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Techno-economic analysis of off-grid photovoltaic LED road lighting systems: A case study for northern, central and southern regions of Turkey

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ABSTRACT

Street lighting is one of the sectors where off-grid energy systems are used, and in the past decade interest in these systems has increased due to recent developments occurred both in LED and PV technology. This paper presents a techno-economic analysis of off-grid PV LED road lighting systems for northern, central and southern regions of Turkey. Road lighting calculations are conducted using DIALux software for M4 and M5 road lighting classes to obtain optimal LED luminaires, pole sizes, and spacings. Among the obtained LED powers, load profiles are created using real lighting hours of operation of the selected regions. And then, the required PV-battery systems are optimized using HOMER software. Finally, sensitivity analysis is performed for future projections considering possible increases in electricity prices and decreases in component cost of the PV systems. The results showed that the levelized COE of the off-grid PV LED road lighting systems vary between 0.229 and 0.362 $/kWh for M4, and 0.254–0.359 $/kWh for M5 road lighting class, depending on the solar potential of the region. And, the total NPC of the entire lighting installation per km vary between 24296 and 29123 $ for M5, and 33225–44318 $ for M4 road lighting class. According to the results, the systems are infeasible under current conditions in Turkey. Nonetheless, they have the added benefits of contributing to the reduction of CO_2 emissions. Moreover, future projections show that the systems can be feasible if the declining trend in PV system costs continues and electricity prices increase.

1. Introduction

Over the past decade, there has been a strong upward trend in renewable energy investments in many sectors with reasons such as global warming, policies to reduce carbon emissions, increased environmental awareness and decline trend in renewable energy system costs. Solar energy has become one of the most promising among the other renewable energy technologies due to rapid decrease in photovoltaic (PV) module spot prices which were above 3 $/W in 2009 and vary between 0.29 and 0.25 $/W today (with an average of 0.285 $/W) [1]. In addition, the prices of other components such as inverters, charge regulators, trackers, mounting and electrical equipment have reduced in the range of 5–7% [2].

PV systems can operate both on-grid and off-grid. Off-grid systems are particularly attractive in rural regions of the world where installation of new transmission lines are required for electrification [3]. According to the World Bank data, approximately 23% of the people in rural areas lack electricity in the world by 2016 [4]. One of the sectors where off-grid systems are used is street and road lighting, and interest in these systems has started to increase in recent years, particularly in developing countries with high solar potential. For instance, Nigeria aims to increase the capacity of PV street lighting from 100 MW to 1000 MW by 2015 and to 10000 MW by 2030 [5]. In Cameroon, 3000 off-grid PV lighting systems were already installed on major streets and public sites [6]. In Malawi, which has one of the lowest grid access in South Africa (9%), 250 off-grid PV street lights were planned to be installed by a Chinese funded project. In Zimbabwe 15 million $ has been set aside for deployment of 4000 off-grid PV road lighting systems which is predicted to save about 200000 $ per month [7].

Increasing interest in the systems is not only due to declining in PV module costs but also developments occurred in light emitting diode (LED) technology in the last 10–15 years. LED luminaires have offered more cost-effective and longer-lasting lighting solutions than the conventionally used high-pressure sodium (HPS) luminaires in road lighting. In the past, roads that can be illuminated using 100–150 W HPS luminaires can now be illuminated using 40–70 W LED ones. This means previously higher PV and battery size can now be reduced and off-grid PV lighting can be achieved at lower costs. In addition, there is no need for inverters because LED luminaires can operate at DC voltage in contrary to HPS luminaires. A lighting pole can carry only a limited

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size of PV, thus providing the same lighting quality of HPSs at lower power consumption with LEDs makes it possible to meet lighting criteria also in higher leveled road lighting classes.

2. Literature review

Above-mentioned developments in PV and LED technology offer promising possibilities for the assessment of solar potential in roadways, and there is a growing body of research dealing with off-grid PV LED road lighting in the literature. Velaga and Kumar [8] carried out techno-economic feasibility of off-grid PV LED street lighting systems for a village in rural India which does not have street lighting and needs new transmission lines for electrification. In the study, off-grid PV LED lighting was economically compared with the conventional on-grid HPS lighting. For on-grid HPS solution, the cost of installation of new transmission lines and the electricity losses during system lifetime were also taken into account. As a result, off-grid PV LED lighting was found as a more economical option with 21% reduced installation cost. Wu et al. [9] investigated the design of an off-grid PV LED roadway lighting system for a 10 km highway with 2 lanes and pole spacing of 30 m. Cost-effectiveness of the off-grid PV LED system was compared with on-grid LED and on-grid luminaires with mercury lamps. The total installation cost of the systems was made in detail including, pole, labor and transformer station costs. On-grid installation with luminaires with mercury lamps provided the lowest initial investment cost, whereas LED systems excelled at energy-efficiency and had lower total net present costs (NPCs). In off-grid road lighting, luminaires can be either energized from PVs mounted on lighting poles or from an islanded PV mini-grid deployed on the ground. Liu [10] performed a comparative feasibility analysis of on-grid and islanded off-grid systems. The Hybrid Optimization Model for Electric Renewables (HOMER) software was used to find out the optimal size of PVs and batteries. Also, monocrystalline and polycrystalline technologies were economically compared for the lighting systems. Das et al. [11] made a cost comparison of off-grid PV LED and HPS flood lights for exterior lighting. Although exterior lighting differs from road lighting from some aspects, the methodology used in the study is worthwhile to mention in terms of taking photometric values into consideration in sizing of the PV systems. Lithonia Visual was used for lighting calculations and HOMER was used in renewable system optimization. Kumar et al. [12] conducted a comparative feasibility study to meet the energy demand of 210 street lights in Nigeria. Four different solutions were compared which were, islanded off-grid PV LED, mounted off-grid PV LED, on-grid LED and off-grid diesel LED. The comparison of the results was based on being technically feasible, financially viable, and environmentally friendly. On-grid PV LED system achieved to meet all the required criteria and the payback period of the system was found to be 20.54 years. Khalil et al. [13] studied techno-economic feasibility of four different street lighting solutions; fossil fuel HPS, fossil fuel LED, on-grid PV LED and off-grid PV LED for a 4 km road in Libya. Grid-connected PV LED was found to be the most favorable option in terms of initial investment cost, operation & maintenance (O&M) cost, fuel cost, and CO_2 emission. Lagorse et al. [14] investigated the improvement of classical PV-battery systems in off-grid lighting and proposed a hybrid system that couples PV-battery with fuel cell. In hybrid system sizing, firstly genetic algorithm was used to approximate the global optimum, and then simplex algorithm was used to improve the result. Parameters such as PV tilt angle and battery state of charge (SoC) were also taken into account in the study. 60 W LED luminaire was powered using 148 W PV, 128 W fuel cell and 2.56 kWh batteries. Sharma and Harinarayana [15] proposed a PV-made roof structure for roadways to both get avoid from land costs and provide sun shading in roads for longer vehicle tire life and reduced road repairs. PVSyst software was used to analyze the performance of the PV system. Masoud [16] studied the economic availability of on-grid PV road lighting in Sultanate of Oman. LED lighting was recommended over HPS as a result of the feasibility analysis. It was found that the proposed system can payback the investment in 3.5 years. However, O&M costs were neglected in the study. Pinter et al. [17] economically compared retrofitting and replacement of an existing street lighting installation with PV LED systems in Hungary and PV LED systems found to be feasible only in case of retrofitting of an existing lighting installation. Montelpare et al. [18] examined performance of a stand-alone hybrid PV-savonius wind turbine system for a lighting installation. Efthymiou et al. [19] pointed out that PV pavements are capable of covering the electrical energy demand of nearby lighting installations.

