Techno-economic Assessment of Traffic-Adaptive Smart Lighting Projects

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Abstract. Rapid population growth in cities results in an increased energy consumption and need for infrastructure development. Street lights are some of the common energy consuming infrastructure in cities. Energy efficiency and demand-side management (EEDSM) interventions are therefore required to lower emissions and energy intensity in cities as well as save costs. The upgrading of infrastructure to include internet-of-things technologies as cities transition towards 'smart cities' presents opportunities to save energy via retrofitting old street light technology with smart lights. This work presents a methodology for techno-economic analysis of evaluating smart lighting retrofit projects that use traffic-adaptive control. The proposed analysis uses a lamp failure rate model to conduct a techno-economic analysis of street lights in a case-study city in South Africa. The resulting payback period for the smart lights retrofit is 3.42 years. The methodology proposed in this paper is more comprehensive than current alternatives in literature; it incorporates the time-value of money, makes use of lighting simulation studies and offers more accurate calculations of maintenance costs.

Keywords: Smart city · Energy efficiency · Streetlights · Smart light

1 Introduction

The population in cities is increasing rapidly, with African cities growing at an annual rate of 3.5% and half of the African population is expected to live in cities by 2030 [1]. This phenomenon is expected to increase energy consumption in cities. The energy use in cities is projected to reach 73% of global energy consumption by 2030. Cities are major sources of carbon emissions, for example accounting for as high as 85% of the national total in China [2]. Thus, there is a need to have energy efficiency interventions to contribute towards the United

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Nation's sustainable development goal (SGD) number 11 - *"Make cities and human settlements inclusive, safe, resilient and sustainable"*.

Lighting in cities is expected to account for about 19% of energy consumption, where a significant portion will be dedicated to street lighting [3]. The light emitting diode (LED) lighting technology is the predominantly recommended alternative for retrofitting the older technologies like the fluorescent, mercury vapour (MV) [4], high pressure sodium (HPS) [5] and metal-halide [6].

LED technology is attractive due to its high luminous efficacy. For example, it is shown to be 1.8× more than that of HPS at 150 W in [5]. Thus, many projects advocate for the retrofitting of current infrastructure with energy-efficient (EE) lights based on LED technology [5,6]. It therefore follows that cities and municipalities require techno-economic analysis tools and methodologies that accurately forecast the likely viability of smart lighting projects.

The advent of a 'smart city' concept, with ubiquitous sensor and telecommunication networks, presents a good opportunity for implementation of smart lighting infrastructure [7]. A range of energy efficiency and demand-side management (EEDSM) activities that can be implemented on street lighting infrastructure include retrofitting of EE luminaires and implementation of advanced control systems such as smart lights [8]. Smart street lights incorporate sensor data-driven control systems to facilitate EE operations, optimized lighting performance and sometimes additional services to the residents [9,10].

Smart light systems use sensed information from traffic patterns to further reduce energy consumption. Sensors applied in recent literature include, timers in [6], proximity sensors in [7], received signal strength - based sensors in [9] and smart camera in [10]. Smart lights are shown to result in varying operating electricity cost reductions based on the amount of traffic [11]. Reported cost reduction rates vary from 15% in [11], through 30% in [10] and to 89.5% in [9].

Accurate techno-economic analysis of smart lighting projects needs to consider lighting performance, electricity tariffs, maintenance cost and the dynamic seasonal operating hours of streetlights [5,8]. The analysis' economic aspect should account for time-value-of-money by applying discounted cash flows because of the long time span of retrofit projects. Studies in Serbia [5], Turkey [6], Laramie - Unite State (US) [4] and El Cajon - US [12] resulted in a pay-back period of 2.83, 2.61, 4 and 3 years, respectively.

The street lighting performance depends on multiple road and street light pole parameters [11]. Thus, lighting simulation studies using software like AGi32 [4] and DIALux in [13,14] are needed for accurate energy modelling. Alternatively, photometric studies need to verify performance against local standards like EN13201 in [11,13].

