

Improving Buildings' Energy Efficiency through Smart Technologies: Case Study of South African University Residences

Siyabonga Mamba, Patrick S. Pouabe Eboule, Jan Harm C. Pretorius

Postgraduate School of Engineering Management

Faculty of Engineering and the Build Environment

University of Johannesburg, PO BOX 524, Auckland Park 2006, South Africa

patrickpe@uj.ac.za, jhcpretorius@uj.ac.za

Abstract

Energy demand is a global crisis. Since the year 2010, most buildings' energy consumption across the globe has increased by almost 14% (Paris Agreement, 2018). As a result, energy-supplying utilities have had to increase the burning of coal and gas to meet the demand, which results in high carbon emissions causing global warming (EcoMetrix Africa, 2021). This study evaluates the impact of implementing smart technologies in high-density residential zones by utilising a system that is energy-efficient and cost-saving. The study compared the energy consumption of two mixed student residences of the University of Johannesburg, where one is equipped with smart technologies while the other functions with a traditional energy supply system. The results obtained show that there is a 46.26% variance between the two residences' energy consumption. This study's results show that the implementation of smart technologies in high-density residential units can reduce energy consumption by approximately 46% compared to a traditional way of energy supply. The results also reveal that the implementation of smart technologies can reduce the contribution of carbon emissions by 33%.

Keywords

Smart Technologies, Energy Saving, Seasonal Energy Usage, Energy Intensity, and Rate on Investment (ROI)

1. Introduction

According to the Paris Agreement, carbon emissions should be reduced drastically to achieve the set target of net-zero carbon emissions by the year 2030 (Paris Agreement, 2018). There are many energy-efficient projects such as retrofitting, PV installations, smart technology installations and others of this nature that are being implemented to reduce energy consumption. These projects guarantee a net-zero carbon emission future (Laurina et al., 2018). Based on the power optimal 2018 report, it is highlighted that over the past decade, South Africa's primary electricity supplier (Eskom) has escalated electricity prices drastically by 356%, at an inflation rate of 74% over a similar period. This shows that the price of electricity in the country has escalated four times faster than the inflation rate over the same period. Therefore, the implementation of energy-efficient projects would also play a role in reducing the steep increase in the electricity price.

The electricity sector in South Africa is generated and powered by the national utility Eskom, which generates approximately 90% of the electricity used in the country. A total of 10% is supplied by municipalities and redistributors, which include independent power producers (IPPs) (Global Energy Demand, 2018). Eskom also supplies roughly 40% of electricity to other African countries (Matteo et al. 2019). The 2020 Eskom Energy Distribution Report indicates that Eskom is directly supplying power to 2 703 industrial, 51 848 commercial, 81 638 agricultural and six million residential customers. Since March 2018, the Eskom net maximum generating capacity amounted to a total of 48 GW (Michael, 2020). The Eskom power station maximum generation matrix is presented in Figure 1.

The South African electricity supply is dominated by coal-fired power stations that have supplied 83% of the baseload since 2018. The combined contribution of maximum generation capacity by other power stations constitutes 17%. The pumped scheme contributes 6%, gas turbines account for 5%, nuclear power stations 4%, and hydro-power stations contribute 2%. The South African primary energy supply includes indigenous products, and considering the

continuously rising cost of traditional fossil fuel-based energy carbon dioxide issues, South Africa has embarked on a journey of promoting the use of renewable energy suppliers. It is currently rated as the 12th most attractive investment for renewable energy (Maistry & Morton McKay, 2020).