There are also few studies in the literature regarding Life Cycle Assessment (LCA) of off-grid PV LED road lighting systems. Tannous et al. [20] conducted a comparative LCA for on-grid HPS and off-grid PV LED road lighting systems for rural areas of Lebanon, and found out that off-grid PV LED systems have a lower environmental impact than the traditional on-grid HPS systems for both landfilling and recycling. Environmental impact of off-grid PV LED systems is higher from raw material extraction to the production phase caused by lead and electronics used in PV systems, however, the damage is counterbalanced during the entire life cycle due to depending less on grid electricity which mainly uses fossil fuels. Hadi et al. [21] conducted an LCA to find out the environmental impact of various street lighting solutions. Off-grid PV LED with battery recycling at 80%, on-grid PV LED, on-grid LED, off-grid PV ceramic metal halide (CMH) with and without battery recycling, and on-grid PV CMH solutions were compared in the analysis. LEDs provided lower consumption than CMHs, and off-grid systems with battery recycling were found to be an environmentally better choice than on-grid systems.

3. Content and contributions

These papers regarding technical and economic feasibility analysis of off-grid PV road lighting systems have provided valuable contributions to the literature. However, it is seen that road lighting criteria are often neglected and based on assumptions. The papers are mainly concentrated on the sizing optimization of the PV and battery systems, but the total cost of the entire energy system also depends on the number of lighting poles to be built which can only be obtained after road lighting calculations. Moreover, unlike other lighting areas, the failure to meet lighting criteria in road lighting not only reduces user comfort, but also violates road safety and may cause fatal accidents, and thus should not be negligible.

Another assumption made in the studies that can be misleading is to make PV and battery sizing over a single lighting pole. This approach leads to minimize PV-battery size and cost on single lighting pole. However, since low-powered LED luminaires provide low lighting level, more number of lighting poles (and accordingly more PVs and batteries) are required to meet lighting criteria alongside the entire road, and thus total installation cost of the system is likely to be increased [22].

Moreover, energy systems to be used for off-grid road lighting should be sized according to the worst conditions of winter months to meet lighting criteria uninterruptedly throughout a year. In winter months, there is not only lower solar potential but also increased lighting hours of operation. Thus, lighting hours of operation should also be determined instead of using average values.

For the above-mentioned reasons, in this paper, techno-economic analysis of off-grid PV LED road lighting systems are conducted regarding detailed road lighting calculations based on the international and national standards which is the main contribution of the study. Road lighting calculations are performed using DIALux software for M4 and M5 road lighting classes to obtain optimal LED luminaires, pole sizes, and spacings. Among the obtained LED powers, load profiles were created using calculated lighting hours of operation of the selected regions which represent regions with low, average and high solar potential within Turkey. And then, the required PV-battery systems are

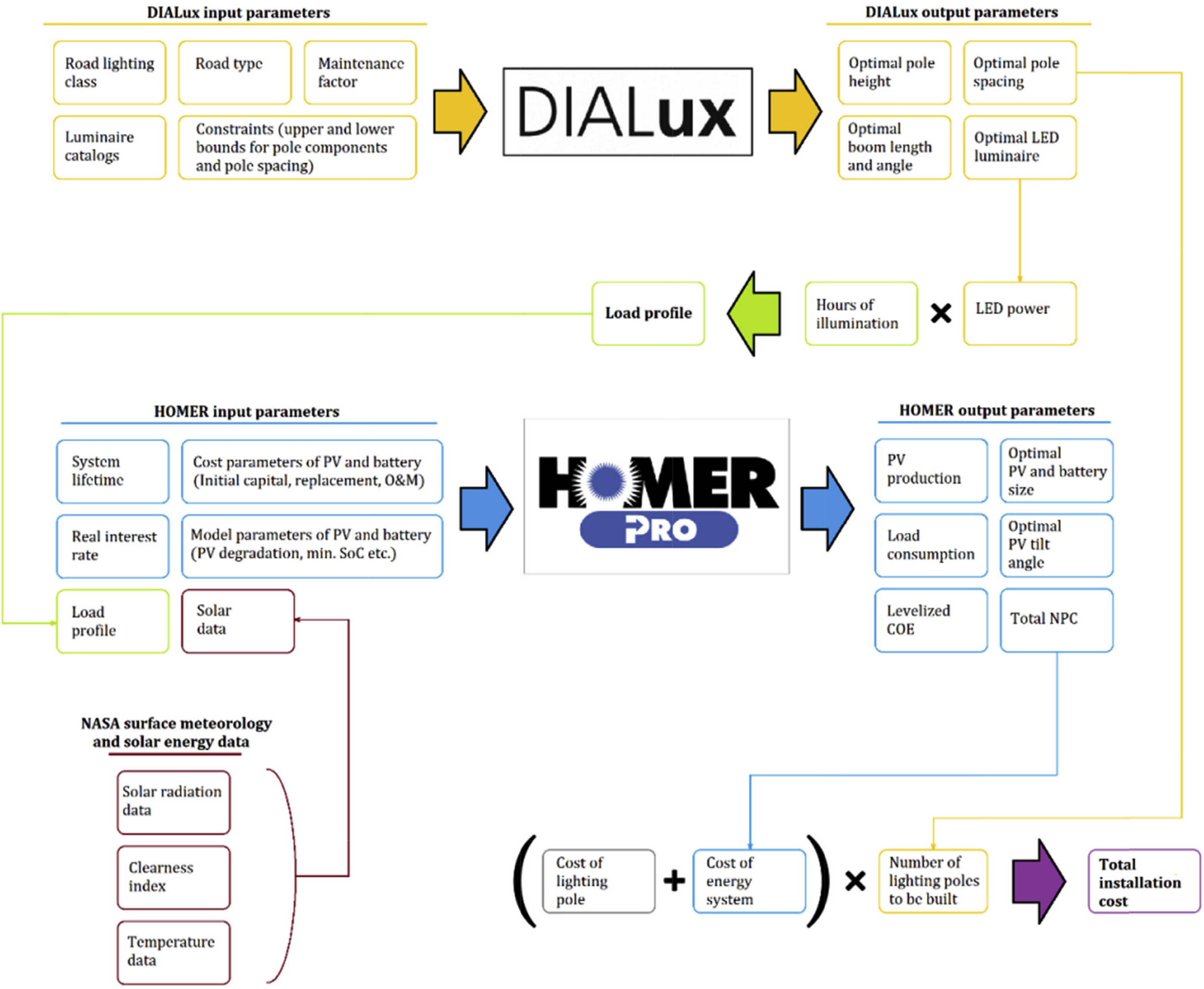


Fig. 1. Conceptual of the methodology used in the study.

