LED there be light: The impact of a lighting efficiency campaign at poor schools in South Africa

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Abstract

South Africa's private sector - under significant pressure to become energy efficient and employ sustainability principles - has long been implementing energy saving mechanisms. Unfortunately, there seems to exist many misplaced incentives in South Africa's public sector that prevent it from embracing energy-efficient technology. With the falling cost of LED lighting and the rising cost of electricity, however, conversions are increasingly cost efficient. Effecting these changes are increasingly urgent given the national utility-imposed rolling blackouts and climate change concerns. The primary education sector is a particularly attractive test case, since money saved on utilities can be allocated to desperately needed value-adding services in schools. From a technical perspective, however, the cost-benefit of replacements and the range of options facing decision makers could be overwhelming. To assess the impact of replacing fluorescent lights with LED lights at schools in South Africa, we propose a model that draws on smart metering data, a bench-test assessment of available LED lights and tariff rates. The model was validated with field tests at three schools and used to assess the impact at seven local schools. The results show that the setup cost differs substantially from the life-cycle cost, and that buying the cheapest lights could prove to be the costliest decision over the light's life cycle. The results also show that lights contribute from 42% to 57% of electricity expenditure, and that monetary savings of 21% to 39% are achievable by replacing fluorescent tubes with the most efficient LED lighting option available.

Keywords: School electricity; School lights; Energy usage; Smart meter; School energy profiles; LED lights; Efficiency improvement; Energy saving

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1. Introduction

South Africa's 23,471 public schools use an estimated 2.2 GWh energy per year: this results in an annual electricity expense of about ZAR 2.9 billion (ca. US$ 179 million). With the country's electricity utility in dire straits, tariff hikes are inevitable and inflation-beating. From 2008 to 2018 the increase in cost was 446% [1].

Moreover, every cent spent on the inefficient use of energy potentially diverts funds away from desperately needed educational resources (its primary purpose), infrastructure investment, and much needed maintenance [2–5]. Given the mammoth challenges faced in basic education itself, however, insufficient attention is given to these

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energy inefficiencies.

1.1. Electricity usage at schools

The South African government's Regulations Relating to Minimum Uniform Norms and Standards for Public School Infrastructure require that all schools must have access to electricity, water, sanitation, electronic connectivity and perimeter security by November 2020 [6]. Between 1994 and 2010 substantial progress in the area of electrification has been made through the Integrated National Electrification Plan (INEP) in terms of universal access to electricity [7]. More than 12,000 schools were grid connected and 3,000 schools were electrified with non-grid technology: only 239 remain without electricity.

Theoretically this should make a range of benefits available to learners, such as: (1) lighting and extended study hours, (2) use of the internet, computers and televisions in classrooms, (3) enhanced staff retention, (4) better school performance and (5) co-benefits to sanitation, health and communities [4].

Despite this high electrification rate, schools' access to the potential benefits of the services is distributed unequally [4, 8]. There remains a daunting backlog in terms of basic infrastructure in schools. In 2018, around 1,000 schools still had no sports facilities; 4,358 still only had illegal plain pit latrines; and 1,027 remained without perimeter fencing. Even more concerning is the manifestation of an apparent digital divide: nearly 17,000 schools do not have access to the internet, and 20,070 schools do not have laboratories and computer laboratories.

Rather than spending their way out of this desperate situation, educational investment per pupil actually decreased by 8% over the 2010 to 2017 period [9]. Security of electricity supply has also been negatively affected by the struggling state utility, Eskom – where rolling blackouts are often applied to prevent a national shutdown [10].

Internationally, a large contributor to energy usage at schools is lightning [11]. Fortunately, recent advances in lighting technology has increased the efficiency of lights - from a typical 90 lm/W for the ubiquitous fluorescent lights to a typical 100 lm/W for LED lights – an 11% improvement. It is imperative to explore the lighting landscape at schools especially since South African schools almost exclusively still use fluorescent lights and could thus benefit from such savings.

1.2. Lighting in schools

Studies on lighting at schools span various areas including energy savings, indoor environmental quality and student productivity. In this section we present some of these studies on the use, impact and benefits of lighting in schools.

Salvia et al. [12] explored the importance and function of public lighting on the municipal level which we have extended to schools. Many accounts exist of older, inefficient lighting technology used in schools, which contributes to a large portion of electricity bills. Examples of this can be seen in Spain, by Gamarra et al. [13] and Lizana et al. [14], where schools lighting usage is estimated 21 - 25%, and in South Africa [15] where a study of a single school found that lighting accounted for 46% of energy usage.

To date, most studies have emphasised technical questions rather than sustainable management. Sustainability in public lighting includes optimal lighting solutions considering functions of the system, reducing operation expenses and minimising electricity usage [12]. They further state that monetary savings through energy reductions could be up to 50%, however this includes all municipal lighting.

Indoor environmental quality affects the health and comfort of occupants [16]. Bluyssen [17] explored light quality as one of four indoor environmental factors with parameters and controls for each factor. Light quality parameters include luminance and illuminance, reflectance, colour temperature and colour index, view and daylight, and frequencies. The controls for lighting quality include luminance distribution, integration of artificial and natural lighting, and daylighting entrance. The indoor environmental lighting quality parameters of importance to this article are luminance and illuminance.

The role of lighting, as a part of indoor climate parameters, extends to productivity. Hviid et al. [18] monitored 92 children over four weeks through questionnaires and three performance tests that focused on lighting conditions and ventilation rates. Their experiment included a warm colour temperature light with a lower light level (2900K at 450 lux) and dynamic cool colour temperature light with a higher light level (4900K at 750 lux), where the dynamic light mimics outdoor lighting conditions. Both of these lighting conditions were combined with tests at a low and high ventilation rate. They found most improvement in performance under the combined scenario with the dynamic cool colour temperature light with high ventilation. These improvements were in student processing speed (6.6%), concentration (8.3%) and maths skills (11.8%). The effect of lighting alone had a smaller improvement in the performance tests. Alazraki and Haselip [19] found that un-electrified Argentinian schools could not start early in the morning due to low light levels. A similar study in Kenya showed that a solar-powered electrification project enabled after hours teaching [4, 20]. This benefit also extended to improved security and protection of school property.