Moreover, the maintenance cost calculations need to consider the varying life spans of different lighting technologies in order to anticipate the likely number of lights expected to fail per period, after installation. A comprehensive list of lamp burnout failure population decay models that can be used to accurately model the maintenance cost is given in [15]. However, many recently published techno-economic analysis studies like [4,5,8,11] ignore the lamp failure model.

Thus, the contribution of this paper is to presents a techno-economic analysis methodology for the assessment smart lighting retrofit project that incorporates the modeling of lamp failure rate to result in accurate maintenance cost calculations.

The paper is organized as follows. Section 2 explains the techno-economic analysis methodology. Section 3 applies the methodology on a case-study in South Africa and the conclusions are provided in Sect. 4.

2 Methodology

The analysis process begins with gathering of data from multiple sources as shown in Fig. 1. These includes both financial and technical data. Technical data includes, traffic information describing daily pattern of traffic, sun-set/rise times and measurements made on the streets. Measurements obtained from the streets include the total number of luminaires N_{tot}, the actual average power usage of the light, the size of the street, location of poles, pattern of poles, beam angle and over hang distance. The financial data gathered will be used for economic analysis. This data includes electricity price π_{elec} per kWh, unit purchase price of the luminaires or lamps π_{pur}, unit cost for installing a lighting fixture π_{inst}, and cost of replacing a lighting fixture π_{repl}. It is also important to gather data on the annual increases in electricity r_{elec}, maintenance r_{man} and discount rate d_r. Other data may include the rated lifetime of both the new and old lights, L.

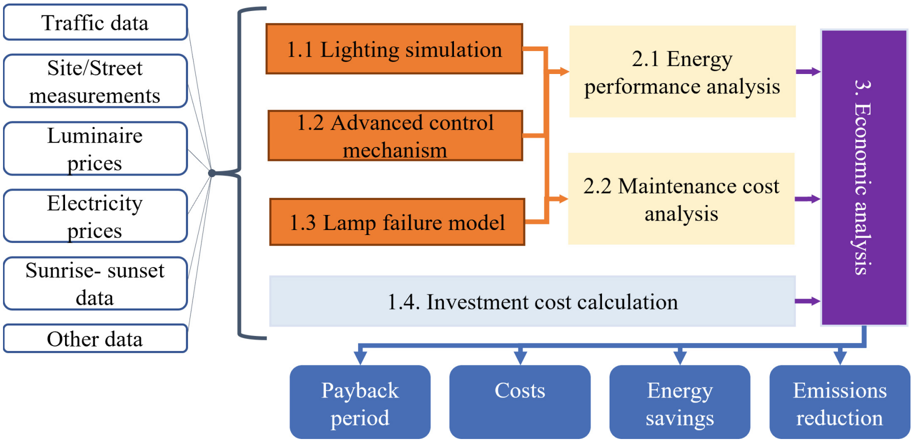

Fig. 1. Techno-economic analysis methodology

The street light measurement will be used to determine current total power usage of the lights P_{curr}. Step 1.1 identifies the most suitable replacement LED technology with its power rating P_{new}. The advanced control mechanism considered in step 1.2 will incorporate the currently installed photo-sensors and future traffic sensor data to dictate the dimming levels of new LED lights. Step 1.3 will determine the number of operating lights at each time period. In step 1.4, the investment cost is obtained by multiplying the installation and purchase price of luminaire units by their numbers given in (1).

$$C_{inv} = (\pi_{inst} + \pi_{pur})\, N_{tot} \tag{1}$$

Thus, steps 1.1, 1.2 and 1.3 gives inputs to the energy performance analysis. The analysis can calculate the current monthly energy usage EB_i for month i, based on the number of days in that month D_i and the average operating hours, $\bar{h}_i$, calculated from sun-rise/set data. The advanced control signal $U_{control}$ is then used to compute the new monthly energy usage ER_i. The energy analysis calculation formulae are given in (3).