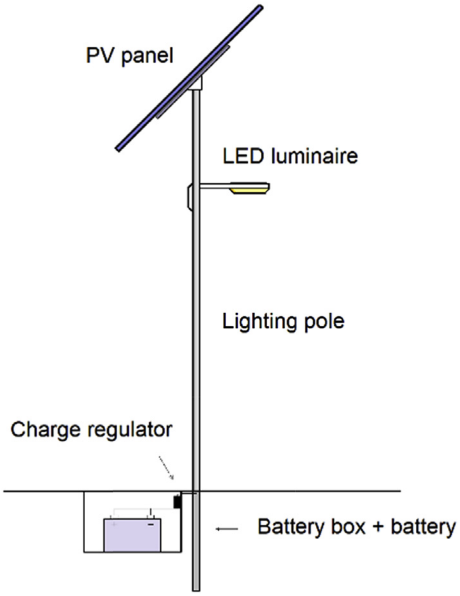


Fig. 2. Structure of an off-grid PV LED road lighting system.

optimized using HOMER software. Finally, sensitivity analysis is performed considering future projections which are;

- 25% increase in electricity prices
- 25% decrease in cost of PV system components
- 50% decrease in cost of PV system components
- 25% increase in electricity prices together with 50% decrease in cost of PV system components.

Conceptual of the methodology used in the study is given in Fig. 1. It's worth to mention that HPS luminaire option is not elaborated in the study due to the proven technology of LEDs in road lighting [23]. The higher initial cost of LEDs which is the main drawback is counterbalanced by the possible savings in energy consumption and O&M costs [24]. Also, LEDs offer new control and dimming strategies in road lighting [25]. In various studies, the cost-effectiveness of LED road lighting is proved both for retrofitting applications and new installations [26,27].

4. Structure of off-grid PV LED road lighting systems

Off-grid PV LED road lighting systems consist of PV modules, battery groups, charge regulators, LED luminaires and lighting poles as shown in Fig. 2. PV panels charge the batteries throughout the day and charge regulators control the PV output voltage and current and protect the batteries from overcharging and discharging. The advantages of off-grid PV LED road lighting systems can be listed as low maintenance requirement, helping to reduce CO_2 emissions, lack of transmission and distribution losses, simple and fast installation, no requirement for an inverter, long service life and making a contribution to social life as well as safety in rural areas [28,29]. The disadvantages include high initial investment costs and dependency on weather conditions.

5. Road lighting

Road lighting can be described as illumination of squares, intersections, streets, inner and outer main traffic roads and it covers the largest portion of total electricity consumption in general lighting. In Turkey, general lighting accounts for 1.8% of the total electricity consumption of 231204 GWh as of 2016 [30].

The International Commission on Illumination (CIE) and the European Union Standards (CEN) develop internationally agreed basic standards and procedures on lighting criteria [31,32]. Government agencies hold the responsibility of regulating the recommended criteria considering their countries' own specific economic, geographical and climatic conditions. The responsibility of the installation and maintenance of approximately 5 million lighting poles located in urban and rural areas in Turkey belongs to Turkish Electricity Distribution Co. (TEDAS).

6. Techno-economic analysis of off-grid PV LED road lighting systems

6.1. Solar energy potential in Turkey and the selection of the case regions

Turkey is situated between 36° and 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 (EIE), Turkey has an average annual total sunshine duration of 2741 h (daily total 7.5 h) and the average total radiation intensity in the country is 1527 kWh/m^2-year (total 4.2 kWh/m^2-day).

Turkey's Solar Energy Potential Atlas called GEPA is used in the selection of the case regions to be studied. GEPA is prepared by the EIE in 2010 using ESRI solar radiation model and calibrated with 22 years old solar measuring data of the EIE [33]. Three regions, representing three different solar energy potential are selected on the northern, central and southern latitudes passing through Turkey. The selected regions and their sunshine duration and solar radiation data according to GEPA is given in Table 1.

Antalya province is located between 29° 20' – 32°35′ east longitudes and 36° 07' – 37° 29′ north latitudes on the southwestern coast of Turkey. The province represents the regions with high solar radiation and sunshine duration in Turkey. Izmir province stays between 37° 45' – 39° 15′ east longitudes and 26° 15' – 28° 20′ north latitudes. Solar potential in the region is close to Turkey's average and sunshine duration is a little higher than the average. Izmir represents the regions with moderate solar potential in Turkey. Istanbul province in northern Turkey is located between 28° 01' – 29° 55′ east longitudes and 41° 33' – 40° 28′ north latitudes. The province represents the regions with low solar radiation and sunshine duration. Fig. 3 shows the location of the selected case regions on the solar energy potential map of Turkey, and Fig. 4 shows daily radiation and clearness index data of case selected regions.

Table 1
Sunshine duration and solar radiation data of Antalya, Izmir, and Istanbul.

Region	Latitude	Annual total solar radiation (kWh/m^2-year)	Sunshine duration (hr/year)
Antalya	36.8969° N	1650	3014
Izmir	38.4237° N	1501	2990
Istanbul	41.0082° N	1338	2449
Turkey avg.	38.9637° N	1527	2737

6.2. Road lighting calculations

Road lighting calculations are performed according to national road lighting standards of Turkey based on CIE and CEN recommendations which are TEDAS Technical Specifications for LED Light Sourced Road Lighting Luminaires, Procedures and Principles on the Usage of LED Luminaires in the General Lighting Scope, TS EN 13201–3 and Technical Specifications for Road Lighting Luminaires TEDAS MYD-95-009.B [34–36]. Table 2 shows the criteria to be met for M4 and M5 road lighting classes.

In the calculations, maintenance factor is set as 0.89 for the protection class of IP66 that is guaranteed according to CIE 154:2003 [37]. Road class is taken as R3. Minimum luminous efficacy of 115 lm/W and minimum service life of 50000 h are ensured for LED luminaires according to TEDAS Technical Specifications for LED Light Sourced Road Lighting Luminaires. Also, the color temperatures of the LED packages to be used in the design of LED luminaires and color rendering index (CRI) of the luminaires are guaranteed to be 4000 K ± 5% and minimum 70, respectively.