1.3. Lighting interventions in schools

In this section we aim to systematically map and explore the state of the literature on lighting and energy savings in the education sector. Although our review is specific to schools and the studies that discuss light interventions in schools, a recent review of general buildings can be found in [44].

We have explored 27 studies on various levels of the education system: namely, elementary, primary, middle, secondary and tertiary educational buildings (i.e. universities). However, most of them were secondary schools. In our sample we have also included a general building review for lighting interventions as this discusses the lighting of a school.

Table 1 contains a summary of lighting studies and shows a literature review map of lighting in educational buildings. In those cases where information was omitted in the articles it is indicated in our table as N/A and, where not mentioned, it is indicated as N/M. These articles were gathered from searches in journals using keywords (and combinations) such as ”Energy consumption”, ”School building”, ”Lighting retrofit” and ”Energy efficiency”.

The studies were analysed against three categories of interventions used by the schools: 1) day-lighting (“Day.” column); 2) lighting replacement (“Retro.” column); and 3) light controls and automation (“Auto.” column). The light interventions listed in the table have the following definitions. Day-lighting is the utilisation of natural light in classrooms. Light replacements are the substitution of current lighting types with better technology. Light control and automation use electronics to control the amount of artificial light in classroom. For the majority of studies (17 out of 28), the lighting intervention referred to a light retrofit or replacement intervention. A few studies also combined interventions, making combinations with day-lighting and automation, or combinations that included all

Table 1: Literature review map of lighting in educational buildings

					Lighting interventions				
Geography	Schls	Core focus	Scholar level	Initial	Day.	Retro.	Auto.	ΔE(%)	Ref.
EU	4	EE interventions in schools	Secondary	FL	No	Yes	No	0.5-7	[21]
Belgium	1	Daylighting in classrooms	Secondary	FL	Yes	No	Yes	18-46	[22]
Canada	3	Real-time electricity analysis	N/M	N/A	N/A	N/A	N/A	N/A	[23]
Greece	10	Simulation of EEMs	Secondary	FL, IN	No	Yes	No	8-40	[24]
Greece	24	Building interventions	Elementary	N/M	Yes	No	No	1.5-2.7	[25]
Switzerland	1	Building automation analysis	N/M	N/M	No	No	Yes	N/A	[26]
USA	289	EEM and student learning	Elementary,Middle	N/M	Yes	Yes	Yes	N/M	[27]
USA	1	School evaluation	Elementary	FL	No	No	No	N/A	[28]
Serbia	9	Savings with LEDs	Secondary	FL	No	Yes	No	53-60	[29]
Italy	1	School retrofit with lighting	Primary	FL	No	Yes	No	35	[30]
Canada	1	School model and energy audit	Secondary	FL	No	Yes	No	N/M	[31]
Spain	1	Retrofit project	N/M	FL	No	Yes	No	11	[32]
Italy	2	Procurement and school efficiency	Primary,Middle	FL	No	Yes	No	N/M	[33]
Italy	2	Cost-optimal analysis of retrofits	N/M	FL	No	Yes	Yes	N/M	[34]
Italy	1	Methods approach for EEMs	Tertiary	FL	No	Yes	Yes	10-13	[35]
Vienna	1	School retrofit method	N/M	N/M	Yes	No	No	N/M	[36]
South Africa	1	Modelling of school lighting	Primary	FL	No	Yes	No	46	[15]
Spain	2	Light improvement in schools	Secondary	FL	No	Yes	No	10-12	[13]
Portugal	4	Lighting use in schools	Secondary	N/M	No	Yes	Yes	28-40	[37]
Portugal	1	IoT and EEM kindergarten	Kindergarten	N/M	No	No	Yes	N/M	[38]
Jordan	1	Illuminance in school buildings	Tertiary	N/M	Yes	No	Yes	N/M	[39]
EU	11	EEM in tertiary buildings	Tertiary	FL	Yes	Yes	Yes	4-16	[40]
Taiwan	231	Review on school electricity	Elementary,Secondary	CFL	No	Yes	No	40	[41]
Greece	1	Retrofit lighting with control	General	FL	Yes	Yes	Yes	18-22	[11]
UK	1	Assess building performance	Secondary	FL	Yes	No	Yes	N/M	[42]
Turkey	1	Lighting system on campus	Tertiary	Fl,CFL,LED,MH	No	Yes	Yes	31-60	[43]
Turkey	3	School retrofits	Primary	IN	Yes	Yes	Yes	60	[44]
General	1	Building lighting review	General	N/M	Yes	No	No	24	[45]

Day.: Daylighting, Retro.: Retrofitting, Auto.: Automation, ΔE: Percentage reduction in energy.
Initial: FL - Fluorescent, IN - Incandescent, MH - Metal Halide, LED, Light-emitting diode, CFL - Compact fluorescent light, N/M -not mentioned in the paper.

the interventions.

Although the schools were from different regions, they mostly had fluorescent lights installed (17 out of 20 studies). All the light replacements at schools were done with LED lights except for one study from Turkey, [43], where LED lights were too expensive and fluorescent lights were used instead to the replace incandescent lights.

The bulk of the studies reported a percentage energy saved from their light interventions. For the light retrofit intervention the energy saved ranged from 8% to 60%. The day-lighting interventions resulted in 2% to 40% of energy saved and for the automation intervention the energy savings ranged from 18% to 60%.

Various energy-saving methods were used in the literature shown in Table 2. We identify these methods as the following categories: combined intervention; scenario comparisons; system comparisons; simulations; surveys and audits; energy evaluation tools; intervention evaluation; and modelling.