$$EB_i = P_{curr} \cdot D_i \cdot \bar{h}_i \text{ and } ER_i = P_{new}(U_{control}) \cdot D_i \cdot \bar{h}_i \tag{2}$$

$$ES_j = \sum_{i}^{12} EB_i - ER_i \tag{3}$$

The maintenance cost will depend on the number of lights that need to be maintained in a given period. The model adopted from [15] is used to calculate the number of failed lights, $N(t)$, according to (4).

$$N(t) = N_{tot}\,(1 - \Phi(t)),\ where\ \Phi(t) = [c + exp(bt - L)]^{-1} \tag{4}$$

The lamp decay model, $\Phi(t)$, depends on modeling parameters c and b as wells as the rated lifetime L. According to [5], $L = 16000$ for HPS bulbs and 50000 for LED luminaires. The model $\Phi(t)$ gives a percentage of surviving lights after a time period t, thus by definition $\Phi(0) = 1$. Moreover by design, the model is calibrated so that half of the lamps have burnedout when $t = L$, thus $\Phi(L) = 0.5$. Therefore, knowing the value of L, this two facts can be used to easily determine parameters c and b by model fitting. It is worth noting that after replacement, the newly installed lights will decay at a different rate than the older already installed lights. Thus, multiple instances of the model, $\Phi(t)$, are required to keep track of the individual groups of lights with different ages.

The annual maintenance cost will depend on the number of lights needing replacement and the technology price π_{pur} as shown in 5.

$$C_{main}(t) = N(t)\,(\pi_{inst} + \pi_{pur}) \tag{5}$$

On the final step 3, in Fig. 1, the economic analysis is conducted to produces indices that can be used by decision makers within cities to determine the viability of projects. For smart lighting projects, the most common indices include pay-back period, net present value, energy savings, and annual CO_2 emission reductions [5,12,13]. In this case, we adopt a cost of ownership model of discounted costs over a period of M years as shown in (6).

$$\begin{aligned} CoM(M) = C_{inv} + \textstyle\sum_{j=1}^{M} \Big[& -ES_j \cdot \pi_{elec} \cdot \tfrac{(1+r_{elec})^j}{(1+d_r)^j} \\ & +(C_{main}^{old}(j) - C_{main}^{new}(j)) \cdot \tfrac{(1+r_{man})^j}{(1+d_r)^j} \Big] \end{aligned} \tag{6}$$

This analysis takes into account the energy and maintenance costs/savings made by retrofitting new luminaires on existing infrastructure. CoM also depends on discount rate d_r and annual increases in electricity price r_{elec} and maintenance costs r_{man}. The value of the annual savings, ES_j, is multiplied by price, π_{elec}, to get the energy cost savings. The value $(C_{main}^{old}(j) - C_{main}^{new}(j))$ is a calculation of cost savings on maintenance. The retrofit project is considered to have repaid its-self the moment, M, the CoM value becomes negative. This moment where the cost of ownership becomes negative is the payback point. The emission reductions can be calculated by multiplying the energy savings by an emission factor.

3 Results and Discussion

The application of the methodology proposed in Sect. 2 is implemented on a 4.2 km case-study road in Vanderbijlpark, South Africa. The road under consideration is show in Fig. 2. The analysis presented in this case-study shall consider three different scenarios, namely HPS, EE lights and smart lights. The HPS scenario maintains the status quo of installed HPS lights, the EE lights scenario simply retrofits HPS lamps with LED luminaires and the smart lights scenario adds the traffic-adaptive control and dimming controls to LED luminaires retrofits.

The road in Fig. 2 has a twin pole arrangement with poles located in the middle of two lanes. The site measurement of 11 m high poles, overreach of 2.5 m and carriageway width of 7 m are used to model the street in DIAlux simulation software as per step 1.1. The daylight duration data is gathered from [16].