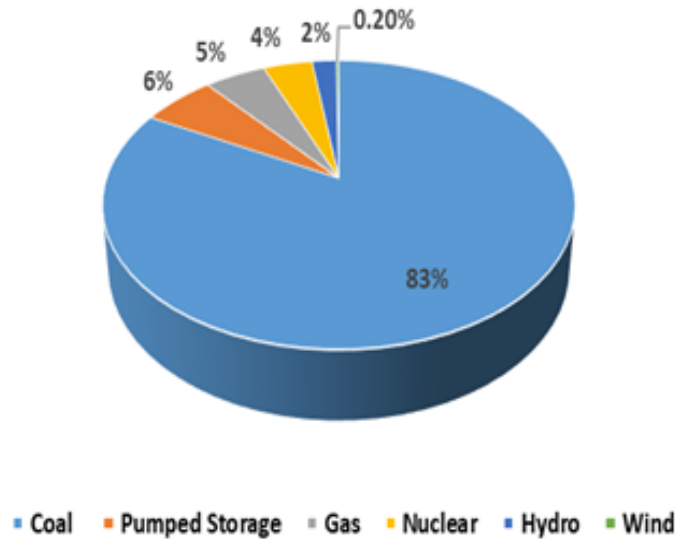


Figure 1. Eskom Power Station Maximum Generation Matrix

The high energy demand, carbon emission, and economic crisis in the world influence energy-serving interventions, and the need for behavioural change across the globe is highly recommended (Marcell et al., 2019). Most of the South African institutional residences accommodate a significant portion of the country's population every year. This is the reason why institutions should start taking part and play their role in encouraging energy consumption reduction behaviour (Laurina et al., 2018). These changes will mean embarking on a long journey since most residences of South African institutions are not designed for energy efficiency as they were built before the energy conservation subject became the topical issue that it is today (Govender, 2020). However, the engineering discipline, together with the architects are doing very important work to ensure that all buildings are now constructed with energy-efficient materials, such as recycled steel, spray-foam insulation, thermostat radiant barrier sheathing, insulation concrete forms and plant-based polyurethane foam (Numbi et al., 2020).

There are many published articles that analyse residences' energy consumption and also conduct a comparison of energy consumption for different residences (Eskom Integrated Report, 2021). However, the novelty of this study is not only about comparing the residences' energy consumption, but it further analyses the various smart technologies to select the most suitable for residences, and only displays the financial modelling according to the return on investment (ROI) for the smart technologies that can be implemented, based on the residence structure and capacity. Below are the questions that were addressed during the fulfilment of the research objective:

- How do the energy consumption levels and the energy costs for these two residences compare with each other?
- What is the return on investment for the installation of smart technologies?
- What is the nature of the energy-efficiency interventions implemented in the smart technology-equipped residence (Thomas Sankara), as opposed to that of Mayine residence?
- How can the university reach energy efficiency in their residences?

The remaining structure of this paper is as follows: Section 2 presents the methodology followed to analyse the data; Section 3 presents the analysis of results, and Section 4 presents the conclusion and recommendations.

1.1 Objectives

The main objective of this study was to evaluate the impact of the implementing of smart technologies in residential buildings, particularly in the reduction of energy consumption and the level of carbon emission. The specific objectives were to compare the energy consumption of the two University of Johannesburg's mixed students' residences, one of

which is equipped with smart technologies while the other is still functioning with a traditional energy supply. The contributions of this study are, firstly to offer insight or a framework to the institution's finance and management departments about the significant amount they can save in a year after investing in smart technologies. Secondly, it is to analyse the possible smart technologies available for residences and identify the most residential-compatible, energy-efficient, and cost-effective options for residences.

2. Literature Review

Michael et al. (2019) indicated that the high energy demand, carbon emission level, and economic crisis in South Africa influence the energy-serving interventions. A need for behavioural change in the country is, therefore, highly recommended. Residences of most South African institutions accommodate a significant portion of the country's population, which is the reason why institutions should start taking part and play their role in encouraging behaviour that will reduce energy consumption. These changes will still take a long time to embark on since most residences of South African institutions are ancient and are not compatible with energy efficiency as they were built before the energy conservation subject became essential. However, the engineering and architecture disciplines are doing significant work in ensuring that all buildings are now constructed with energy-efficient materials, such as recycled steel, spray-foam insulation, thermostat radiant barrier sheathing, insulation concrete forms, and plant-based polyurethane foam (Saha et al., 2013). Numbi et al. (2020) highlighted that commercial buildings are the highest energy consumers within the building sectors. The biggest share goes to malls, retail buildings, hotels, offices, restaurants, and educational buildings.