Out of the sixteen studies included in the light intervention literature in school buildings, the majority (8 out of 16) of the methods used involved scenario comparisons. This entailed combinations of multiple interventions done at schools and comparisons of them for the optimal option. Four of the studies investigated a combined-intervention approach, where multiple interventions were done in the same project. Four of the studies also included simulation, modelling or energy performance tools in order to evaluate retrofits. These methods were mostly in addition to other methods. Two studies evaluated systems, where an implementation of a different systems were done for the same intervention. Only one study presented an individual intervention evaluation, where only one interventions is

Table 2: Literature review map of methods used for lighting intervention studies

Geography	Method description	Method category	Ref.
EU	Erhorn-Kluttig et al. [21] improved the energy performance of school building with multiple retrofits to school buildings. They report the measured lighting energy differences with no model included.	Combined intervention	[21]
Belgium	Delvaeye et al. [22] compared the energy savings of daylight control systems through monitoring.	System comparison	[22]
Greece	Katsaprakakis and Zidianakis [24] investigated low energy lighting installation among multiple school building upgrades. Light replacements are simulated with shorter LED lights.	Combined intervention	[24]
Greece	Tsikra and Andreou [25] investigated energy saving and comfort interventions in schools with light shading systems and building envelope changes. Their evaluation was done through simulation.	Combined intervention and simulation	[25]
Serbia	Josijević et al. [29] presented a method of estimating savings with LED retrofits. They analysed the lighting share of total electricity consumption and the savings due to LED replacements. Their method excluded modelling.	Intervention evaluation	[29]
Italy	Ferrari and Romeo [30] simulated the retrofits and their cost-effectiveness in schools. Multiple scenarios were compared.	Scenario comparison	[30]
Spain	Berardi et al. [32] simulated a retrofit school project with multiple measures. The lighting retrofit was evaluated in terms of energy and cost.	Combined intervention	[32]
Italy	Bonomolo et al. [34] analysed lighting retrofit scenarios in schools. Different scenarios (partial installation and control systems) are considered for the cost-optimal option. The lighting replacements used a constant profile.	Scenario comparison	[34]
Italy	Bellia et al. [35] presented a methods approach for implementation of the cost-optimal EEMs. They modelled the retrofit changes compared to a reference building. A specific lighting model was excluded.	Scenerio comparison, modelling	[35]
South Africa	Gibberd [15] evaluated retrofit potential for schools using energy audits and an energy performance tool. Lighting share of electricity was modelled using a constant lighting profile.	Energy performance tool	[15]
Spain	Gamarra et al. [13] analysed EEMs in schools. They showed the impact of lighting replacements and other measures. A constant lighting profile was considered.	Scenario comparison	[13]
Portugal	Lourenço et al. [37] investigated light-use management in schools with simulated models considering seasonality. Their results showed reductions through lighting interventions. Light energy models were excluded.	Scenario comparison and simulation	[37]
EU	Patiño-Cambeiro et al. [40] economically evaluated multiple EEMs in schools. They present the simplistic lighting intervention only showing energy and cost reduction using a constant lighting profile.	Scenario comparison	[40]
Greece	Doulos et al. [11] optimised lighting consumption in classrooms. They evaluated lighting control systems with different photosensors.	System comparison	[11]
Turkey	Gorgulu and Kocabey [43] analysed outdoor campus lighting energy saving using retrofit scenarios. A constant lighting profile was used excluding the control light system EEM.	Scenario comparison	[43]
Turkey	Moazzen et al. [44] defined a multi-parameter approach to understand the (cost, energy and environmetal) benefits of EEMs. They considered implementing partial replacements, full replacements and/or lighting control systems. Simulation of a constant lighting profile was used excluding the control system.	Scenario comparison	[44]

evaluated for the project.

None of these studies present a meaningful way to understand and model the lighting interventions in terms of impact on electricity usage and cost thereof. Where light replacements were considered, a constant-usage profile was used instead of a scaling-usage light profile as presented in this study.

It is also clear from Tables 1 and 2 that most of the related studies were done in developed countries, with Turkey, Jordan and Russia (Siberia) the only developing countries represented. Moreover, only a single study with a single affluent school has originated from the continent of Africa.

1.4. Contribution

To contribute towards solving the problems faced by South African education facilities – such as lack of basic infrastructure, large electricity bills and large energy consumption - we explored replacing lights with efficient LED lights in schools and the savings (monetary savings, peak demand reductions, and energy savings) that are possible through such interventions.

We introduce a validated model to assess the impact of LED light replacements - the most prevalent light intervention from the literature - at schools. To parameterise the model, we performed bench tests to characterise

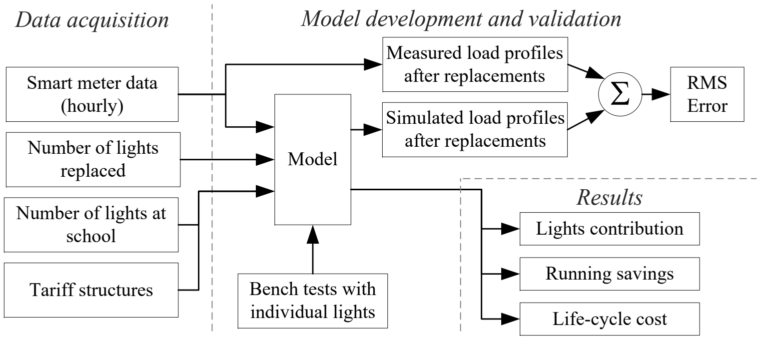


Figure 1: Three phases of work presented in this paper.

the LED lights that are commonly used for replacements. We used this model to estimate the contribution of lighting to schools' electricity expenses; to assess the impact of LED replacements at seven schools; and to perform life cycle cost assessments of the tested LED lights.

We present a holistic approach to lighting impact at South African schools consisting of three phases: data acquisition; modelling; and implementation of the lighting interventions. The following sections discuss the method used; the lighting impact model; the lighting bench tests; and the results of our study.

2. Method

We took a phased approach to assess the impact of our light replacement campaign at the schools. In the first phase, we characterised each school's electricity load profile with smart meter data. From these profiles, we evaluated their electricity cost from the applicable electricity tariff structures. In the second phase, we developed and validated a model to estimate contribution of lighting to the hourly load profile during a school day. To this end, we performed bench tests of individual lights, replaced the majority of lights at three schools, and measured the change. During the third and final phase, we used the validated model and smart meter data from seven schools to establish the contribution of lights to the eventual bill; determine the life-cycle costs of the tested LED replacement lights; and calculate the running savings (financial, peak demand, energy, and CO2) achieved by LED replacements.