DIALux calculates luminance of point P on a road surface as follows (Fig. 5):

$$L_P = \sum_{i=1}^{a} \frac{I(C,\gamma)\cdot r(\beta, tan\gamma)\cdot\Phi_L}{h^2\cdot 10^7}\cdot MF \tag{1}$$

where, L_P is the luminance of a point on the road surface (cd/m^2), a is the number of luminaires, I is the luminous intensity of luminaire in the direction of point on road (cd), C is the plane angle, γ is the angle of light incidence, r is the reduced luminance coefficient of the road surface for the angles and corresponding to light incidence and observation direction relative to the point considered (cd/m^2/lux), β is the angle between plane of light incidence and plane of observation, Φ_L is the luminous flux of the luminaire, h is the mounting height of luminaire (m), α_g is the angle of observation (from the horizontal), and MF the is maintenance factor.

According to the TEDAS Technical Specifications for LED Light Sourced Road Lighting Luminaires, minimum pole spacing to be provided in M4 and M5 road lighting class should be 28 m. Therefore, in DIALux calculations, pole spacing lower and upper bounds are set as 28–55 m in 1 m increments. Pole height lower and upper bounds are set as 7–10 m in 0.5 m increments and boom length lower and upper bounds are set as 0–1.5 m in 0.5 increments with 0° angle of inclination. A set of luminaires were selected from the catalogs of well-known brands and DIALux sorted the luminaires according to given preferences. The selected 67 W and 46 W luminaires provide the least power consumption at the longest pole distance for M4 and M5 road lighting classes, respectively. Table 3 shows the results of road lighting calculations for M4 and M5 road lighting classes and the luminous intensity diagram of the selected luminaires is given in Fig. 6.

6.3. HOMER optimization

In the study, HOMER software is used in the modeling and simulation of the energy systems. HOMER is an optimization model developed by National Renewable Energy Laboratory (NREL) to design micropower systems [38]. HOMER software is widely used and accepted with microgrid modeling purposes both in academic and commercial environments [39,40]. The software simulates the operation of a system through the renewable source data, user-defined operational constraints and capital, replacement, salvage and O&M costs of the system

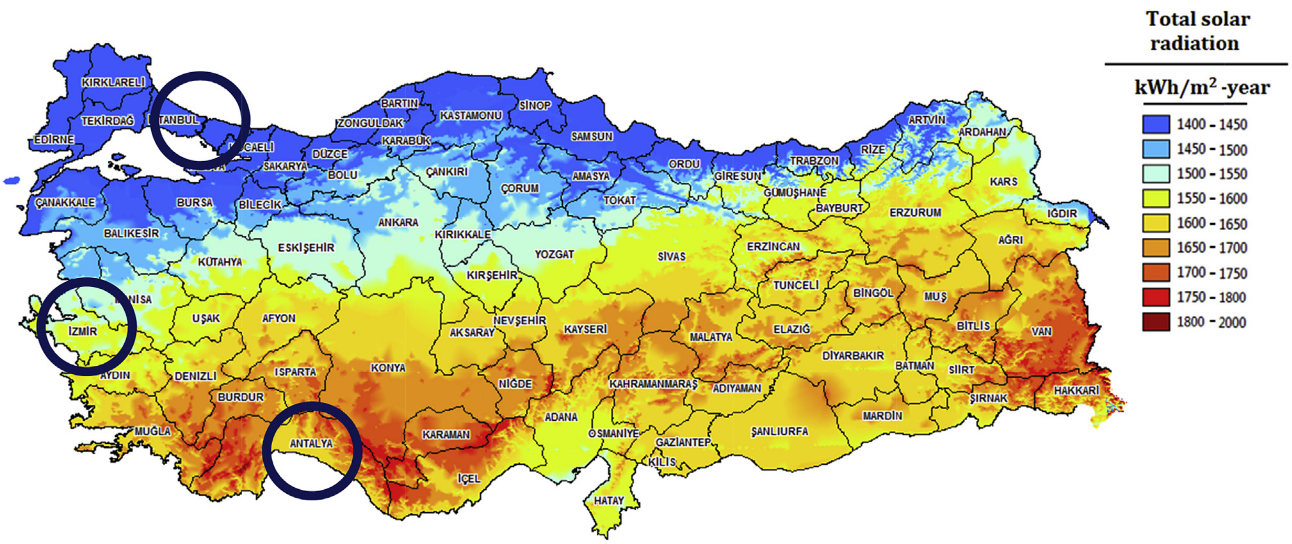


Fig. 3. Solar energy potential atlas of Turkey and the case regions (Istanbul, Izmir, Antalya).

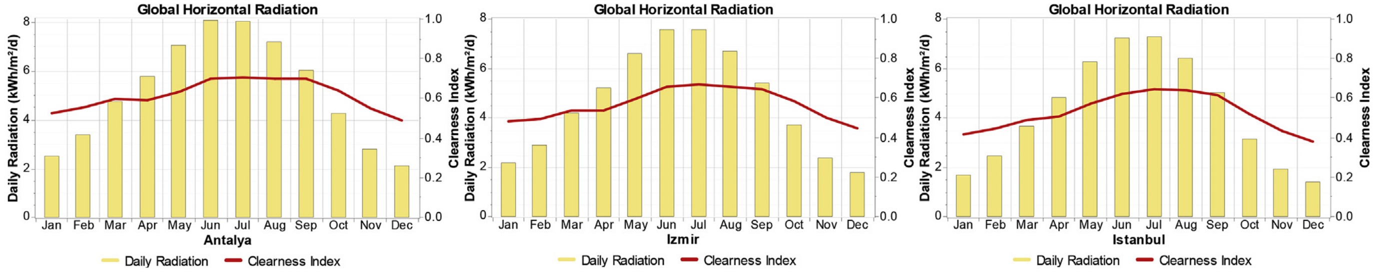


Fig. 4. Daily radiation and clearness index data of the case regions.

Table 2
Road lighting criteria to be met for the selected road lighting classes.

Lighting Class	L_{avg} (cd/m^2)	U_o	U_l	TI (%)	SR
M4	≥0.75	≥0.4	≥0.5	≤15	≥0.5
M5	≥0.5	≥0.35	≥0.4	≤15	≥0.5

L_{avg}: average luminance; U_o: overall uniformity; U_l: longitudinal uniformity; TI: threshold increment; SR: surround ratio.

