.13
Feb	06:20 / 18:03	12:17	343.93
Mar	05:41 / 18:31	11:10	346.17
Apr	05:55 / 20:00	09:55	297.5
May	05:19 / 20:28	08:51	274.35
Jun	05:07 / 20:49	08:18	249
Jul	05:21 / 20:45	08:36	266.6
Aug	05:48 / 20:14	09:34	296.57
Sep	06:13 / 19:30	10:43	321.5
Oct	06:40 / 18:45	11:55	369.42
Nov	06:09 / 17:15	12:54	387
Dec	06:35 / 17:11	13:24	402
Total			3961.17

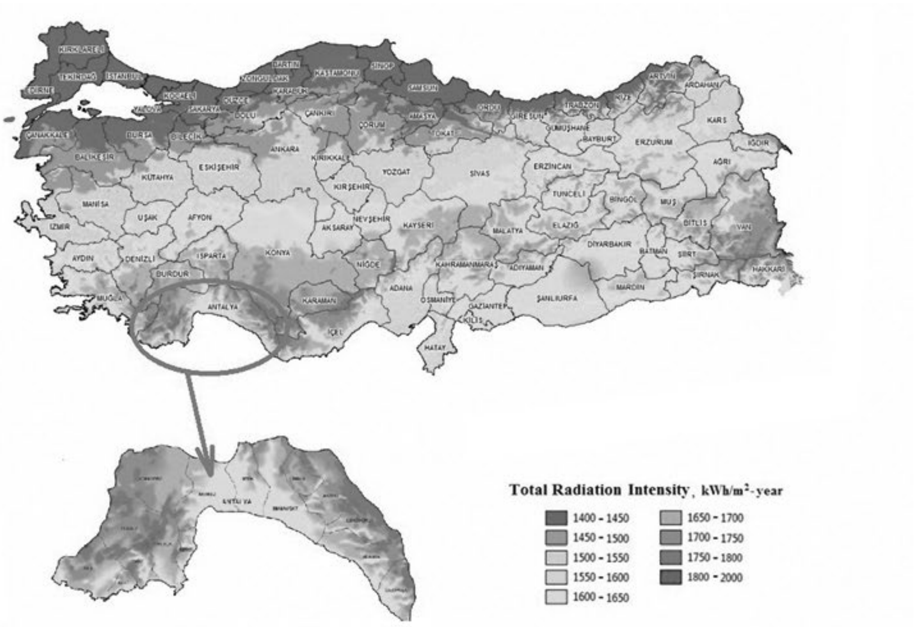
fore, in DIALux calculations, pole spacing ranged from 30 m to 55 m and 28 m to 55 m in 1 m increments, pole length ranged from 7 m to 10 m in 0.5 m increments and boom length ranged from 0 m to 1.5 m in 0.5 m increments with 0° boom angle.

In the study, to determine the most cost effective off-grid lighting installation for the *M3* road lighting class, the twin-bracket central and opposite arrangements are compared. Besides, maximum and minimum pole spacing options are compared in order to determine whether higher number of lighting poles with lower capacity luminaires, PV panels, and batteries or lower number of lighting poles with higher capacity luminaires, PV panels, and batteries give the most feasible result. Road lighting calculations according to the maximum and minimum pole spacing options for both twin-bracket central and opposite arrangements for the *M3* road lighting class are shown in Table 2.

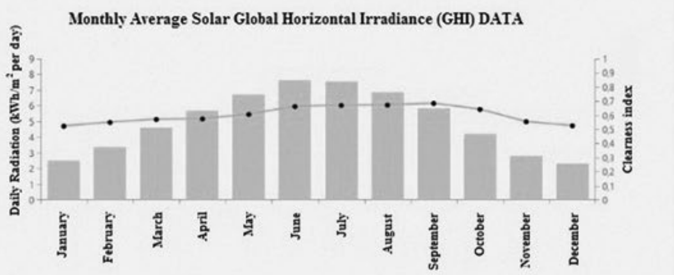
3. CALCULATIONS

3.1. Modelling of Energy Systems

Energy system optimization is carried out using National Renewable Energy Laboratory (NREL)'s



Month	Clearness index	Daily Radiation (kWh/m^2 per day)
January	0.521	2.485
February	0.548	3.371
March	0.568	4.585
April	0.572	5.658
May	0.604	6.710
June	0.660	7.638
July	0.668	7.533
August	0.670	6.855
September	0.682	5.828
October	0.640	4.225
November	0.553	2.774
December	0.524	2.277



Annual Average (kWh/m^2 per day): 4.99

Fig. 2. Solar map of Turkey and global radiation and clearness index data of Antalya

micropower optimization model HOMER software. The lifetime of the energy systems to be installed is considered to be 20 years with 3 % real interest rate. Since lighting load demand must be supplied uninterruptedly throughout a year, no capacity shortage is allowed.