According to the energy consumption literature review, most researchers have achieved their objective by conducting energy audits via real-time monitoring of electric consumption for buildings. They mostly use Power and Energy Data Loggers for data collection, which are installed at the electricity distribution board of the targeted buildings. The Logger tool has an application programming interface (API) that is capable of reading power and energy and at the same time displaying their readings (Wafula, 2012). The implementation of most of the smart technologies has shown a significant save in energy consumption, even though some of them are not easy to maintain (Cristani et al., 2014). Some of the technologies, cannot be easily incorporated at the residences, not only because of the high initial investment but because they require the full building to be a smart building, which means the consumer's appliances (such, fridge, stove, heaters, TV, sound system, etc.) must comply with a certain standard, which might be very costly for students to afford (Beetge et al., 2017).

3. Methods

The chosen study area is the Thomas Sankara residence which is located at the University of Johannesburg's Auckland Park Kingsway Campus, situated at 17th Streatly Ave, and the Mayine Residence at the Bunting Road Campus situated on 17th Bunting Rd, Cottesloe Auckland Park, Gauteng, South Africa. One of the reasons for selecting these two residences is because they almost have the same number of rooms. In addition, they are both for post-graduate, mixed-gender students.

The energy consumption data used in this study is from February 2019 to December 2019, which makes it eleven months. This is a period covering the university's academic calendar. This was profound energy consumption data available for this study since it reflects the situation after the Thomas Sankara residence had undergone the transformation process of being equipped with modern smart technologies in 2017. The data had to be analysed and interpreted to fulfil the main objective of this research.

To compare the energy consumption of the two residence data sets, their mean values (\bar{x}) were calculated and the energy difference was found using the format $\bar{x}_{Mayine} - \bar{x}_{Thomas\ Sankara}$. The difference between the two energy mean values provides the percentage energy variance between the residence that still uses the traditional energy supply and the one with smart technologies. Equation 1 was used in calculating the mean values for the two sets of data. The ROI for the installation of the smart technologies was also estimated using Equation 2 below. Furthermore, it was necessary to determine the annual carbon dioxide (CO_2) emission contributed by the residences' consumption. This was calculated using Equation 3.

$$\bar{x} = \frac{\sum fx}{N} \quad (1)$$

$$ROI = \frac{\text{Initial Investment } (\varphi)}{\text{Yearly Savings } (\beta)} \quad (2)$$

$$E_{\left(\frac{kwh}{day}\right)} = P_{(W)} * \frac{t_{\left(\frac{h}{day}\right)}}{1000_{\left(\frac{W}{kW}\right)}} \quad (3)$$

4. Data Collection

During this study, both quantitative and qualitative methods were used to collect various data from the two residences. Some of these data were collected through interviews with the energy consumers (students) for both residences. Fifty students participated in the interviews of which fifty percent were males and fifty percent were females. The interview questions were to find out the users' energy usage patterns. This included how often they switched off unused appliances and lights, and also how much time they spent cooking and taking a shower. Data that might be considered most representative of the residences' energy consumption patterns were found on the actual energy bill that was provided by the residential management offices in the form of daily, monthly and yearly consumption.

The analysed data were presented in tabular and graphical forms. The student data were received from the residence's managers. The data indicate that the number of students in these two residences is almost the same, with 240 residents for Thomas Sankara and 246 for Mayine (Student Accommodation, 2018/19). There is a six-student variance between the two residences. Also, the Mayine residence accommodates more female students compared to the Thomas Sankara residence, which also has an impact on the energy pattern as presented in the results. Figure 2 below presents student statistics.