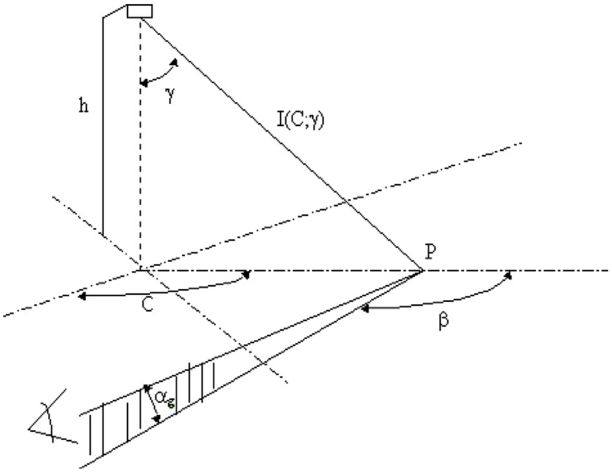


Fig. 5. Angles upon which the luminance coefficient is dependent.

Table 3
Road lighting calculations for M4 and M5 road lighting classes.

Lighting Class	M4	M5
Luminaire power (W)	67	46
Luminaire luminous flux (lm)	8280	5642
Luminous efficacy of luminaire (lm/W)	123.59	122.65
S (m) (Spacing)	47	53
h (m) (height)	10	10
k (m) (boom length)	0	1
L_{avg} (cd/m^2)	0.81	0.50
U_o	0.49	0.41
U_l	0.51	0.41
TI (%)	12	12
SR	0.63	0.61

components. After the simulation process, HOMER sorts all the possible hybrid system combination by the two principal economic indicators; the total NPC and the levelized cost of energy (COE). HOMER uses the following equation to calculate the total NPC [38]:

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF\,(i,\ R_{proj})} \tag{2}$$

where $C_{ann,tot}$ is the total annualized cost ($/year), CRF is the capital recovery factor, i is the annual real interest rate, and R_{proj} is the project lifetime (year). CRF is a ratio to calculate the present value of an annuity can be found by using the following equation:

$$CRF\,(i,\ N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where N is number of years, and i is the annual real interest rate. The equation for real interest rate i which is used by HOMER to calculate

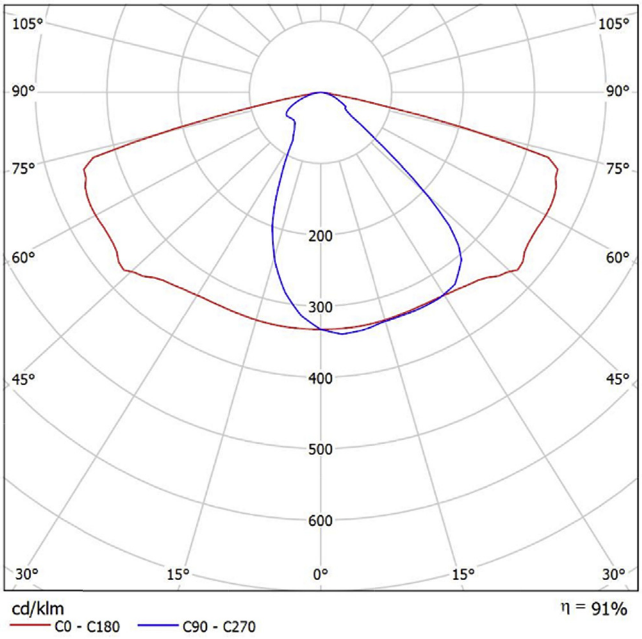


Fig. 6. The luminous intensity diagram of the luminaires used in the study.

discount factors and to convert between on-time costs and annualized costs can be found with the following equation:

$$i = \frac{i' - f}{1 + f} \quad (4)$$

where i is the real interest rate, i' is the nominal discount rate and f is the expected inflation rate. The COE can be stated as the net present value of the average cost per kWh over the lifetime of a generating asset. HOMER calculates COE with the following equation:

$$COE = \frac{C_{ann,tot}}{E_{served} + E_{grid,sales}} \quad (5)$$

where $C_{ann,tot}$ is the total annual cost ($/year) which is the annualized value of the total NPC, E_{served} is the primary load served (kWh/year), and $E_{grid,sales}$ is the amount of energy injected to the grid which is not applicable in off-grid case.

6.3.1. Input parameters

Solar radiation data is extracted from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy Database through HOMER. The project lifetime is set as 20 years. The real interest rate is calculated as 3% for Turkey. No inverter is modeled since the LED luminaires are supplied with DC voltage and the system is off-grid. Polycrystalline PV module price including charge regulator is taken as 0.52 $/kW. The cost of installation labor is not added here. Lighting pole and PV is assumed to be installed at the same time, and the labor cost of PV is added to the labor cost of pole mounting. O&M cost of each PV panel is set as 7 $/yr regardless of the size of the PV. PV lifetime is taken as 20 years and since it is equal to the system lifetime, replacement cost and salvage value for PV are discluded in the calculations and taken as zero. In the simulations, maximum PV capacity that can be mounted on a pole is estimated to be 0.885 kW and PV panel lower and upper bounds are set as 100–885 W in 10 W increments. PV derating factor to include dusting effect, high temperature, shading, snow cover, aging and cable losses is taken as 80% which varies between 70% and 90% in hot climates. The percentage of ground reflectance, which is the proportion of the radiation coming to the earth to reflected by the earth is taken as 20%. HOMER calculates the output of the PV array with the following equation [38]:

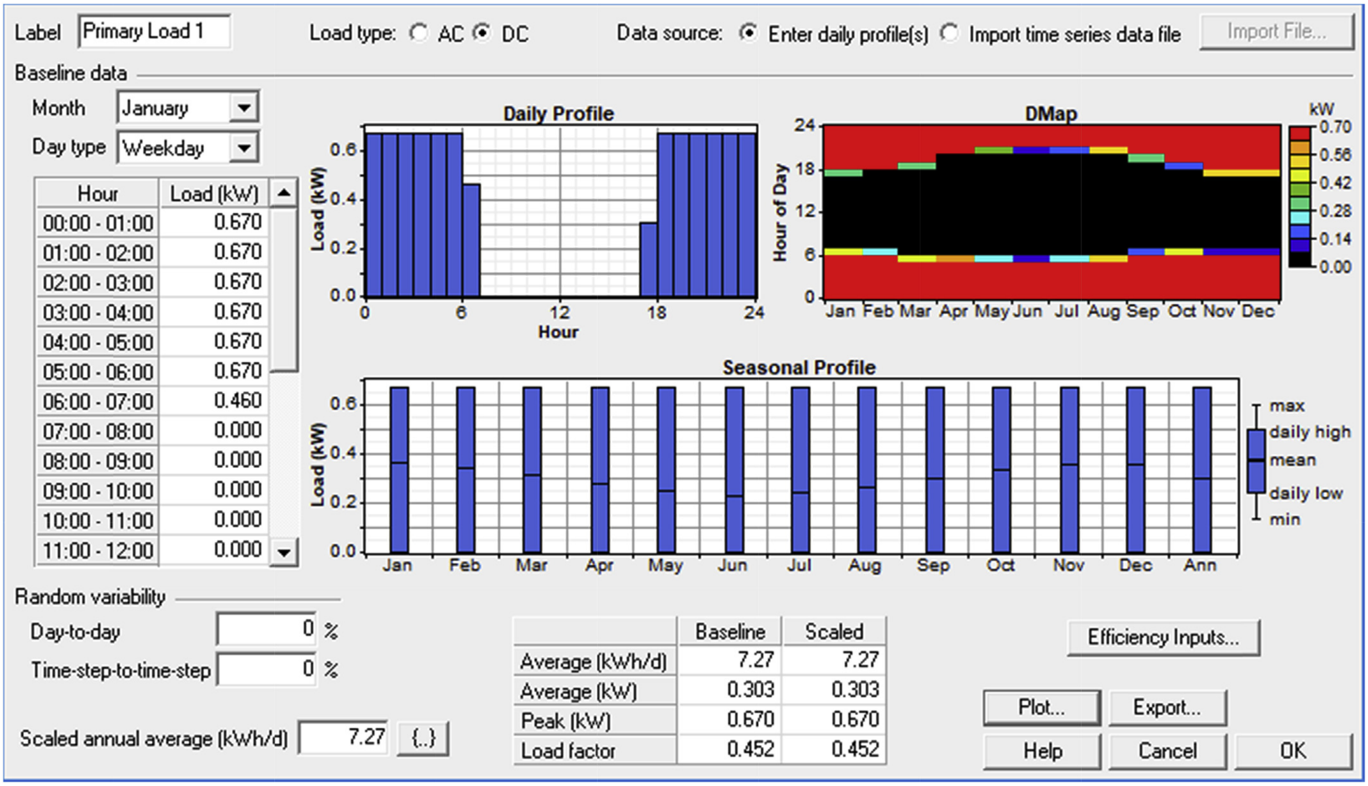
$$P_{PV} = Y_{PV} d_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \quad (6)$$