2.1. Data acquisition

The study takes place in and around Stellenbosch, in the Western Cape province of South Africa. It forms part of a larger project, in which the electrical profiles of sixteen schools were analysed with smart meters [46]. Schools in South Africa are categorised into five groups - called "quintiles" - based on the income levels of the surroundings areas. The schools in our study are of different affluence levels (increasing affluence from Quintile 1 - 5) and include both primary and secondary schools. In this paper we report on the measured impact of actual light replacements at three of these schools, and on the simulated impact of light replacements at these and another four schools for which we had sufficient information.

We used two types of smart meters to analyse, to a high time resolution, the electricity usage of the schools: municipal billing electricity smart meters with a 30 minute resolution and, where these were not installed, we used a

Table 3: Basic tariff structures (2019/2020 tariffs) according to which the schools are billed.

Tariff structure	Component	Symbol	Summer	Winter	Unit
Commercial (COM4)	Energy	r_{COM}	1.99	1.99	ZAR/kWh
Industrial (IND1)	Energy	$r_{\mathrm{IND,E}}$	0.98	0.98	ZAR/kWh
	Peak demand charge	$r_{\mathrm{IND,d}}$	248.43	248.43	ZAR/kVA
Time of use (ToU)	Peak energy	$r_{\mathrm{ToU,pk}}$	1.55	4.87	ZAR/kWh
	Standard energy	$r_{\mathrm{ToU,std}}$	1.02	1.46	ZAR/kWh
	Off-peak energy	$r_{\mathrm{ToU,off}}$	0.77	0.86	ZAR/kWh
	Peak demand charge	$r_{\mathrm{ToU,d}}$	47.49	47.49	ZAR/kVA

third-party retrofit clamp-on smart energy meter with a 10 minute resolution [47]. Demand profiles were generated from these meters.

We used the tariff structures in two ways: first, to determine what proportion of the school's electricity cost is attributable to lighting, and then in the results section to assess the financial impact of replacing the lights with LED lights.

Each school in our study is billed according to one of three tariff structures shown in Table 3. There are two main variable components that are charged by the municipality. The first is the energy rate: this is used to charge school users for every kWh unit (i.e. magnitude of energy) used. This energy rate varies based on the tariff structure. For the commercial and the industrial tariffs, this energy rate remains constant regardless of the time of the day. For the Time-of-use (ToU) tariff, however, the energy rates charged at schools differ based on the time of day. The second component is the demand charge. This component is charged for each kVA unit (i.e. the magnitude of apparent power) used by a school.

For each school in our study we obtained the monthly utility bills and a monthly summary of bills over the last year from the local municipality (council), which acts as the electricity retailer.

3. Bench tests: Individual lights

Eight often-used and readily available LED light replacements were tested under the same conditions to determine their power and illuminance characteristics. These lights and summary of the results are shown in Table 4.

We used bench tests to measure the actual performance of the individual lights to determine the power draws of the fluorescent lights, $\boldsymbol{S}_{\mathrm{fl}}$, and the replacement LED lights, $\boldsymbol{S}_{\mathrm{LED}}$. The bench test consisted of measuring active power and power factor with a digital power meter, a Yokogawa 2533.

Table 4: Comparison of lights power characteristics

	OrbitX 19W	Philips CorePro 20W	ClearSky 22W	ClearSky 32W	Philips EcoFit 22W	LighTec 22W	Philips Master VLE 21W	Osram Substitute 22W
Cost [ZAR]	180	170	145	170	80	148	180	120
Active power [W]	18.8	20.5	23.5	27.5	22. 0	21.9	20.8	21.9
Power factor	0.96	0.96	0.89	0.71	0.61	0.55	0.95	0.95
Apparent power [VA]	20	21	26	39	36	40	22	23
Max lux [lx]	813	560	809	900	569	670	770	736
% of statutory EOL brightness	106%	73%	105%	117%	74%	89%	100%	96%
Demand reduction [VA]	42	40	35	22	25	22	39	38
Energy savings [W]	41	40	37	33	38	38	39	38

The power draw of each light was measured with the same power meter for all lights to confirm the specifications quoted by the light manufacturers. As shown in Table 4, the OrbitX light's power draw was lower than specified and the other lights measured above or equal to their specified power draws. The power factor was also measured for all the lights with the same meter since the ToU tariff structure includes reactive/apparent power: a lower power factor indicates an increased reactive power usage of the light. The fluorescent tubes have high power factors - almost 0.98. This needed to be matched otherwise the schools billed with ToU tariffs could receive a replacement that may increase the bills. The OrbitX and the Philips CorePro lights measured the same power factor of 0.96. The Philips Master VLE and Osram substitute measured a power factor of 0.95. The rest of the lights measured lower power factors ranging from 0.55 - 0.89. Such lower power factors result in higher apparent power, measured in VA, and this is also included in their bill under demand charge. From these measurements the demand reductions and energy savings were calculated for each light. The lights with lower power factors had higher apparent powers and therefore lower demand reductions. The energy savings of each light was calculated by subtracting the power used by the lights for the school hour from the fluorescent lights for the same amount of time. The OrbitX and Philips CorePro lights had the highest savings: 41 W and 40 W respectively. Although these tests show the key parameters, the savings and life cycle cost projections will show which lights perform best in the long term.

Finally, illuminance was measured for all lights under the same experimental setup. The maximum lux of each light was measured with a light meter. It was repeated in the same room for the eight LED lights at the same height. Their light output was then compared to the minimum statutory illuminance required. A simulation in Dialux was used to iteratively determine the minimum illuminance required at the beginning of life to achieve the minimum statutory illuminance of 200 lux at the end of life at the far side of a typical classroom. This gave 767 lux at the beginning of life. The classroom room illuminance requirement is 300 lux (SANS standard 10114-1). The percentage measured illuminance compared with the required beginning of life illuminance was then calculated. These conditions were one dark room with a measured ambient illuminance of 0.1 Lux, and the lights measured individually at a height of 0.78m. The light meter was placed at 0.78 meters below the middle of the tested light. The OrbitX and both ClearSky lights measured a light level that is higher than the required level, but the others were all below 100% of the statutory brightness.

4. Model

4.1. Model development

In this section we develop the model used to calculate the impact of replacing the fluorescent lights at schools with energy-efficient LED lights. The approach is demonstrated in Figure 2 and described below. The main unknowns are the difference in power draw between the lights, the number of replaced lights, and the times at which the lights are turned on during the typical school day.