The PV panel capacity is searched in the range of (100–855) W for the twin-bracket central and in the range of (100–570) W for the opposite arrangements in 10 W increments with a lifetime of 20 years. The capital and replacement cost of a panel is taken as 0.52 \$/W and operation and maintenance cost is taken as 7 \$/year. Panels are tilted with a slope of 36.90º in respect to the latitude of the study area. The PV derating factor is assumed to be 90 %, and ground reflectance is set as 20 %. Solar irradiation data is extracted from the National Aeronautics and Space Administration (NASA) Meteorology and Solar Energy Database through HOMER. Batteries with nominal voltage of 12 V and nominal capacity varying between 33.3 Ah and 500 Ah are used. 30 % minimum state of charge (SoC) is allowed with round trip efficiency of 86 %. Battery prices varied between \$117 and \$997.5. Due to being installed on the same lighting pole, maintenance cost of the batteries are included in maintenance cost of the PV panels.

In the calculations, road lighting systems are assumed to be operating from dusk until dawn and out of operation during the daytime and civil twilight. Civil twilight is the time of the day, where the angle between the horizon and the Sun is less than 6º, the objects are identifiable, and people can perform daily tasks without any requirement of artificial lighting. Table 3 shows the daily and monthly average lighting durations for Antalya. As of the study date, daylight saving time is taken into account in the calculation of lighting durations.

Table 4. Optimization Results for Antalya under *M3* Lighting Class

Parameter	Arrangement			
	Opposite		Twin-bracket central	
	Min.	Max.	Min.	Max.
Pole spacing (m)	28	51	30	49
Luminaire power (W)	39	73	2x46	2x73
Battery capacity (V/Ah)	12/166.6	12/250	12/416.6	2x12/333.3
PV panel power (W)	240	540	530	800
PV tilt angle (°)	36.90			
Cost of energy ($/kWh)	0.258	0.228	0.227	0.225
Battery + PV initial cost ($)	490.05	790.80	1129	1829
Battery + PV net present cost ($)	594.19	977.51	1233	1933
Operation&maintenance cost ($)	104.14			
PV electricity production (kWh per year)	384	886	823	1227
Excess electricity production (kWh per year)	204.5	551.7	400.3	559.7
Excess electricity production / electricity production (%)	53.3	62.3	48.7	45.6
Load electricity consumption (kWh per year)	155	289	365	578
Unmet load (%)	0			
Autonomy (h)	79.13	63.66	83.84	84.86
CO_2 emission reduction (kg per year)	75.95	141.61	178.85	283.22

In the study, off-grid PV LED road lighting systems' contribution to the environmental sustainability is also taken into consideration, since one of the goals of the systems is to reduce CO_2 emissions. In CO_2 reduction calculations, the International Energy Agency (IEA) data are used, which determine the amount of CO_2 emission produced per kWh in Turkey as 490 g/kWh [18].

3.2. Optimization Results, Payback Periods, and Total Installation Costs per km

Turkey is situated between 36° – 42° North latitudes and 26° – 45° East longitudes and has the highest solar potential in Europe after Spain. According to the study carried out by the Electricity Affairs Survey Administration (EİE), Turkey has an average annual total sunshine duration of 2737 hours (daily total 7.5 hours) and the average total radiation intensity is 1527 kWh/m^2 per year (total 4.2 kWh/m^2 per day). Antalya is situated between North latitudes at 36° 07' – 37° 29' and East longitudes at 29° 20' – 32° 35'. Located in the Mediterranean Region of Turkey, Antalya is the tourism centre of Turkey and the fifth most populous province. The province has an average annual total sunshine duration of 3014 hours and the average total radiation intensity is 1650 kWh/m^2 per year [19]. The solar potential map of Turkey and the clearness index and global radiation data of Antalya province are shown in Fig 2. The data have been extracted from NASA's Surface Meteorology and Solar Energy Database through HOMER software.

Energy system configurations are simulated and optimized according to the lowest total net present costs (NPC) using HOMER. Detailed optimization results for single pole are given in Table 4.