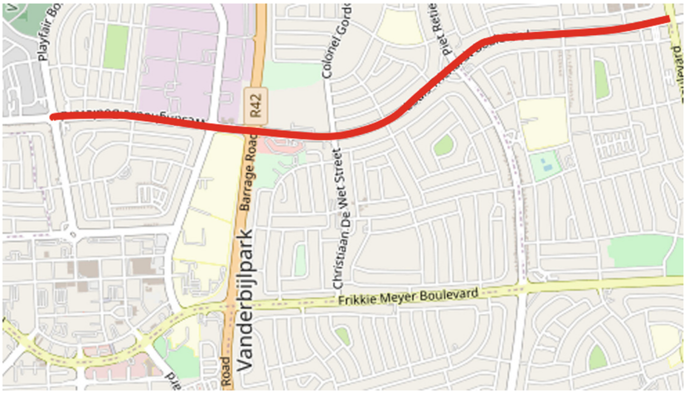

Fig. 2. Case-study road in South Africa

Analysis shows that this is a class A3 road according to the standard [17]. The simulation results indicate that the currently installed 250 W HPS lights can be replaced with 180 W EE LED luminaires.

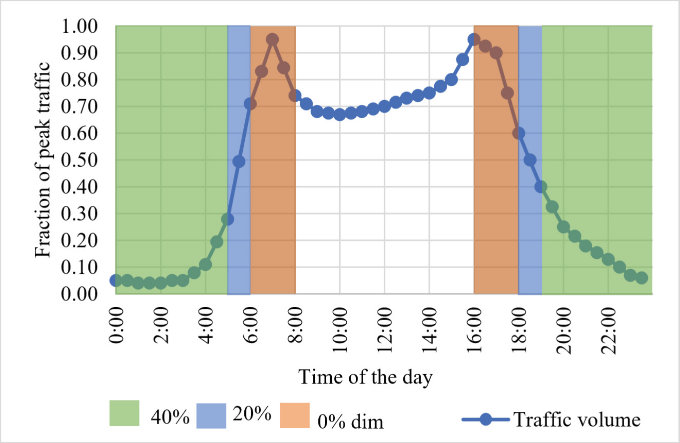

Fig. 3. Traffic based dimming schedule

The traffic data of the nearest city, Johannesburg, is used to analyse the likely traffic patterns on the road [18]. This analysis shows that the peak times for traffic are 7 am and 4 pm, during the weekdays. However, the traffic volumes are below 70% of the peak before 6 am in morning and after 6 pm in the evening, as illustrated in Fig. 3. Figure 3 also shows that there is very little traffic between the hours of 730 pm and 5 am the following morning (below 30%). These observations read together with SANS 10098 inspire the dimming schedule shown in Fig. 3, for evaluating the application of smart lights. Thus, the smart lights can operate at 60% of flux (or 40% dimming) from 730 pm to 5 am in the morning, at 100%

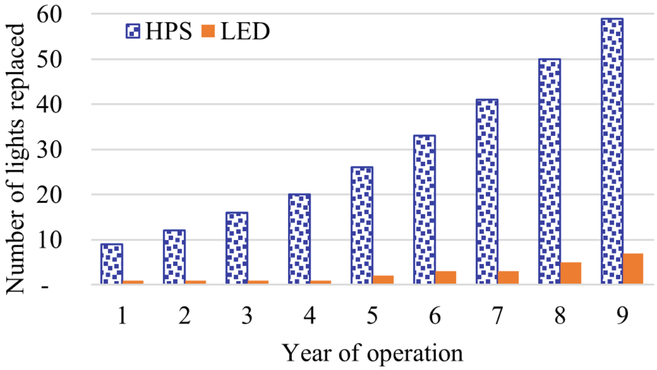

Fig. 4. Number of failed lamps/luminaires per annum

of flux from 6am to sunrise and from dusk to 6 pm. The rest of the time the lights will at 80% of flux, as shown in Fig. 3.