An adjusted lighting utilisation profile is needed since the load profile for each school differs in time and amplitude (see Figure 3). We estimate this profile from the whole school's average weekday load profile before the light replacements. Accordingly, we estimate the times at which there are substantial changes in the number of lights that are switched on, and subsequently, the number of lights turned on for each hour of the day. To achieve this, a proportional load function, $\boldsymbol{p}(t)$, is used to represent the light utilisation. This function is partially fitted to the specific school's total load profile with 0% of the replaced lights assumed to be on when the school is at or near to its base-load at night, and 100% of the replaced lights are turned on when the school's load is near maximum in the middle of the school day. Four infliction points are then identified from the school's average load profile: $t_{\mathrm{am},0\%}$, $t_{\mathrm{am},100\%}$, $t_{\mathrm{pm},100\%}$ and $t_{\mathrm{pm},0\%}$.

These infliction points are assumed to occur at the same times on the projected light usage profile and transferred to the proportional load function, as shown Figure 2b. The proportions in the transitions between the 0% and 100% levels are calculated using proportional interpolation with the school's total load profile as base. This resulting load profile of only the LED lights (see Figure 2c) is produced by scaling the proportional load function by the expected load of all the replaced lights, and is given by

$$\boldsymbol{s}_{\mathrm{school,LED}}(t) = n\boldsymbol{p}(t)\boldsymbol{S}_{\mathrm{LED}} \tag{1}$$

where $\boldsymbol{s}_{\mathrm{LED}}$ is the load of one LED light and n is the number of lights that were replaced. The load reduction due to the replacements is also proportional to the light usage profile. The school's projected energy usage after the light replacement is given by

$$\boldsymbol{s}(t)_{\mathrm{school,proj}} = \boldsymbol{s}(t)_{\mathrm{school,before}} - n\boldsymbol{p}(t)[\boldsymbol{S}_{\mathrm{fl}} - \boldsymbol{S}_{\mathrm{LED}}] \tag{2}$$

where $\boldsymbol{s}(t)_{\mathrm{school,before}}$ is the average measured load profile of the school during a school day before the light replacement; $\boldsymbol{p}(t)$ is the proportional light load factor shown in Figure 2b; and $[\boldsymbol{S}_{\mathrm{fl}} - \boldsymbol{S}_{\mathrm{LED}}]$ is the complex difference in power usage between a single fluorescent and LED light. The resulting projected load profile for the whole school with the replaced lights is shown in Figure 2d.

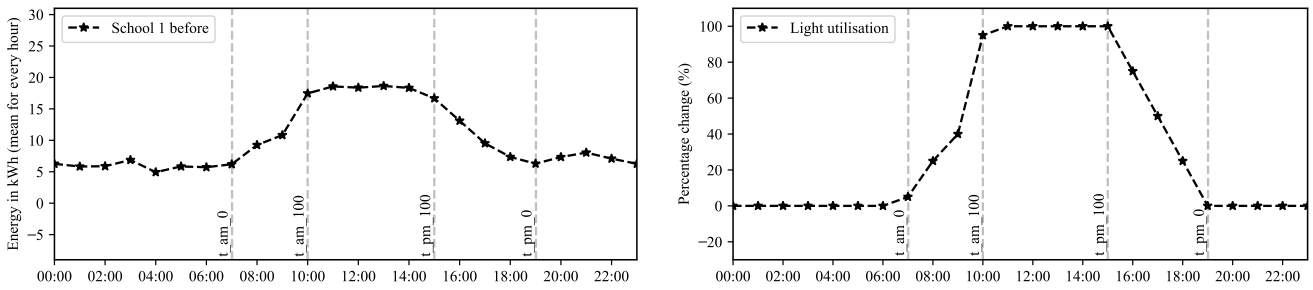
Since $\boldsymbol{s}$ is complex, the power draw is affected by the difference in apparent power and real power. The apparent power combines the active and reactive power components expressed in kVA and is charged as the demand used. The real power is the active component that affects the energy usage expressed in kWh and is charged as energy used.

The difference between the energy usage of the installed lights and the replacement lights was used to calculate theoretical savings. These calculated savings would differ based on the selected replacement light and the number of lights replaced. Each schools' theoretical savings therefore were calculated based on their unique choice of replacement light and the number of lights replaced.

4.2. Model assessment

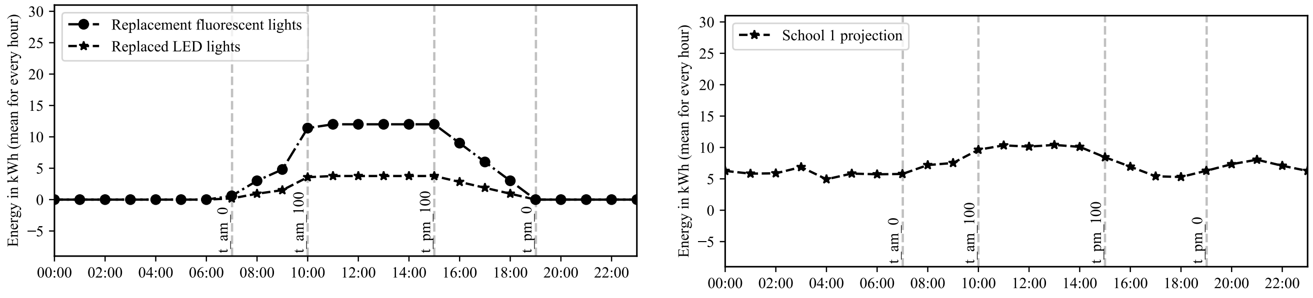
Lights were replaced at three schools as shown in Table 5: one primary school and two secondary schools. We replaced the lights at these schools and measured their electricity usage before and after the intervention. These replacements were done in three to five workings days for each school.

The schools' interventions differed slightly in terms of lights used and the installation of lights. Although most of the current lights were fluorescent lights, the schools had different lamp fixtures installed. The current lights in the schools were identified and counted through surveys. Their power usages ranged from 58W to 60W for 1.5m T8



(a) The average load profile of School 1 before replacement, $\boldsymbol{s}_{\text{school,before}}$.

(b) Proportional load function, $\boldsymbol{p}(t)$.



(c) The projected light utilisation scaled to the energy usage of the replaced fluorescent lights and the replacement LED lights.

