Journal of Energy in Southern Africa

Volume 29 Number 3 • August 2018

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Journal of Energy in Southern Africa

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Journal of Energy
in Southern Africa

Volume 29 Number 3 • August 2018

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Volume 29 Number 3

Energy use in informal food enterprises: A gender perspective

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Abstract

The informal sector provides economic opportunities to the poor, and in sub-Saharan African countries it is dominated by women. Energy is a key input into the food sector enterprises. A study was carried out to review academic and non-academic literature on the use and gender impacts of modern energy in informal food enterprises. The review established that few studies have addressed energy for the informal food sector from a gender perspective. Although these few are qualitative in nature, they tend to lack in-depth analysis of gender and of the cause-and-effect linkages between modern energy use in the informal sector and the gendered goals of women and men. Moreover, a lack of understanding of gender from a relational perspective focusing on both women and men impeded conclusions on empowerment in terms of whether increased access to modern energy in the informal food sector contributes to closing the gender gap. This paper makes three key recommendations. First, scholars need to address the gaps and take a relational approach, so that studies are not just about women but also about the power relations between various groups of women and men. Secondly, policy needs to recognise that biomass is sometimes desired not just as an energy source but also for the flavour it imparts to food. Lastly, policy should be informed by the needs of informal enterprise owners and their customers, not by the general discourse in the energy sector that assumes that increased uptake of modern energy services makes positive contributions to enterprises.

Keywords: *informal food sector, gender, energy use*

Highlights:

- *There is a lack of evidence on the role of energy in the informal food sector from a gender perspective.*
- *Biomass is prevalent in the informal food sector due to the sector's specific energy needs and to socio-cultural practices.*
- *There is a need for studies on gender and energy from a relational perspective in relation to energy and entrepreneurship.*

Journal of Energy in Southern Africa 29(3): 1–9
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a4357

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

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1. Introduction

This study presents the results of a literature review on the use of modern energy services in informal food enterprise and related gender impacts. The review established that, despite energy being a key input for food preparation and process enterprises, few studies have investigated the informal food sector taking a gender approach.

Over the last two decades, the informal economic sector outpaced the formal economy in creating economic opportunities for women and men in developing countries, particularly in Sub-Saharan Africa, where employment opportunities in the formal sector are scarce, especially in areas where literacy levels are low. The informal economy had an advantage over the formal because of low entry barriers – including low capital requirements and reduced business costs because many informal businesses do not pay tax or have costs such as holiday and maternity cover and insurance. The ILO (2015a) reports that non-agricultural employment in the informal economy represents 66 per cent of total employment in Sub-Saharan Africa and 52 per cent in North Africa.

As in all aspects of socio-economic life, there is a gender divide in the informal sector. For example, 'in Sub-Saharan Africa, 74 per cent of women's employment (non-agricultural) is informal, in contrast with 61 per cent for men' (ILO, 2015b:01). Women tend to be concentrated in food processing and preparation, domestic work, and health and education services. They tend to dominate these sub-sectors because they rarely have the vocational and skills training to enter other sectors, and so tend to use skills gained in their gendered roles to start enterprises (Meagher, 2010). Women's enterprises tend to be more vulnerable to economic shocks and restructuring because of their subjugated status in many developing countries. It was found, for example, that modernisation and restructuring of economies often takes away jobs traditionally done by women, such as food processing or sewing (Kemp, 1993). Similarly, in times of economic crisis, men join the informal sector in greater numbers, sometimes altering traditional gender patterns (Yasmeen, 2001).

One informal sub-sector in which women dominate is the food processing and preparation sector (Chen, 2001; Brown, 2006). Even in countries where women typically do not work outside the home for religious and cultural reasons, they have opportunities in the informal food sector by either selling their products from home or by being 'the hands behind the male face' of the business – cooking and processing food at home, while male relatives or business partners sell it in the public sphere (Etzhold, 2015). On the other hand, there is an increase in men's participation in sectors that have previously been dominated by women, including the informal food sector (Overå, 2007). These dynamics call for critical questions relating to gender and economic opportunities, especially in urban areas.

The study set out to identify and examine the empirical literature on gender and modern energy use in the informal food sector, to explore the gender, energy and informal food sector nexus. This area of enquiry is important because, despite expectations that access to energy for productive use empowers women by enabling them to generate income, women in developing countries face a range of barriers when establishing and operating enterprises, including access to energy (de Groot et al., 2017).