Following the optimization stage, payback periods of PV energy systems and total cost of entire lighting installations per km are calculated. The electricity cost of 0.128 $/kWh for general lighting is used in the calculation of payback periods as of May 2016. As can be seen in Table 5, the lowest payback period and installation cost per km are found as 27.82 years and $62526.45 respectively with maximum pole spacing for the twin-bracket central arrangement whereas the highest payback period and installation cost per km is found to be

Table 5. Comparison of Payback Periods and System Installation Costs per km

Parameter	Arrangement			
	Opposite		Twin-bracket central	
	Min.	Max.	Min.	Max.
Pole spacing (m)	28	51	30	49
Luminaire power (W)	39	73	92	146
Pole length (m)	7	10	8	9.5
Battery + PV net present cost ($)	594.19	977.51	1233	1933
LED luminaire cost ($)	285	295.5	591	649.5
Charge regulator cost ($)	75	100	100	125
Payback period of the energy system (years)	33.73	29.13	28.53	27.82
Single pole system CoE ($/kWh)	0.258	0.228	0.227	0.225
Galvanized steel polygon lighting pole cost ($)	102.62	184.10	123.04	170.36
Boom cost ($)	7.35	7.35	10.09	4.60
Pole mounting cost ($)	54.47	97.72	65.31	90.43
Cable cost ($)	2.52	3.6	2.88	3.42
Cabling cost ($)	0.84	1.2	0.96	1.14
Total cost of single pole system ($)	1121.99	1666.98	2126.28	2977.45
Number of poles per km	36×2	20×2	34	21
Total installation cost per km ($/km)	80783.28	66679.2	72293.52	62526.45
Annual operation duration (h)	3961.17			
Annual electricity consumption per km (kWh)	11122.96	11566.62	12390.54	12144.95

33.73 years and $80783.28 respectively with minimum pole spacing for the opposite arrangement.

3.3. Calculation Results in Case of Dimming

According to the Procedures and Principles Regarding the Usage of LED Luminaires in the Scope of General Lighting [13] published by the Ministry of Energy and Natural Resources, it is obligatory to use dimmable luminaires in the LED lighting installations in order to reduce the illuminance levels. Dimming for the *M3* road lighting class is done by lowering the lighting class from *M3* to *M4*.

The calculations are carried out for the *M3* road lighting class using the twin-bracket central arrangement and dimming is applied from the *M3* to the *M4* road lighting class. The lighting hours of operation and load energy consumption during one year for the selected road are given in Table 6.

It is assumed that from the beginning of lighting operation until midnight illumination will be performed according to the *M3* road lighting class and from midnight until the end of lighting operation, lights will be dimmed and illumination will be performed according to the *M4* road lighting class. In this case, the lighting system will be under operation for 3961.17 hours annually and will illuminate for 1777.26 hours under the *M3* and 2183.91 hours under the *M4* road lighting class. Lighting calculations in case of dimming are given in Table 7.

In case of dimming, to switch from the *M3* lighting class to the *M4* lighting class after midnight, luminous flux of 73 W luminaire is reduced by 25 % and thus power consumption is decreased from 73 W to 51.1 W. In order to obtain new PV and battery capacity under dimming conditions, HOMER simulations are conducted once again. Comparison of detailed optimization results for normal case and dimming case are given in Table 8.

3.4 Payback Periods and Total Installation Costs under Current Conditions and for Future Scenarios

Following the optimization stage, payback periods of PV energy systems and total cost of entire

Table 6. The Lighting Hours of Operation and Load Energy Consumption (kWh) During One Year in Case of Dimming

Hour	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
0	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
1	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
2	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
3	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
4	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
5	0.102	0.102	0.07	0.094	0.032	0.011	0.036	0.081	0.102	0.102	0.102	0.102
6	0.07	0.034	0	0	0	0	0	0	0.022	0.067	0.015	0.015
There is no need for lighting between 7 and 17												
17	0.066	0	0	0	0	0	0	0	0	0	0.11	0.11
18	0.146	0.144	0.07	0	0	0	0	0	0	0.036	0.146	0.146
19	0.146	0.146	0.146	0	0	0	0	0	0.074	0.146	0.146	0.146
20	0.146	0.146	0.146	0.146	0.078	0.026	0.036	0.112	0.146	0.146	0.146	0.146
21	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146
22	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146
23	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146