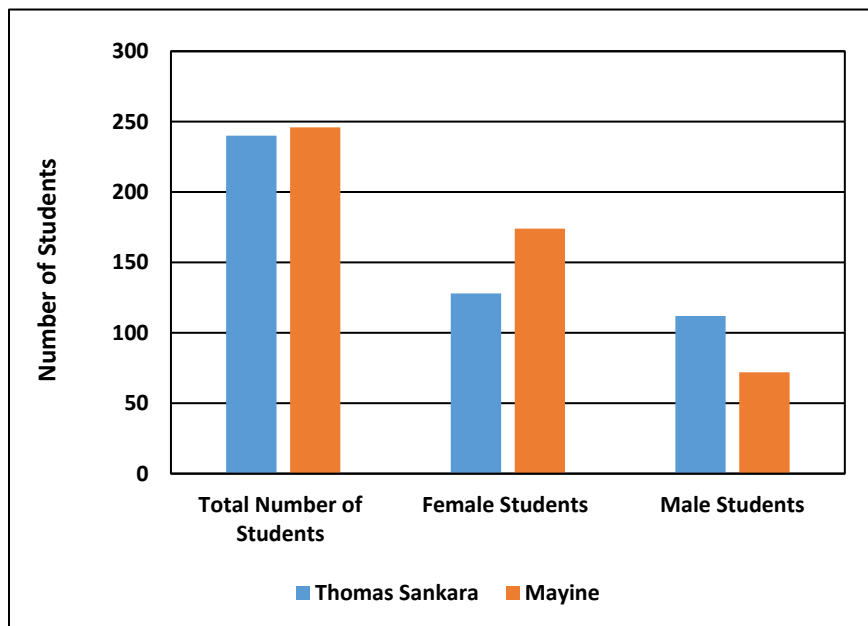


Figure 2. Student Statistics

Table 1 presents the monthly data for both residences. It shows how much energy is consumed and the associated costs for both residences.

Table 1. Energy Consumption and Costs

Date	Thomas Sankara kWh	Thomas Sankara Cost (R)	Mayine kWh	Mayine Cost (R)
02/19	33532	81131.96	47703	133,769.31
03/19	35835	87857.03	53471	142,646.47
04/19	39343	90,897.60	75155	176,959.21
05/19	44333	95,365.29	77690	184,525.15
06/19	48223	99,426.06	83083	192,386.94
07/19	60793	144,127.19	91955	247,821.42
08/19	51531	131,569.39	87214	226,800.13
09/19	45323	100,914.29	81277	176,014.06
10/19	46224	98,719.97	77346	174396.71
11/19	43895	95,129.94	68830	165,253.52
12/19	38123	89,898.48	60477	162261.38

5. Results and Discussion

The trends of the residence's energy consumption and their associated costs were analysed through line charts and are presented in Figures 3 and 4 below.