A brief account of methodology in Section 2 is followed in Sections 3 and 4 by the identification of key gender dynamics applicable to modern energy use in the informal food sector. Section 5 examines the evidence on the positive and negative impacts of modern energy services on women's and men's informal food enterprises. Section 6 discusses the advantages and limitations of modern energy services in the informal food sector, based on the emerging evidence. A concluding section highlights the key gaps in the literature and draws out implications for current and future developments in research and policy making.

2. Methodology

A review of empirical academic and non-academic literature such as project reports, both published and unpublished, was undertaken. The selection was based on three themes: the informal food sector, gender, and energy for productive uses. A range of search engines was used to find material, including Web of Science, African Journals Online and Google Scholar; with further papers found by the snowball technique. Inclusion criteria were that studies focused on urban areas, outlined effects of modern energy use on businesses or business owners, used sex-disaggregated data, and concerned informal food preparation and processing.

3. Importance of the informal food sector for livelihoods

Initially understood as a temporary mechanism for coping with economic shocks, the informal sector in general appears to be resilient and has over the years expanded rather than shrunk as expected (Chen et al, 2002; ILO, 2002; Bigsten et al., 2004). The informal food sector is no different. Even though academic and policy categorisations would classify many of the informal food sector enterprises as survivalist in nature, some informal food sector enterprises do grow and are medium-to-long-term livelihood strategies. Survivalist enterprises tend to be regarded as informal in nature and found mainly in poor areas, operating on roadsides and without financial security to sustain the businesses, which are mainly operated by women (Berner et al., 2012). Growth of informal enterprises could entail earning incomes above the poverty line, expanding the customer base or product or service range, and increasing profitability or revenue. A snapshot study of women in the informal food sector in Accra showed that women participated in street food vendors as a long-term enterprise, actively trading for 7–20 years and growing their businesses from feeding a few customers to selling several meals a day and even catering for events (Matinga, 2015). In Rwanda, Senegal and South Africa, female-owned enterprises in the sector have been in existence longer than those owned by men; for example, up to 89% (41 out of 46) of enterprises that are more than ten years old belonged to women. Furthermore, 75% of enterprises that were five to ten years old were owned by women (Bressers et al., 2016).

The informal food sector, especially street-vended food on the consumer side, changed from the occasional meal to an important source of affordable nutrition, particularly for the urban poor across the globe as shown by Chukuezi (2010) in Nigeria; Mosupye and von Holy (1999) in South Africa; and Muzaffar et al., (2009) in Bangladesh among others. The studies by FAO in Ghana and in Thailand show that the informal food sector often provide one to two meals a day for office-workers, travellers, school-children and households (Fellows and Hilmi, 2011; FAO, 2012). It is estimated that, globally, over 2.5 billion people eat street food every day (FAO, 2012). Among buyers of street food in Bangkok, Thailand, the second-most-cited reason for purchasing street food (after proximity to home) was because it is cheap. In Bamako, Mali, street food constitutes 19–27% of the household food budget (Ag Bendech et al., 2013). In Lusaka, Zambia, food vendors sell about 81 million meals per annum (Graffham et al., 2005).

There is less documentation of informal food processing, especially in the urban environment, while there is an emerging interest in street food. A brief period of interest in informal food processing was observed in the 1980s, when debates on women's drudgery and issues of appropriate technologies and mechanisation were common (Tinker, 1981; Carr, 1981). Many of these discussions pertained, however, to domestic production in rural areas and ignored women as economic agents in food processing. Both food vending and food processing subsectors experience low levels of access to modern technologies, modern energy services and finances, and have little social and legal protection (Horn, 2009; de Groot, 2017; ILO, 2015).