Figure 4 shows the number of lights requiring replacement. Based on the lifetime values, L, and an average annual hourly operating rate of 11.9 h, a typical HPS lamp will last for 3.7 years while an LED luminaire will last for 11.5 years. Given this information, the subsequent analysis is applied for a total of 9 years. The results of step 1.3 shown in Fig. 4 illustrate that there is minimal replacement required for LED luminaires, with only one replacement for each of the first 4 years. On the other hand as many as 9 HPS lights need replacing during the first year and this number rises to 40 in the year 7. It is apparent from the trend shown in Fig. 4 that the number of lights needing replacement increases with the age of the lamps. Thus, the maintenance cost calculated using (5), gives a more accurate estimation of the cost as opposed to using an average value throughout all the years of investment. Using an average annual value of maintenance cost will therefore over estimate of cost in the earlier years, and under estimate in later year. This analysis is a result of step 2.2.

Based on the local market prices of LED technologies from quotations and online stores, the investment cost of 104 LED lights is calculated in step 1.4 to be ZAR 382,720.00 for EE lighting (≈ 21,409 USD). The investment cost price of smart lighting will include an added cost of cheap sensing infrastructure and dimming controllers [5]. An additional 10% is added to the investment cost to make a total of ZAR 459,264.00 (≈ 25,691 USD). The unit purchase price and installation cost values used are $\pi_{pur} = 3,200$ and $\pi_{inst} = 480$, respectively.

The results of step 2.1 are shown in Fig. 5. Applying (3) results in a total annual energy usage of 131 MWh for the HPS, 81.6 MWh for EE lights and 78.6 MWh for smart lights. The results in Fig. 5 show that the energy usage of street lights is highest during winter months of May, June and July when

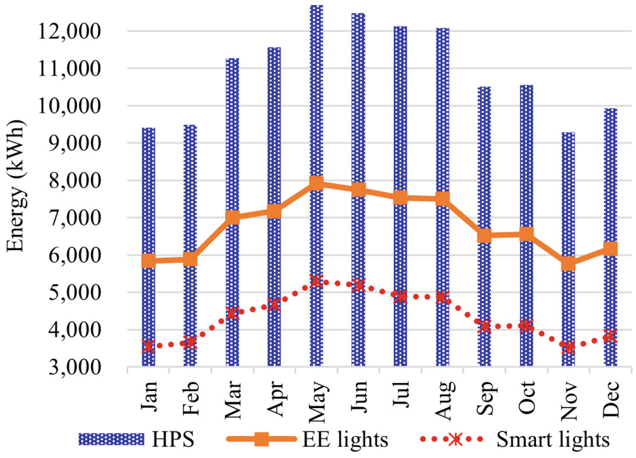

Fig. 5. Simulated monthly energy usage

daytime is shorter in the Southern hemisphere, as expected. It can also be seen from Fig. 5 that, while EE lights seem to save almost half of the HPS energy consumption, the smart lights perform even better.

Economic analysis in step 3 applies (6) for a total of $M = 9$ years. The results of the cumulative sum of the discounted cash-flows is shown in Fig. 6. Linearly extrapolating the results in Fig. 6 shows that EE lights have a payback period of 4.26 years, while smart lights have a payback period of 3.42 years. These figures are relatively high but comparable to the values obtained in other studies from US, Serbia and Turkey [4–6, 12]. The payback period also depends on electricity pricing. The assessment currently considers only the energy rate of a single tariff offered by Eskom, a public utility supplying the majority of municipalities in South Africa [19].