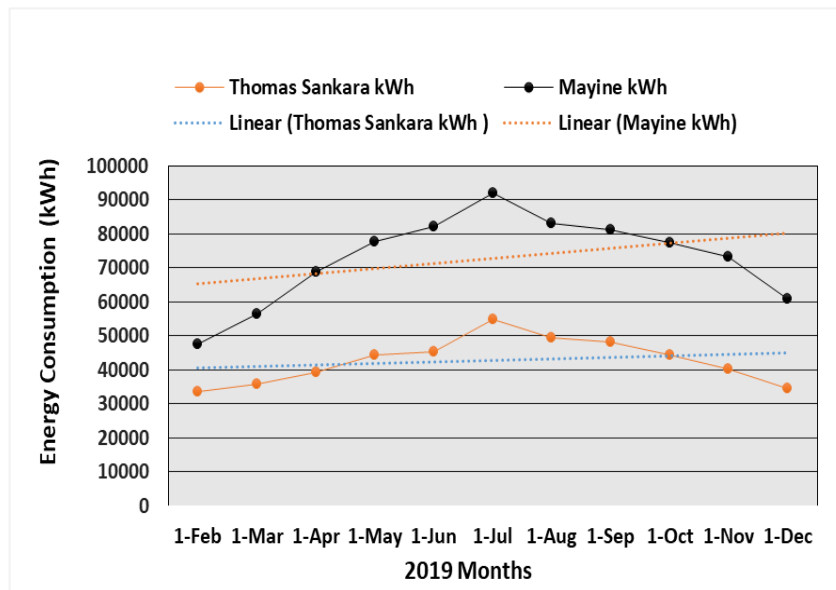


Figure 3. Monthly Energy Consumption in kWh for Both Residences

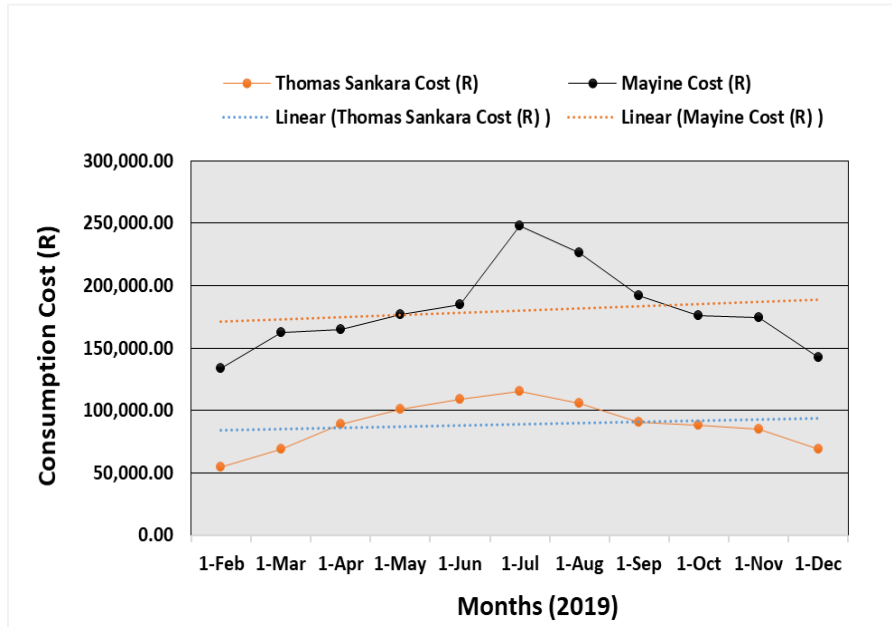


Figure 4. Monthly Energy Costs in Rands for Both Residences

Both energy consumption trends above show a steady increase from February to May, then it started to decline in the June period, and it picked up again in July until it dropped in August. The slight decrease in energy consumption during the June period is an indication of the university recess, where many students are at home until July. The steady increase trend in energy consumption shows that more energy is consumed during the winter season, which is an indication of the use of higher energy heating appliances, such as space heaters and geysers. The high increase at Mayine during this season is due to the high number of female residents. Interviews with the students showed that female students spend more time in the shower compared to males, which results in more water being heated. The consumption trends start to decrease steadily from August to December, which is an indication of the hot temperature season, where fewer heating appliances are being used. The December energy consumption significantly drops because most of the students leave the university premises after their exams and go home for the festive season.

The winter gradient for the Mayine's energy consumption costs shows a very sharp increase compared to the Thomas Sankara winter energy consumption costs. The reason for such a high gradient is that the municipality electricity rates are higher during the winter season and there is more heating of water taking place at Mayine using the municipality electricity. Yet, on the other hand, Thomas Sankara residence is equipped with water heat pump systems, which significantly help in stabilising the energy consumption for water heating. The months June, July, and part of August are categorised as the winter season for the year 2019, and the energy consumption trends show correspondence between energy usage and weather, with more energy consumed during the winter period with its peak in July. Thomas Sankara shows good energy savings due to the installed smart technologies. The cost of implementing their smart technologies was analysed and is presented in Table 2 below.

5.1 Numerical Results

Table 2. Thomas Sankara Smart Technology Description and Energy Savings

Energy Efficiency Technology	Energy Capacity for the Smart Technologies.	Lifespan (Years)	Costing	Modern Technologies Possible Energy Savings (%) when compared to buildings with traditional technologies
Heat Pump System	Coefficient of performance is between 2.0 and 4.0.	10-25	US\$ 42818.39	75%
Standard LED Lighting System	14W	10-35	US\$ 6595.32	10-40%
Occupancy Lighting System	14W	10-35	US\$ 7331.10	>45%
Outdoor Lighting System	20W	10-35	US\$ 2311.04	>30%
Generator (200 kVA for backup)	200kVA	15-50	US\$ 34130.17	-
Showerheads	1.5 Gallons Per Minute (GPM)	10-30	US\$ 1683.75	30%
Smart HVAC System	30% of building energy capacity	10-25	US\$ 14043.48	30-50%
Total			US\$ 108913.25	