Studies on the impact of the sector from a gender perspective are few, despite the contributions of the informal food sector to livelihoods and its importance as a livelihood strategy for women. Some of biggest gaps in knowledge are with respect to the impact of energy, whether modern or traditional, on these informal businesses, as well as to women's role and positions in them. Common among these characteristics is that women with low levels of literacy tend to dominate street food vending. A 2003 census of street vendors in Harare, Zimbabwe, for example, showed that about 8 631 people were involved, of whom 81% were women (Graffham et al., 2005). In Bahia, Brazil, 55.9% of 247 food vendors interviewed were female with low levels of education (49% had elementary education or lower) (da Silva et al., 2014). A study of 334 street vendors in Accra, Ghana, showed the sector employing more than 60 000 women and men, with 94% of food vendors being women with minimal or no education (NRI, 2015). These findings were later corroborated by studies in Ghana and elsewhere in Africa where the majority of vendors, including street food vendors, were illiterate or semiliterate women (Osei-Boateng & Amaratwum, 2011). This important aspect of the informal food sector – that it presents economic opportunities for women with few prospects – is dealt with in Section 4.

4. Gender dynamics in the informal food sector

In processing cassava, grating, dewatering and milling operations are dominated by men, while peeling, washing, drying and frying operations are dominated by women (Davies et al., 2008). In West African diary processing, men are involved in livestock care, but it is women that do the milking and dairy processing, although this is also governed by complex arrangements based on ethnicity, religion, and economic status, among other variables (Waters-Bayer, 1985). In Nigeria and Senegal, for example, the Fulani women process, market and make decisions over milk, including how much is consumed and sold, and do sell it directly themselves, as do women in Somalia (Dietz et al., 2001). Wealthy Fulani women and strict Muslim women, however, often use intermediary women (Corniaux, 2003; Waters-Bayer, 1985) such that critical power relations are between women of different status as much as between women and men.

5. Evidence of gendered energy use and impacts in the informal food sector

5.1 Gendered patterns of energy use in food enterprises

One study highlighted the gender and energy dynamics in the food sector as a whole, including both formal and informal sectors (Onyeneho and Hedberg, 2013). This study was on food safety in restaurants in Imo State, Nigeria, where restaurants were classified into four categories: Class A being major hotels, Class B school cafeterias, Class C regular/fast food restaurants, and Class D 'bukas' or 'bukaterias' – consisting of food kiosks, roadside food sellers and mobile food sellers or food hawkers (collectively termed street food vendors in the present study). It was found that all the bukaterias were owned by females with only primary school education and that none of them had refrigerators, while all other categories had some refrigerators. The reasons for bukaterias not having these facilities were not explored, but could be attributed to lack of capital, lack of access to modern energy, or lack of security of location, since bukaterias are often harassed and moved by local authorities.

In India, productive uses of energy were explored, and it was found that the uptake of both electricity and liquefied petroleum gas (LPG) among entrepreneurs, many of whom ran restaurants and tea shops, was not significantly different for males and females (Kooijman-van Dijk, 2008). Men's enterprises, however, had better opportunity to improve access to modern energy services because they could occupy central locations. Men could also increase access to customers, while women in most Indian communities faced barriers in trading outside the family home. The DfID-funded study on energy and urban livelihoods in Plataforma and Canabrava communities, Bahia, Brazil, divided food-producing and -selling businesses into three categories: those that used one to two LPG cylinders, those that used more than two, and those that used none (Winrock, 2005). The majority (89% or 25 out of 28) of these businesses were women-owned. It was found that 72% of women entrepreneurs who sold food and beverages used one to two cylinders per month. Among the food businesses owned by men, 33% used more than two cylinders a month compared with only 20% of women's businesses (Winrock, 2005). The proportion of men likely to use no LPG was 67%, compared with 8% for women. The study does not offer reasons for this discrepancy; one reason could be that men are less likely than women to engage in food enterprises requiring thermal energy, but the study is unclear as to what food the different enterprises prepared. Bressers et al. (2016) showed that 78% (32 out of 41) of males with enterprises in the informal food sector in Rwanda, Senegal and South Africa used traditional sources of energy such as wood and charcoal, while 62% (86 out of 138) of females also used traditional energy sources.