(d) The projected load profile after replacement, $\boldsymbol{s}_{\text{school,proj}}$.

Figure 2: The light projection model stages, representing the school's usage before and after the intervention, are shown with the modelled light utilisation.

Table 5: Details of schools where lights were replaced

	Scholar level	Tariff	Quint.	Learners	Lights installed	Lights re-placed	Labour cost [ZAR]	Light cost [ZAR]	Supplier
School 1	Secondary	COM4	1	800	240	240	0	43,200	OrbitX
School 2	Primary	COM4	4	900	420	220	6,000	39,200	Philips
School 3	Secondary	ToU	4	1100	510	194	4,400	34,200	OrbitX

lights - almost triple the average LED light power rating. Based on the bench test results, the active power of the nominally installed fluorescent light to be used in the model was chosen as 60W with the measured power factor of 0.98.

Figure 3a shows the results for School 1, a secondary school, at which 240 fluorescent lights were installed, of which 240 classroom lights were replaced with OrbitX LED lights. The lights were replaced by the caretakers and the researchers, at no extra labour costs. The installation took five afternoons to complete. A three-week baseline was used for the energy profile before the light intervention, which is referred to as the before profile. A nine-week period was used after the light intervention, which is referred to as the after profile. These were consecutive periods and only weekdays were considered.

The overall mean reduction was 85 kWh per school day – an energy reduction of 35% on the pre-existing lights. The reduction in peak demand was 8 kVA – a reduction of 26% from the peak demand on the pre-existing lights. The RMS (root-mean-squared) error between the prediction and the measured profiles was 6 kWh over a day. This is 2% of the daily energy usage before the replacement. The maximum observed error in load was 1 kVA, which is 3% of the maximum peak load observed from before the replacement.

Figure 3b shows the results for School 2, a primary school, at which 420 fluorescent inside lights and 20 metal halide outside lights were installed. Of these, 240 lights were replaced: 220 classroom lights with Philips EcoFit; and 20 outside lights with lights from a combination of suppliers. At this school contracted technicians installed the replacement lights at a labour cost of ZAR 6,000. The installation took three afternoons. A 20 week baseline was used for the energy profile before the light intervention, which is referred to as the before profile. A consecutive four-week energy measurement period was used after the light intervention, which is referred to as the after profile and only weekdays were considered.

Between the before and after energy profiles the overall mean reduction was 65 kWh per school day – an energy reduction of 27%. The reduction in peak demand was 9 kVA – a reduction of 18% from the peak demand on the pre-existing lights. Although the projected and after energy profiles are close, they differ by energy error of 5 kWh (2% of daily energy used before). The maximum observed error in load was 0.7 kVA, which is 1% of the maximum peak load observed from before the replacement.

Figure 3c shows the results for School 3, another secondary school. This school had 510 fluorescent lights installed, of which 194 inside lights were replaced with OrbitX LED lights. Contracted technicians installed the replacement lights in two afternoons at a labour cost of ZAR 4,400.

For this particular school, the same one week period was used for both before and after energy measurement periods, referred to as before and after profiles respectively. Although only weekdays were considered, these periods were not consecutive periods but were one year apart.

Between the before and after energy profiles the overall mean reduction was 81 kWh per school day: 23%. The reduction in peak demand was 13 kVA – a reduction of 37% from the peak demand on the pre-existing lights. Although the projected and after energy profiles are close, they differ by energy error of 7 kWh (2% of daily energy used before). The maximum observed error in load was 2 kVA, which is 5% of the maximum peak load observed from before the replacement.

Figure 3d shows the average difference between the measured and the projected profiles for the three schools over a 24 hour period.

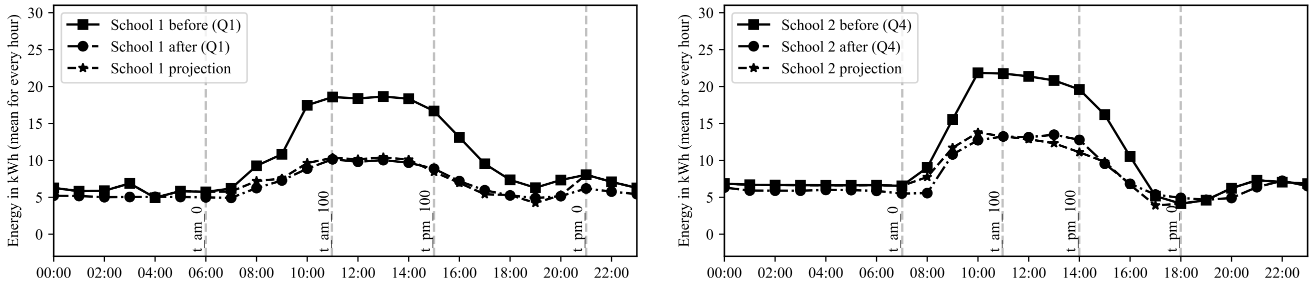
5. Results

5.1. Contribution of lighting costs in schools

We used the following to calculate the lighting portion of the annual school bill, before and after light replacements: municipal bills, smart-meter data, tariff structures, and our model. Figure 4 shows the billing information for each school and the estimated contribution of lighting to the annual bill first with fluorescent lights, and then with LED replacements.

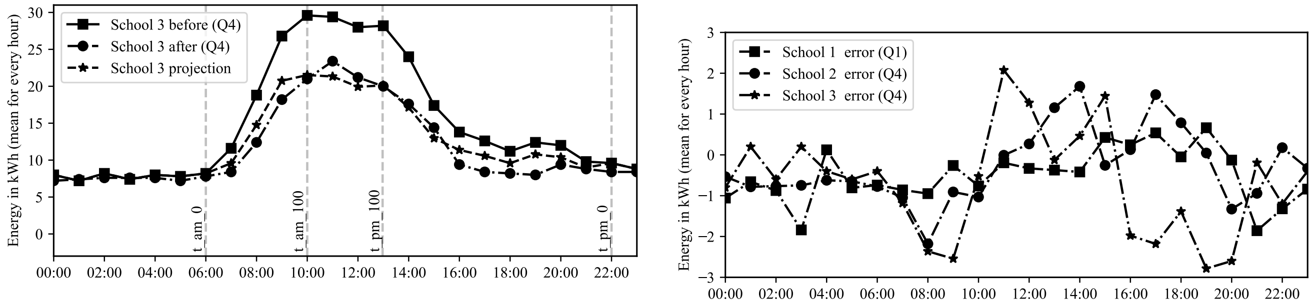
Before the impact of the lighting interventions, the annual lighting costs for the observed schools ranged from ZAR 41,250 to ZAR 109,340. For the schools on the commercial tariff, annual lighting costs ranged from ZAR 41,250 to ZAR 63,740. The annual lighting costs of the two ToU schools were ZAR 101,580 and ZAR 109,340. The school with the industrial tariff had a lighting cost of ZAR 76,190.