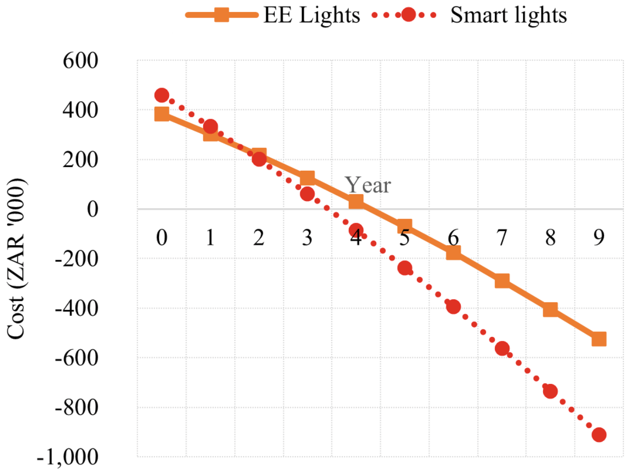

Fig. 6. Cost of ownership - cumulative sum of discounted cash flows

Figure 7 shows the cost components and savings of the different scenarios relative to the total cost of the HPS scenario. The maintenance cost accounts for a small, 10%, portion of the overall cost in the HPS scenario. However, comparing the HPS and the two retrofit scenarios shows that the LED retrofit does provide maintenance cost savings. The 5% increase in investment cost when moving from EE lights to smart lights is shown to result in a significant increase in savings, by more than 10%. Using a simple annual average value, without the model in (4), results in the under estimation of maintenance cost by a factor 4 in the first year and 25 by the 9th year, for the HPS scenario. This underestimates the annual savings on maintenance cost leading to a 6 months delay in payback period calculations for EE lights. This deviation is likely to be significant when the cost of maintenance is modeled more accurately so that it becomes significant in the overall operating cost of streetlights. The currently proposed cost model does

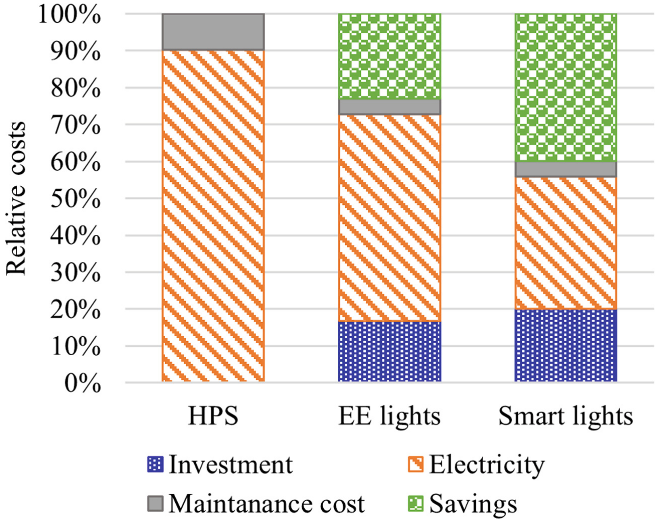

Fig. 7. Relative costs with respect to total cost of the base case over a period of 9 years

not for instance take into account the labour costs associated with performing maintenance rounds and fuel used by the municipality personnel to drive around. These costs are nullified by the use of smart sensors when smart lights are deployed [7]. Thus, even greater savings on maintenance cost are expected.

4 Conclusion

This paper presented an application case-study for a new methodology of performing techno-economic analysis of street lighting retrofit projects that involve energy-efficient lights and smart lights using traffic-adaptive control. The proposed methodology is generic and can be applied to cities in any country in the world using appropriate case-study data. The case-study area applied currently has HPS lamps that are switched by photo sensors. The methodology presented aims to offer an accurate assessment using lighting simulations, considering seasonal variations of light operating hours, a lamp failure model to inform maintenance cost calculations and discounted cash flows. The application of the proposed model resulted in a payback periods of 3.42 and 4.26 years, for smart lights and EE lights retrofits, respectively. The current modeling of maintenance cost is shown to improve the economic evaluation. Future work in this area needs to consider a more thorough modeling of maintenance costs, evaluations of streets where timing control is used, the impact of dimming level on pedestrian safety and detailed analysis of the electricity pricing tariffs.

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