5.2 Use and impacts of different energy types in cooked food vending

Few studies have attempted to examine the impacts of modern energy services on women's and men's informal food enterprises in any depth, and all were qualitative in nature. In a study of the impacts of LPG on women's livelihoods in Accra, Ghana, female respondents reported that LPG reduces drudgery by eliminating tedious processes of lighting and tending to traditional open fires. Furthermore, the clean-burning LPG reduced the time spent on scrubbing pots, leaving business owners more time to spend with their families (Matinga, 2015). The LPG-fuelled ovens were also said to improve time management compared with (improved) wood-ovens because they come to temperature instantly, as opposed to wood ovens where one has to wait longer for the oven to heat. The LPG was, in general, seen as being useful in improving product quality because of better temperature control, thus improving the ability to respond speedily to customer needs. Kooijman-van Dijk (2008) found that in India one female owner of a teashop valued the fact that using LPG reduced the destruction of forests and lessened the need for helpers in the kitchen, the latter factor suggesting that LPG reduces drudgery. Women were more likely than men to value the fact that LPG kept kitchen walls and dishes clean; male owners of teashops cited only the values of comfort of use and providing fast service as the motivation for using LPG. A study in the Philippines cited clean burning and enabling fast service as the benefits of using LPG in *carinderias* (Approtech-Asia, 2005).

A study by Tedd et al. (2003) focused on the promotion of improved cookstoves for street food vendors in Dhaka, Senegal. Impacts of these cookstoves were assessed among 100 enterprises, where 95% of the vendors were female, of whom 27% were food processors. All cookstove users reported experiencing increased savings and could use the savings for purchasing other items. A total of 26 (97%) reported experiencing increases in stock as well as improvement in lifestyle, and 53% of these entrepreneurs also reported a reduction in medical costs. The study, however, made no in-depth analysis of the pathways to these benefits but attributed them to the improved efficiency of the cookstoves. About 14 respondents used improved commercial cookstoves and ten of these reported increases of 31% or more in profit margins, while the other four experienced improved profit margins of 16–30%. All users also felt that they required less time to cook on improved cookstoves than on traditional stoves. It is noted that the 95% female component of this study was part of the project and not reflective of the actual situation. In the actual context of this Dhaka study, men dominated street food vending because, while women were involved in preparing the food, it was often men that were present at the point of sale (Tedd et al., 2003), probably because of religious and cultural constraints; but the research wanted to specifically capture women's views.

Of the four studies cited above, examining use and impacts of different energy types, only Kooijman-van Dijk (2008) compared women's and men's food enterprises, She found no difference in the impacts that women and men's businesses experienced (Kooijman-van Dijk, 2008). The results from Matinga (2015) were based on intentionally interviewing women only; and those of Approtech Asia (2005) in the Philippines were also based on focus group discussions with women only. The study by Tedd et al. (2003) included data from women and men but did not provide a breakdown on differences in benefits; given the gender divide in roles, however, it is likely that benefits such as time-saving and improved health as a result of improved stove utilisation accrued to women, and increased revenue to men. The study by Bressers et al. (2016) The present survey asked enterprises if they were using energy sources that reduced their workload. Out of 178 respondents, 48% indicated that they did not use energy sources that could reduce the time spent on difficult tasks and 38% saw no (energy) alternatives to the ones they were using. Only 11% of the female respondents indicated that they used sources that reduced their workload, while only 3% of males indicated the same.

5.3 Use and impacts of energy in food processing

Studies on gender, energy, and food processing (as opposed to preparation) are generally lacking, but the Mali multifunctional platforms – a government managed, multilaterally sponsored energy programme, which powers food processing as well as water pumping, battery charging, welding and other services does provide some insights (Sovacool et al., 2013). The platforms provide women's groups with diesel-powered engines that allow them to process grains, nuts, cereals and other food products (Sovacool et al., 2013). In the assessment of its impacts, women reported that their incomes improved; the increase was estimated to be as much as USD 44 per year. Increase in incomes was attributed to better productivity and better product quality because of powered processing, which enabled women to charge higher prices. Changing from manual to powered food processing also reduced drudgery and time spent on the process. The time saved was used to cook for family, whereas previously, meals for men and children were skipped because of women's time pressures; this had the potential to improve family nutrition. In addition, women had more time for leisure and entertainment. Men also saved time and used it to start businesses and benefited from women's saved time because they had timely meals. The study by Sovacool et al. does not elaborate on how men saved time, but the platforms powered other activities in addition to food processing, which could account for it.