The overall cost impact of lights before interventions ranged from 31% to 57%, with a median contribution of 40%. For the four schools on the commercial tariff, lighting was responsible for 31% to 43% of the bill. At the two



(a) School 1 (Secondary): 240 lights were replaced with OrbitX lights, resulting in 35% energy saving and 9 kVA demand reduction on in-term days.

(b) School 2 (Primary): 220 lights were replaced with EcoFit lights, resulting in 27% energy saving and 13 kVA demand reduction on in-term days.



(c) School 3 (Secondary): 194 lights were replaced with OrbitX lights, resulting in 25% energy saving and 6 kVA demand reduction on in-term days.

(d) Average energy error between the projected and measured savings.

Figure 3: The light profiles of schools, representing the school's usage before and after the intervention, are shown compared to the light projections for the specific school.

schools on the ToU tariff lighting was responsible for 38% and 55%. The school with the industrial tariff had a lighting contribution of 57%.

After replacing the lights, their contribution reduced to ZAR 13,390 to ZAR 34,430, which is equal to 12% to 30% of their electricity bills, with a median of 17%.

5.2. Running savings

The running savings are shown in Table 6. The school's individual smart meter data and the model were used to calculate the energy saved during an average school day. These savings were then extrapolated to usage for a school year (196 days), taking seasonality into account. The calculations assume OrbitX T8 lights, except for School 2 where the Philips EcoFit was used.

The projected energy saved per school day was 80 to 190 kWh. The schools reduced their daily carbon emissions by 80 to 180 kg CO_2. The projected demand reduction per year ranges from 80 to 290 kVA. The yearly projected energy saved was 14,710 to 38.030 kWh.

The running savings of the projected replacements resulted in an energy cost difference of ZAR 15,020 to ZAR 60,850 and a load cost difference of ZAR 13,510 to ZAR 37,150 across all the schools. The total cost difference was between ZAR 25,740 to ZAR 76,750.

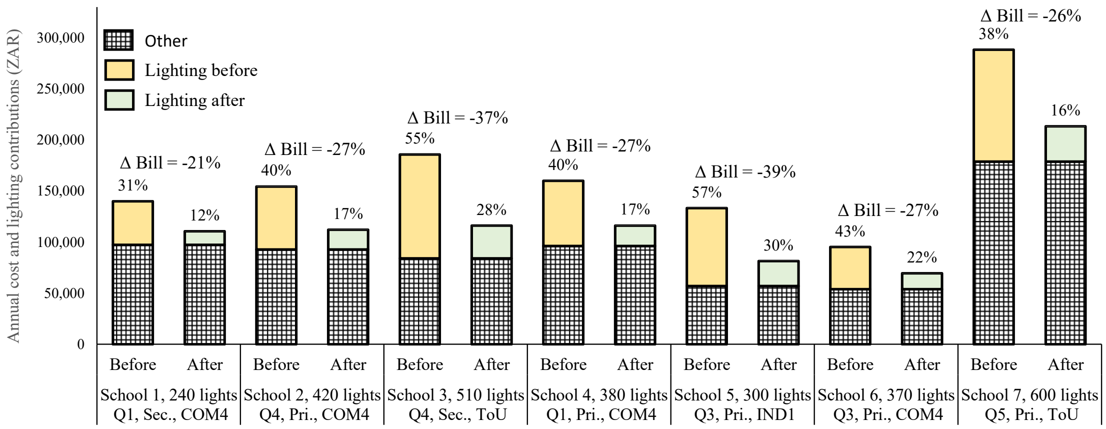


Figure 4: Lighting proportion of annual electricity bills before the replacements, and projected contributions after replacement of all the lights.

Table 6: Running savings achieved by the projected contribution of the LED replacements of all lights at each school

	Tariff	School-day energy reduction [kWh/d]	Carbon footprint [kg/d]	Peak demand reduction [kVA/m]	Demand cost difference [ZAR/y]	Energy reduction [kWh/y]	Energy cost difference [ZAR/y]	Bill reduction [ZAR/y]
School 1	COM4	90	90	120	0	16,760	29,340	29,340
School 2	COM4	120	110	240	0	24,250	42,440	42,440
School 3	ToU	180	170	250	13,510	36,040	57,660	71,170
School 4	COM4	130	120	190	0	25,010	43,770	43,770
School 5	IND1	80	80	150	37,150	15,020	14,720	51,870
School 6	COM4	80	80	140	0	14,710	25,740	25,740
School 7	ToU	190	180	290	15,900	38,030	60,850	76,750

5.3. Life-cycle costs for different light choices

The savings were calculated over six years. They take into account the number of school days per year and assume that a school has 600 lights per school using the mathematical expression. We assumed lights are on for an average of six hours per school day. The assumptions are based on a sample school light count and school operating hours.

Table 7 represents the three typical tariff structures: a flat fee (commercial tariff) for energy, time-of-use and the industrial tariff. The manufacturer guarantee periods were used to calculate the replacement periods.

The net savings for each light were calculated. The monthly savings of the light compared to the fluorescent tubes were considered. The price of the light, labour and replacement costs were considered and deducted. Over a six year period the OrbitX lights had the highest net savings for all the tariff structures as ZAR 360 (flat rate), ZAR 450 (ToU) and ZAR 950. However, lights that compared well in the flat rate tariff structure were the LighTec and the Osram lights with a ZAR 10 difference. For the ToU tariff this difference was greater at ZAR 10 by the Osram light.