Table 3. Summary for the Thomas Sankara's Return on Investment (ROI)

Thomas Sankara Energy Consumption and Savings Summary	Amounts	Years
Yearly Energy Consumption, Before Installation of Modern Technologies.	US\$ 136747.19	1 year
Yearly Energy Consumption, after Installation of Modern Technologies.	US\$ 83990.80	1 year
Thomas Sankara Savings Per Year.	US\$ 52756.39	1 year
Installation of Smart Technology	US\$ 108913.25	1 year
Average Estimated Smart Technologies' Lifespan.	-	10 to 50 Years
Initial Investment Payback Period, For the Installed Modern Technologies.	-	2.05 Years
Estimated /Profit Period, after recovering initial investment	-	5 to 35 Years

The return on investment (ROI) for the installation of the modern technologies at Thomas Sankara was calculated as shown below.

A. Return on Investment (ROI) Calculations

Yearly Savings = β , Energy Before Installing Modern Technologies = α , and Energy After Installing Smart Technologies = γ .

$$\beta = \alpha - \gamma = \text{US\$ } 136747.19 - \text{US\$ } 83990.80 = \text{US\$ } 52756.39$$

$$\begin{aligned} \text{ROI} &= \frac{\text{Initial investment } (\varphi)}{\text{Yearly Savings } (\beta)} \\ &= \frac{\text{US\$ } 108913.25}{\text{US\$ } 52756.39} \\ &= \mathbf{2.06 \text{ years}} \end{aligned}$$

Table 2 shows the cost of the modern technologies that have been installed at Thomas Sankara, as a measure of energy efficiency. As the estimated cost for installing modern technologies is about \$0.137m, it is obvious that installing modern technologies is rather expensive. However, when performing the data analysis as shown in Table 3 above, the return on investment (ROI) shows that it is a good investment since the capital can be recovered within a period of two years, and still benefit from those technologies for a further estimated 25 years on average. This shows that after two years of installing the modern technologies the Thomas Sankara residence will save quite an extensive amount of energy. The carbon emission (CO_2) calculations are presented below. This reveals that their carbon emission contributions are higher due to energy consumption if a building is without smart technologies. Below are the calculation and comparison of the two residences carbon emission contribution based on their energy consumption.

B. Carbon Emission Calculations

Coal-Fired CO_2 emission rate = 1020kg/MWh.

Carbon emission calculations, for Thomas Sankara:

$$P_{(W)} = E_{\left(\frac{kwh}{day}\right)} * 100 \left(\frac{W}{kW}\right) * \frac{day}{24hrs} = 61509 \text{ W}$$

- 0.062 MW * 24hrs * 0.567 cap.fac = 0.844 MWh/day
- 0.844 MWh * 1020 kg = 860.88 kg/day
- 860.88 kg/2000 = 0.430 tons CO_2 /day

$$0.430 \text{ tons} * 365 \text{ days} = 157.11 \text{ tons } CO_2/\text{year}$$

Carbon emission calculations, for Mayine Residence:

$$P_{(W)} = E_{\left(\frac{kwh}{day}\right)} * 100 \left(\frac{W}{kW}\right) * \frac{day}{24hrs} = 101540.4 \text{ W}$$

- 0.10154 MW * 24hrs * 0.567 cap.fac = 1.259 MWh/day
- 1.259 MWh * 1020 kg = 1284.18 kg/day
- 1284.2 kg/2000 = 0.642 tons CO_2 /day

$$0.642 \text{ tons} * 365 \text{ days} = 234.36 \text{ tons } CO_2/\text{year}$$

The calculations above show that the Mayine and Thomas Sankara residences' energy contributes 234.36 tons CO_2 /year and the 157.11 tons CO_2 /year of carbon emission. These reveal that the implementation of smart technologies can reduce the carbon emissions of residential buildings by 33%.