At a very basic level, energy is critical to food processing, as it allows transformation of foodstuffs into desired forms, e.g., through cooking, preservation through drying in the sun or smoking and sterilisation (including pasteurisation). Conducting these processes without appropriate and affordable forms of modern energy is arduous and therefore often left to women because their time is valued less. The absence of refrigeration, sterilisation and temperature control means food can go putrid, increasing chances of food-poisoning, to the detriment of both customers and businesses. Reduced drudgery and improved food safety means that modern energy can contribute to the practical needs of women and men. However, while modern energy use can have several advantages over traditional forms of energy for informal food businesses, it is not without its limitations, as illustrated in Section 5.4.

5.4 Limitations of modern energy services in the informal food sector

Studies that focus on the negative impacts or limitations that might result from switching to modern energy use are scarce. Other literature on energy transitions, however, reveals potential negative impacts that could result from an unreliable supply of modern energy or from consumer preferences associated with the flavour of food cooked on open fires or charcoal. The DfID-funded study on energy, gender and urban livelihoods in Nigeria examined energy use in fish-smoking enterprises, a sector dominated by women (Maduka, 2006). Fuels used were firewood, sawdust and kerosene. Price hikes in petrol affected businesses because the firewood was transported by car into urban areas. It was also found that the women, despite acknowledging disadvantages of fuelwood such as eye problems from smoke, were reluctant to switch to LPG because its smokeless operation was perceived to affect the characteristic flavour of smoked fish, leading to women fearing a loss of customers (Maduka, 2006). The women's priority was not modern energy but (micro) credit.

Matinga (2015) and Approtech-Asia (2005) referred to modern energy supply issues and its impact on the informal food sectors in Ghana and the Philippines, respectively. At the time of both studies, supply reliability of modern energy (LPG in the case of Ghana and LPG and electricity in the case of the Philippines) was not considered problematic, although it had been so in the past. In both cases, however, the costs of LPG and electricity were said to be a form of constraint on businesses. In the Philippines study, a coping mechanism demonstrated by only one of the eleven eateries studied was to use kerosene and wood as complementary fuels. This appeared to be in line with the Ghana case where, after an increase in LPG costs, enterprises did not switch fuels. In both studies, most entrepreneurs did not appear to have changed fuels because of increased cost. A mechanism used for coping with high energy costs in the case of the Philippines was reducing staff numbers. Choosing to do this rather than regress to traditional fuels signifies the high value placed on modern energy fuels. It is likely that, in the case of food enterprises in these two countries, the advantages of using LPG were highly valued and enterprises would rather incorporate energy price changes into food prices as a coping mechanism than regress to traditional fuels and lose the benefits of modern energy. In neither study was there any assessment of gender differences in the impacts on informal food businesses or coping mechanisms.

While there are no specific explorations of potential limitations related to food flavour, studies from household energy use have shown that the flavour imparted by firewood or charcoal can affect a household's decisions about changing to modern energy for cooking. A question to be asked in the informal sector, then, is whether and in what informal food enterprises a transition to modern energy services would result in customer loss because of changes in food flavours. Matinga (2015) observed that informal food vendors in Ghana used charcoal particularly for traditional foods – this could be as a way of both coping with the costs of LPG and of maintaining expected flavours. In the Philippines study, one eatery used charcoal not because of LPG or other modern fuel constraints but because it was the preferred fuel for grilling (Approtech Asia, 2005). As mentioned above, in Nigeria, women entrepreneurs feared of losing customers through switching from wood to LPG in fish-smoking (Maduka, 2006), but whether this loss materialised is not known, since the study did not compare businesses that had changed to LPG with those that used firewood.

The fact that the introduction of modern fuels such as LPG could reduce necessary labour to the extent of allowing a reduction in the workforce (Kooijman-van Dijk, 2008) is an advantage to business-owners, though obviously a disadvantage for those who lose their employment. Such loss of employment is likely to impact women more than men because it is women who are often employed in this sector.