where Y_{PV} is the PV rated capacity at standard test conditions (STC) (kW), d_{PV} is the PV derating factor [%], $\bar{G}_T$ is the solar radiation incident on the PV array in the current time step [kW/m^2]. $\bar{G}_{T,STC}$ is the solar radiation incident at STC (1000 W/m^2). α_P is the temperature coefficient of power [%/°C], T_c is the PV cell temperature in the current time step (°C), and the $T_{c,STC}$ is the PV cell temperature at STC (25 °C).

12 V lead-acid batteries are used in the modeling with allowed

Table 4
Average lighting times and lighting hours of operation for Antalya, Izmir and Istanbul.

	Daily average lighting time			Daily average lighting hours of operation			Monthly average lighting hours of operation (hours)		
	Antalya	Izmir	Istanbul	Antalya	Izmir	Istanbul	Antalya	Izmir	Istanbul
Jan	06:41 17:33	06:58 17:44	06:56 17:31	13 h 08 m	13 h 14 m	13 h 25 m	407.13	410.23	415.92
Feb	06:20 18:03	06:36 18:16	06:31 18:06	12 h 17 m	12 h 20 m	12 h 25 m	343.93	345.33	347.67
Mar	05:41 18:31	05:54 18:46	05:46 18:40	11 h 10 m	11 h 08 m	11 h 06 m	346.17	345.13	344.1
Apr	05:55 20:00	06:08 20:16	05:56 20:13	09 h 55 m	09 h 52 m	09 h 43 m	297.5	296	291.5
May	05:19 20:28	05:29 20:47	05:14 20:48	08 h 51 m	08 h 42 m	08 h 26 m	274.35	269.7	261.43
Jun	05:07 20:49	05:15 21:09	04:58 21:12	08 h 18 m	08 h 06 m	07 h 46 m	249	243	233
Jul	05:21 20:45	05:30 21:05	05:13 21:06	08 h 36 m	08 h 25 m	08 h 07 m	266.6	260.92	251.62
Aug	05:48 20:14	05:39 20:32	05:46 20:30	09 h 34 m	09 h 27 m	09 h 16 m	296.57	292.95	287.27
Sep	06:13 19:30	06:27 19:46	06:17 19:40	10 h 43 m	10 h 41 m	10 h 37 m	321.5	320.5	318.5
Oct	06:40 18:45	06:55 18:58	06:49 18:49	11 h 55 m	11 h 57 m	12 h 00 m	369.42	370.45	372
Nov	06:09 17:15	06:25 17:27	06:22 17:15	12 h 54 m	12 h 58 m	13 h 07 m	387	389	393.5
Dec	06:35 17:11	06:53 17:22	06:52 17:08	13 h 24 m	13 h 31 m	13 h 44 m	402	405.5	412
Total							3961.17	3948,71	3928.51



Label: Primary Load 1

Load type: ○ AC ● DC

Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data

Month: January

Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	0.670
01:00 - 02:00	0.670
02:00 - 03:00	0.670
03:00 - 04:00	0.670
04:00 - 05:00	0.670
05:00 - 06:00	0.670
06:00 - 07:00	0.460
07:00 - 08:00	0.000
08:00 - 09:00	0.000
09:00 - 10:00	0.000
10:00 - 11:00	0.000
11:00 - 12:00	0.000

Random variability

Day-to-day: 0 %

Time-step-to-time-step: 0 %

Scaled annual average (kWh/d): 7.27

	Baseline	Scaled
Average (kWh/d)	7.27	7.27
Average (kW)	0.303	0.303
Peak (kW)	0.670	0.670
Load factor	0.452	0.452

Fig. 7. The load profile of 67 W luminaire for M4 road lighting class in Antalya as a sample.

Table 5
Optimization results for M5 road lighting class (46 W luminaire).

	Antalya	Izmir	Istanbul
Battery capacity (V, Ah)	12 V 200Ah	12 V 200Ah	12 V 250Ah
PV panel power (W)	280	330	680
PV tilt angle (°)	39–73	47–56	44–59
Levelized COE ($/kWh)	0.254	0.265	0.359
PV + battery initial investment cost ($)	585.10	611.10	893.60
PV + battery net present cost ($)	689.24	715.24	967.74
Operation & maintenance cost ($)	104.14		
PV electricity production (kWh/year)	448	505	857
Annual excess production (kWh/year)	236.3	295.4	647.4
Excess electricity production/Total production (%)	52.8	58.5	75.6
Load electricity consumption (kWh/year)	183	182	181
Unmet electric load (%)	0		
Autonomy (hr)	80.51	80.94	101.39
CO_2 emission reduction ($kgCO_2$/yr)	89.67	89.18	88.69

Table 6
Optimization results for M4 road lighting class (67 W luminaire).