6. Conclusion

The main objective of this study was to evaluate the impact of implementing smart technologies in residential buildings. It was achieved by analysing and comparing the energy consumption of the University of Johannesburg's Mayine and Thomas Sankara's residences during the 2019 calendar year. The energy consumption and their respective energy costs data were analysed and compared graphically. The difference between the two energy consumption means values indicates that there is a 46.26% variance between the two residences' energy consumption. This means that the consumption at Mayine residence is almost double that of Thomas Sankara residence. The reason for this significant variance is because various energy-saving initiatives have been implemented at Thomas Sankara, such as occupancy, energy-saving lights, installation of high-efficient showerheads, installation of water heat pumps, as well as control ripple relays. The Mayine and Thomas Sankara residences contribute 234.36 tons CO_2 per year and the 157.11 tons CO_2 per year of carbon emission. These reveal that the implementation of smart technologies can reduce the carbon emissions of residential buildings by 33%.

The analysed data showed that most energy consumption occurs during the winter season. The research findings also prove that there is higher consumption during the peak hours, from the morning at 6 am to 10 am and also in the evening from 5 pm till 10 pm. Furthermore, the electricity consumption rate during the winter season is more expensive as compared to all the other seasons. In addition, other significant energy consumption contributors that are not taken seriously at residences are the passage, bathroom and toilet lights which are always left on even when there is no activity taking place. These are the most crucial areas which need smart technology systems in the residences of institutions.

For energy reduction at the residences, it is recommended that residence management implement an incentive strategy that will encourage an energy-saving culture in students, for example, hosting energy awareness per semester and during the event reward the residents who have used less energy for that semester. In addition, management can implement a programme where residents of university accommodation come up with innovative ideas for energy-saving, such as designing motion sensor lighting systems and smart plug systems. These ideas can then be sponsored and implemented at the university residences as a means of energy efficiency. Furthermore, it is recommended that all the existing residential buildings are retrofitted. It can be done through the use of smart windows, smart roofing systems, smart plug systems and other innovations.

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Biographies

Siyabonga Mamba is a graduate of Engineering Management at the University of Johannesburg. He has also completed his Honours degree qualification in Electrical and Electronic Engineering from the same university. He started his career path in 2018 with Eskom as a system engineer. Through his under and post-graduate qualifications, he has acquired substantial skills that are related to project management. The scope of the projects executed empowered him to develop key project management skills and acumen such as teamwork, critical thinking, planning, time management, efficient and effective communication, risk management, development of timelines, as well as setting SMART project goals. Furthermore, he is an ECSA registered candidate and qualified electrician with a wireman certificate. Furthermore, he is a SETA-certified course facilitator and evaluator.

Patrick S.P. Eboule obtained his PhD in Electrical and Electronic Engineering at the department of Engineering Sciences at the University of Johannesburg in 2020. His PhD research was based on the study and the feasibility of a nine-phase power transmission line system and the utilisation of artificial intelligence techniques to detect, classify and locate faults in such a transmission line. He has been a post-doctorate fellow researcher at the Department of Engineering Management at the University of Johannesburg since February 2021. He is interested in renewable energies, power systems, machine learning, and artificial intelligence. Patrick Eboule is an engineer, member of the Institute of Intelligent Systems (IIS) in the School of Electrical and Electronic Engineering, University of Johannesburg, member of the Engineering Council of South Africa (ECSA), and member of the Association for Computing Machinery (ACM) and Power and Energy Society in the Institute of Electrical and Electronics Engineers (IEEE). In December 2019, Patrick Eboule received a student paper award at the 11th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC2019) held in Macau.

Jan-Harm Christiaan Pretorius obtained his BSc Hons (Electrotechnics) (1980), MEng (1982) and DEng (1997) degrees in Electrical and Electronic Engineering at the Rand Afrikaans University and an MSc (Laser Engineering and Pulse Power) at the University of St Andrews in Scotland (1989). He worked at the South African Atomic Energy Corporation as a Senior Consulting Engineer for 15 years. He also worked as the Technology Manager at the Satellite Applications Centre. He is currently a professor at the Postgraduate School of Engineering Management in the Faculty of Engineering and the Built Environment where he worked since 1998. He has co-authored over 240 research papers and supervised 61 PhDs and over 270 Master's students. He is a registered professional engineer, professional Measurement and Verification practitioner, senior member of the Institute of the IEEE, fellow of the SAIEE and a fellow of the South African Academy of Engineering.