The absolute life-cycle cost includes the cost of the lights (labour, light and replacement) and their cost due to using the lights or energy costs. Over a six year period the OrbitX light had the lowest cost overall as ZAR 500 (flat rate), ZAR 540 (ToU) and ZAR 780 (ind). The second-best light for the flat tariff was the Osram Substitute at ZAR 500 and for the time-of-use and industrial tariffs it was the Osram Substitute at ZAR 560 and ZAR 840 respectively. The light with the most cost over the period was the Philips CorePro, differing by more than ZAR 230

Table 7: Comparison of the life-cycle cost and savings over six years of energy efficient lights on Commercial 4 (COM4), Time-of-use (ToU) and industrial 1 (IND1) tariffs.

		OrbitX 19W [ZAR]	ClearSky 22W [ZAR]	Philips EcoFit 22W [ZAR]	ClearSky 32W [ZAR]	Philips CorePro 20W [ZAR]	LighTec 22W [ZAR]	Philips Master VLE 21W [ZAR]	Osram Substitute 22W [ZAR]
COM4	Per light: Savings	360	280	310	200	120	350	280	350
	Per light: Cost	500	570	540	650	730	500	570	500
	Per school: Savings	213,030	170,220	187,770	119,580	74,350	208,700	168,390	208,700
	Per school: Cost	298,180	340,980	325,440	391,620	436,860	302,510	342,820	302,510
ToU	Per light: Savings	450	360	350	240	220	370	370	440
	Per light: Cost	540	630	650	760	780	620	624	560
	Per school: Savings	270,910	216,880	208,710	141,250	129,680	222,850	223,060	261,600
	Per school: Cost	326,300	380,330	388,490	456,000	467,520	374,360	374,420	335,600
IND1	Per light: Savings	950	770	590	460	700	550	850	890
	Per light: Cost	780	970	1,140	1,280	1,040	1,180	890	840
	Per school: Savings	571,250	463,140	355,270	275,340	416,970	331,840	507,130	536,680
	Per school: Cost	470,660	578,770	686,640	766,570	624,940	710,070	534,780	505,230

Savings: Net savings vs. fluorescent, and
Cost: Absolute life-cycle cost.

from the least expensive light for the time-of-use and flat rate tariff structures. The light with the most life-cycle cost for the industrial tariff was the ClearSky 32W.

When viewed in the short term, the OrbitX light is the most expensive - considering it is only the tube - and the Philips EcoFit costs the least, but they differ substantially in energy and light quality. When viewing them over the longer term, the OrbitX light saves more and costs less.

With the figures of savings and cost per light over six years, the projections were linearly scaled up to a school level of 600 lights. For the flat rate tariff, the best light is the OrbitX and second is the Philips EcoFit. For the time-of-use and industrial tariffs the best light is the OrbitX and second is the ClearSky 22W. The savings for the best light amounts to ZAR 213,030 for the flat tariff, ZAR 270,910 for the time-of-use tariff, and ZAR 571,250 for the industrial tariff.

The absolute life-cycle cost on a school projection level for the flat rate ranged between approximately ZAR 298,180 and ZAR 436,860. For this tariff, the OrbitX lights - the least expensive option - would cost a school ZAR 298,180. The Philips EcoFit and ClearSky lights would cost a school between ZAR 325,440 and ZAR 391,620, at least ZAR 27,000 more than the least expensive option. The Philips CorePro has a larger difference in cost of almost ZAR 140,000 in comparison with the least expensive option.

Considering the absolute life-cycle cost in a ToU tariff structure for a school, the range of cost is between approximately ZAR 326,300 and ZAR 467,520. The arrangement of lights is ranked similarly to the previous tariff structure, however the Osram Substitute light was the second least expensive ToU option, with a ZAR 9,300 difference in comparison with the least expensive option.

The cost for the industrial tariff ranged from ZAR 470,660 and ZAR 766,570, the most expensive of all the tariffs. The light cost order is like the time-of-use tariff. The most expensive light is the ClearSky 32W followed by the Philips EcoFit.

The replacement cost of the lights had a large impact on the absolute cost. This was based on the manufacturer's written guarantee - although the lights may last longer. Their guarantees were as follows: OrbitX (six years), Philips EcoFit (three years), ClearSky 22W (five years), ClearSky 32W (five years), Philips CorePro (three years), LighTec (five years), Philips Master VLE (five years) and Osram Substitute (five years). Linear extrapolation was used to calculate the costs for all at six years.

6. Conclusion

South Africa is under pressure to grow its economy, reduce emissions, and to ensure energy security and affordability. This is especially true of the often-neglected primary education sector, which is struggling to meet even its primary obligations. One easy answer to reduce costs, reduce electricity demand, reduce emissions, and improve the prospects in the education sector is to replace the outdated fluorescent lights with energy-efficient LED lights. Despite existing publications describing international efforts to replace lights at schools, little is known of the cost of replacements, the financial and environmental benefits of such replacements, and the effect of choosing one of the many available lights as a better replacement. Moreover, none of the existing research reviewed for this has developed a model with which to assess the impact; none of them have evaluated the available lights for the purpose; very few have considered developing country contexts, and none of them have considered schools in Africa.

To that end, we explored electricity used at public schools in South Africa, assessed the proportion of the annual cost attributable to lighting, determined the financial and environmental benefits of replacements, and assessed the available options. We developed a model that was validated with smart meter data and partial light replacements at three schools. We used the model to assess the impact at seven schools for which we had smart meter data and light audits.

Bench tests of the available lights proved that different savings can be achieved through the lights tested. The savings of some were more than double that of others, and the life-cycle costs varied from ZAR 298,180 to ZAR 766,570 between lights and tariff structures.

At the schools in our sample, we found that lighting constitutes from 31% to 57% of annual electricity costs before LED replacements. By replacing all the lights, the annual electricity bills were reduced by 21% to 39%, and the proportion of lighting from 12% to 30%.

Future work could include case and/or pilot studies of different light replacements for the two tariff structures at schools. This would be for verification of the light cost and savings projections. Furthermore, decision makers could include the bench test results in their specifications for LED lights criteria.

This study showed the value of longer-term projections compared with the short-term cost of the lights. We found that the most expensive light in the short them yielded the most savings in the long term, and that the price tag and long-term savings do not necessarily correspond to light quality.

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