Table 7. Lighting Calculations with and without Dimming

Parameter	Lighting Class	
	M3	M4
Arrangement	Twin-bracket central	
Luminaire luminous flux (lm)	9270	6952.5
Luminaire power (W)	73	51.1
Luminous efficacy of luminaire (lm/W)	126.99	136.06
Spacing (m)	49	
Height (m)	9.5	
Boom length (m)	0.5	
L_{avg} (cd/m^2)	1.02	0.77
U_o	0.40	0.40
U_l	0.51	0.51
TI (%)	14	13
SR	0.89	

lighting installations per km are calculated in case of dimming under the *M3* lighting class according to the maximum pole spacing for the twin-bracket central arrangement. In addition to current conditions, payback periods of the energy system investments are also calculated considering future scenarios: 1) 25 % increase in electricity tariffs; 2) 25 % decrease in PV system components and battery costs; 3) 50 % decrease in PV system components and battery costs; 4) 25 % increase in electricity tariffs with 50 % decrease in PV system components and battery costs. The payback periods of the energy system investments and total installation costs per km under current conditions and for future scenarios are given in Table 9.

4. CONCLUSION

In this study, a techno-economic analysis of off-grid PV LED road lighting systems have been made for Antalya province of Turkey. In the first part of the study, optimal system design for off-grid PV LED road lightings systems under the *M3* lighting class in Antalya is obtained with the twin-bracket central arrangement using maximum pole spacing. In the second part of the study, over the determined optimal design, the techno-economic analysis of the energy system in case of dimming LED luminaires after midnight is made. In case of dimming, LED luminaire power is decreased from 2×73 W to 2×51.1 W after midnight and thus, required PV and battery size of the energy system to supply LED luminaires are decreased

Table 8. Comparison of Optimization Results for Normal Case and Dimming Case

Parameter	Normal case	Dimming case
Battery capacity (V/Ah)	2×12/333.3	12/500
PV panel power (W)	800	770
PV tilt angle (°)	36.90	
Levelized COE ($/kWh)	0.225	0.210
Battery + PV initial cost ($)	1829	1398
Battery + PV net present cost ($)	1933	1506
Charge regulator cost ($)	125	
Operation&maintenance cost ($)	104.14	
Load consumption (kWh per year)	578	483
Unmet electric load (%)	0	
Autonomy (h)	84.86	76.16
CO_2 emission reduction (kg per year)	283.22	236.67

Table 9. The Payback Periods of the Energy System Investments and Total Installation costs per km under current conditions and for future scenarios

Scenario	Case	Energy System Net Present Cost ($)	Load Electricity Consumption (kWh per year)	Payback Period (years)	Total Installation Cost per km ($)
Current conditions	Normal case	2058	578	27.82	62526.45
	Dimming case	1631	483	26.38	53559.45
25 % increase in electricity tariffs	Normal case	2058	578	22.25	62526.45
	Dimming case	1631	483	21.10	53559.45
25 % decrease in PV system component and battery costs	Normal case	1599	578	21.61	52887.45
	Dimming case	1280	483	20.70	46188.45
50 % decrease in PV system component and battery costs	Normal case	1144	578	15.46	43332.45
	Dimming case	929.87	483	15.04	38835.72
25 % increase in electricity tariff and 50 % decrease in PV system component and battery costs	Normal case	1144	578	12.37	43332.45
	Dimming case	929.87	483	12.03	38835.72

from 800 W to 770 W and from 2×12 V 333.3 Ah to 12 V 500 Ah respectively. LED luminaires operated 2183.91 hours dimmed and 1777.26 hours without dimming annually.

For both normal and dimming cases, payback periods of the systems are found to be between 28–26 years under current conditions and between 22–20 years when electricity tariffs increase by 25 % or PV system component and battery costs decrease by 25 %. While payback periods are above the system lifetime in the former scenarios, payback periods can go below 20 years and be reduced to 15 years in case of 50 % reduction in PV system component and battery costs, and moreover can be reduced to 12 years along with 25 % increase in electricity tariffs.

When dimming is applied, in current case the total NPC of the entire lighting installation per km decreases from \$62 526.45 to \$53 559.45 by 14.3 % and in the most favourable future scenario (25 % increase in electricity tariffs with 50 % decrease in PV system component and battery costs) the total NPC of the entire lighting installation per km decreases from \$43 332.45 to \$38 835.72 by 10.4 %.

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A.Can Duman,
M.Sc. He is an employee of Istanbul Technical University, Energy Institute

Önder Güler,
Ph.D. Prof. of the Istanbul Technical University, Energy Institute. Member of the Turkish National Lighting Commission and Society of electrical engineers. Research interests: road lighting, energy saving, energy consumption management in industry and buildings, wind energy, power quality