	Antalya	Izmir	Istanbul
Battery capacity (V, Ah)	12 V 250Ah	12 V 250Ah	12 V 416.6Ah
PV panel power (W)	480	590	885
PV tilt angle (°)	35–57	36–48	37–48
Levelized COE ($/kWh)	0.229	0.245	0.362
PV + battery initial investment cost ($)	759.60	816.80	1316
PV + battery net present cost ($)	907.11	963	1420
Operation & maintenance cost ($)	104.14		
PV electricity production (kWh/year)	779	920	1132
Annual excess production (kWh/year)	471	614.1	828.2
Excess electricity production/Total production (%)	60.5	66.7	73.1
Load electricity consumption (kWh/year)	266	265	264
Unmet electric load (%)	0		
Autonomy (hr)	69.09	69.03	116.15
CO_2 emission reduction ($kgCO_2$/yr)	130.34	129.85	129.36

minimum SoC of 30% and round trip efficiency of 86%. Nine different battery choices of the same brand were proposed according to different capacity requirements. Battery prices vary between \$117 - \$997.5 and nominal capacity of the batteries vary between 33.3 Ah and 500 Ah. As the battery and panel are installed on the same pole, the O&M cost of the batteries are included in the O&M cost of the PV panels. HOMER calculates the battery life L_{batt} as follows:

$$L_{batt} = min\left(\frac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \tag{7}$$

where N_{batt} is the number of batteries, $Q_{lifetime}$ is the lifetime throughput of a single storage (kWh), and Q_{thrpt} is the annual storage throughput (kWh/year).

In the study, off-grid PV LED road lighting systems' contribution to environmental sustainability is also taken into consideration since one of the goals of the systems is to reduce CO_2 emissions. The International Energy Agency (IEA) data is used in the calculation of CO_2 emission reduction, which determines the amount of CO_2 emission produced per kWh in Turkey as 490 gCO_2/kWh [41].

6.3.2. Modeling of the load profile

The load profile is modeled using real daylight data. To model the load profile, operation hours of LED luminaires are calculated assuming that the road lighting will be performed between twilight and dawn, and out of operation during the daytime and civil twilight (the part of the day when the angle between the horizon and the sun is less than 6° and where the objects can still be easily selected and people can perform daily tasks without any requirement of artificial lighting). Daylight saving time is also taken into account. Table 4 shows the daily

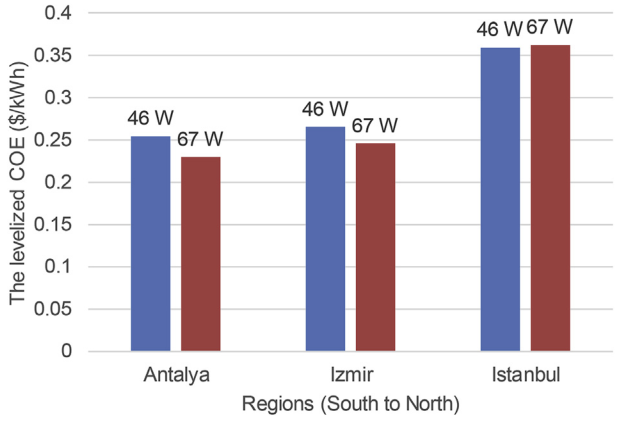


Fig. 8. Relation between the power of the LEDs and the COE of the energy systems.

Table 7
Payback periods of the energy systems under current conditions.

	Road lighting class	Luminaire power (W)	Payback period (year)	The total NPC of the energy system ($)	Electricity consumption (kWh/year)
Antalya	M5	46	29.42	689.24	183
	M4	67	26.64	907.11	266
Izmir	M5	46	30.70	715.24	182
	M4	67	28.39	963	265
Istanbul	M5	46	41.77	967.74	181
	M4	67	42.02	1420	264

Table 8
Payback periods of the energy systems in case of 25% increase in electricity prices.

	Road lighting class	Luminaire power (W)	Payback period (year)	The total NPC of the energy system ($)	Electricity consumption (kWh/year)
Antalya	M5	46	23.54	689.24	183
	M4	67	21.31	907.11	266
Izmir	M5	46	24.56	715.24	182
	M4	67	22.71	963	265
Istanbul	M5	46	33.42	967.74	181
	M4	67	33.62	1420	264

Table 9
Payback periods of the energy systems in case of 25% decrease in cost of PV system components.

	Road lighting class	Luminaire power (W)	Payback period (year)	The total NPC of the energy system ($)	Electricity consumption (kWh/year)
Antalya	M5	46	23.18	542.96	183
	M4	67	20.75	706.37	266
Izmir	M5	46	24.14	562.46	182
	M4	67	22.06	748.29	265
Istanbul	M5	46	32.45	751.84	181
	M4	67	32.29	1091	264

Table 10
Payback periods of the energy systems in case of 50% decrease in cost of PV system components.

	Road lighting class	Luminaire power (W)	Payback period (year)	The total NPC of the energy system ($)	Electricity consumption (kWh/year)
Antalya	M5	46	16.94	396.69	183
	M4	67	14.85	505.62	266
Izmir	M5	46	17.59	409.69	182
	M4	67	15.73	533.57	265
Istanbul	M5	46	23.13	535.94	181
	M4	67	22.56	762.29	264

Table 11
Payback periods of the energy systems in case of 25% increase in electricity prices together with 50% decrease in cost of PV system components.

	Road lighting class	Luminaire power (W)	Payback period (year)	The total NPC of the energy system ($)	Electricity consumption (kWh/year)
Antalya	M5	46	13.55	396.69	183
	M4	67	11.88	505.62	266
Izmir	M5	46	14.07	409.69	182
	M4	67	12.58	533.57	265
Istanbul	M5	46	18.51	535.94	181
	M4	67	18.04	762.29	264

and monthly average lighting hours of operation for Antalya, Izmir, and Istanbul. It is seen that in the selected provinces lighting hours of operation is below 250 h in June, above 400 h in January, and the monthly average is 328 h. The daily and seasonal load profile of 67 W luminaire modeled in HOMER for M4 road lighting class in Antalya is given in Fig. 7 as a sample.

6.3.3. *Optimization results*

According to the optimization results, in case of using 46 W luminaire in M5 road lighting class, the required PV and battery capacities are 280 W PV and 12 V 200 Ah battery for Antalya in the south, 330 W PV and 12 V 200 Ah battery for Izmir in the middle, and 680 W PV and 12 V 250 Ah battery for Istanbul in the north. The total NPC and the levelized COE of the PV and battery investments are 689.24 $, 715.24 $ and 967.74 $ and 0.254 $/kWh, 0.265 $/kWh and 0.359 $/kWh for Antalya, Izmir and Istanbul, respectively. The results are given in Table 5 in detail.

In case of using 67 W luminaire in M4 road lighting class, the required PV and battery capacities are 480 W PV and 12 V 250 Ah battery for Antalya in the south, 590 W PV and 12 V 250 Ah battery for Izmir in the middle, and 885 W PV and 12 V 416.6 Ah battery for Istanbul in the north. The total NPC and the levelized COE of the PV and battery investments are 907.11 $, 963 $ and 1420 $ and 0.229 $/kWh, 0.245 $/kWh and 0.362 $/kWh for Antalya, Izmir and Istanbul, respectively. The results are given in Table 6 in detail.

Fig. 8 shows the relation between the power of LED luminaires and levelized COE of the energy systems. It is seen that in Antalya and Izmir levelized COE of the systems are lower when higher-powered LEDs are used, and this is actually what was expected as it can be generalized for the off-grid PV systems that the installation cost per kWh is lower when the system capacity is higher. However, in off-grid road lighting case, there is a restriction which is the limited PV capacity that can be mounted on a lighting pole. Note that, in Istanbul the levelized COE of the energy system with 885 W PV and 12 V 416.6 Ah battery (76 W luminaire) is slightly higher than the levelized COE of the system with 680 PV and 12 V 250 Ah battery (46 W luminaire). This is because, during the optimization stage, the PV capacity could not exceed the limited capacity of 885 W, and to ensure the system autonomy, more costly battery capacity is increased instead of PV.

Table 12
System installation costs per km for M4 and M5 road lighting classes in Antalya, Izmir, and Istanbul.

Region	Antalya		Izmir		Istanbul	
Lighting class	M5	M4	M5	M4	M5	M4
Luminaire power (W)	46	67	46	67	46	67
Pole spacing (m)	53	47	53	47	53	47
Pole length (m)	10	10	10	10	10	10
PV + charge regulator + battery net present cost ($)	689.24	907.11	715.24	963	967.74	1420
LED luminaire cost ($)	295.5	316.5	295.5	316.5	295.5	316.5
Galvanized steel polygon lighting pole cost ($)	184.10	184.10	184.10	184.10	184.10	184.10
Boom cost ($)	7.35	0	7.35	0	7.35	0
Pole mounting cost ($)	97.72	97.72	89.08	89.08	89.08	89.08
Cable cost ($)	3.6	3.6	3.6	3.6	3.6	3.6
Cabling cost ($)	1.2	1.2	1.2	1.2	1.2	1.2
Single pole system cost ($)	1278.71	1510.23	1296.07	1557.48	1548.57	2014.49
Number of poles per km	19	22	19	22	19	22
System installation cost per km ($/km)	24295.49	33225.06	24625.33	34264.56	29423.02	44318.78
The levelized COE ($/kWh)	0.254	0.229	0.265	0.245	0.359	0.362
Annual lighting hours of operation (hours)	3961.17		3948.71		3928.51	
Annual electricity consumption per km (kWh)	3462.06	5838.76	3451.17	5820.40	3433.52	5790.62

7. Simple payback periods under current conditions and for future scenarios

After obtaining the total NPC of the energy systems and the electricity consumption of the loads, simple payback periods of the systems were calculated for the current case and the future projections. The electricity price is taken as 0.128 $/kWh for general lighting [42]. Tables 7–11 show the results of payback periods, respectively under current conditions and for future scenarios which are 1) 25% increase in electricity prices, 2) 25% decrease in cost of PV system components, 3) 50% decrease in cost of PV system components, and 4) 25% increase in electricity prices together with 50% decrease in cost of PV system components.

8. System installation costs per kilometer

In this part, the total cost of system installation per km is calculated according to the results obtained in the previous two parts. At first, cost of single pole system is calculated, and then the result is multiplied with the number of poles to be installed per km. System installation costs per km for M4 and M5 road lighting classes in Antalya, Izmir, and Istanbul are given in Table 12 in detail.

9. Discussion and conclusions

In this study, techno-economic feasibility analysis of off-grid PV LED road lighting systems is performed under M4 and M5 road lighting in three case regions from Turkey. Since the accuracy of the load profile is related to the power consumption of the LED luminaire, and the total installation cost is dependent on the size and number of lighting poles to be installed, firstly detailed road lighting calculations were performed using DIALux software based on the international and national road lighting standards, and then HOMER software is used to optimize the required PV – battery capacity. In addition to current conditions, calculations are also performed for future scenarios considering possible increases in electricity prices and decreases in component cost of the PV systems.

The results showed that, in Turkey, for M4 road lighting class, the levelized COE of the off-grid PV LED road lighting systems vary between 0.229 and 0.362 $/kWh and the total NPC of the entire lighting installations per km vary between 33225 and 44318 $. For M5 road lighting class, the levelized COE of the systems increase and vary between 0.254 and 0.359 $/kWh and the total NPC of the installations per km vary between 24296 and 29123 $.

As a result of the study, it is seen that off-grid PV road lighting system investments seem infeasible in all the three regions under current conditions, that payback period of the systems cannot go below 20 years which is the system lifetime. For M4 road lighting class, in the current case, the payback period of the systems are 26.64, 28.39 and 42.02 years for Antalya, Izmir, and Istanbul, respectively. In the most favorable scenario (25% increase in electricity unit prices and 50% reduction in battery and PV prices), payback periods can decrease below 20 years and reach 11.88, 12.58 and 18.04 years for Antalya, Izmir, and Istanbul, respectively. For M5 road lighting class, in the current case payback period of the systems are 29.42, 30.70 and 41.77 years for Antalya, Izmir, and Istanbul, respectively. In the most favorable scenario, payback periods decrease to 13.55, 14.07 and 18.51 years for Antalya, Izmir, and Istanbul, respectively.

Nonetheless, the systems can be feasible under current conditions as well in countries where electricity prices are higher than in Turkey. For instance, the solar potential of Spain and Italy is relatively similar to Turkey's, whereas the price of electricity is twice as high. This means that the profitability of the systems doubles and the payback period falls by half in these countries. Also, in countries in which laws allow dimming in road lighting, the profitability of the systems can be increased some more with reduced PV and battery capacity.

Moreover, the systems can be feasible than on-grid systems if they are installed in rural areas where new transmission lines are required to be built. As the road lighting criteria were aimed to be uninterruptedly met throughout the year, PV and battery sizes were optimized according to the lowest solar radiation and sunshine duration of winter months, which increased the costs. In addition to low solar potential, during winter months lighting hours of operation is more, as for instance in Antalya 407 h of lighting is needed in January whereas it is 249 h in June. More than half of the annual energy produced could not be consumed which will constitute the subject of the future study to benefit from the excess storage as electric vehicle (EV) charging stations in rural roadways. Also, when combined with other rural off-grid applications, the systems can become feasible in urban areas as well with decreased levelized COE.

Despite the infeasible results in urban areas for Turkey, the systems have the added benefits of contributing to the reduction of CO_2 emissions, increasing awareness of environmental policies and supporting work and experiments in PV lighting. Moreover, future projections show that the systems can also be feasible if the declining trend in PV system components continues and electricity unit prices increase. The proposed method can be applied in different parts of the world as well, and more feasible results can be achieved in regions where solar potential and electricity prices are higher than in Turkey.

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