6. Discussion

The studies reviewed in this paper expose some areas of interest in terms of considerations for academic and policy inquiry. Beyond showing the importance of the informal food sector as a source of income (mostly for women but also for men), it was found that, for the informal food sector, differentials of energy access between women- and men-owned businesses were unclear, but that sex was an unlikely factor in whether an informal food business has modern energy access. Studies, conducted in Brazil and India (Winrock, 2005; Kooijman-van Dijk, 2008) and in Sub Saharan Africa (Bressers et al., 2016), examined the sex of the business owner and modern energy use, and found that sex was not a factor in determining the use of modern energy in the informal food sector. The study in India, however, found that improving modern energy use was limited for women because of cultural constraints, which also limited their access to customers. It was also found that the location of the business might be a more significant factor than the sex of the owner in determining access to modern energy services. Men in the India study had better business locations and these have better access to modern energy such as LPG and electricity. The Brazil study (Winrock, 2005) noted women's strong wish use LPG. Nonetheless, men's informal food businesses were likely to use more LPG than women's, with the study showing women likely to use one to two cylinders a month, while the proportion of male-owned businesses using more than two cylinders a month was marginally more than that for female-owned food businesses. The reasons for limited use of LPG in women's businesses in the Brazil study were less clear but likely to be economic, and related to the location and the size of the businesses. The three studies showed further that, while access to modern energy might be the same for female- and male-owned businesses, increased use of it was more limited for women. Women's inability to increase modern energy use after initial access might be attributable to lower capital capacity, although reasons for the difference remain uncertain.

A critical gap in the studies on energy access for the informal food sector is that, despite the suggestion that location matters in access to modern energy services, the studies do not address whether location and local government and planning policies affect whether men and women access modern energy services. The studies are silent on whether and how such local government and planning policies and reforms (e.g. decentralisation policies) might affect energy access in the sector, and the gender differences of such effects. For example, would women and men risk investing in modern energy access if their businesses can be confiscated or if they can be moved to different locations on spurious grounds? What happens to energy-use patterns, including costs and other associated risks, when women and men in the informal food sector are forcibly relocated in the interest of urban planning and modernisation goals? Does local government and planning policy take into consideration modern energy access for the informal food sector? Semi-formalisation of previously informal street businesses in Rwanda, for example, might decrease police harassment and dependency on civil servants, given that business registration guarantees certain rights and provides some protection (Bressers et al. 2016).

There is little in-depth investigation of whether impacts are different for women and men, but studies have identified several impacts that are beneficial for women. Those cited in the six studies that discussed impacts include reducing drudgery and saving time. Further, four studies show that modern energy services improve product quality and customer service, both of which are likely to improve profitability. The studies by Matinga (2015) and Tedd et al. (2003) show improvements in profitability as a direct result of using modern energy in food preparation enterprises that previously used traditional energy sources, while Kooijman-van Dijk (2008) suggests reduction in labour costs, which could in turn improve profitability. Only Kooijman shows benefits to both women and men and concludes that sexes experience the same benefits but that there were different motivations for female and male food enterprise owners opting for modern energy. While women were motivated by broader concerns such as environment (deforestation), customer comfort and clean kitchen walls and dishes, men cited only comfort of use and providing fast service as the motivation for using LPG. . The lack of studies that compare impacts on women and men, and their different experiences, is a critical gap. Further studies are needed to inform how best to promote modern energy services to women and men in the informal food sector by, among other things, highlighting if and how women and men in the sector differ in their energy needs, access to opportunities, and the causes for these differences.

Gender roles in the domestic spheres where women are the main cooks and men are seen as economic heads (despite women also earning incomes) are reflected in informal businesses where women are largely responsible for cooking while, in some cases, men are the ones that sell the products (Kooijman-van Dijk, 2008; Tedd et al., 2003). On the other hand, household members provided labour for the businesses as shown by Matinga (2015). A question then arises as to whether energy policies for household energy access and use, such as subsidy policies for poor families, should go beyond household consumption to include energy for informal enterprises.

Another gap in the literature is that of access to capital and energy in the informal food sector. Although not specifying whether the businesses are formal or informal, but including rural and urban enterprises, and not an energy study per se, at least one study by USAID showed that food processing businesses were least likely to be served by formal financing institutions and constituted only 5% of customers (whether new or repeat) for the banks examined in the study (Agabin and Gusto, 2006: 14). Carinderias or Filipino food kiosks were 8% of repeat customers and 9% of new ones, although their average first loan amounts were the highest. The Approtech Asia (2005) study points to problematic access to credit for carinderias and canteens, arguing that most of these carinderias access informal credit at an interest rate of 20% per week (although it does not go into detail). Given that women's access to capital is problematic and that modern energy services policy has taken on a neoliberal, market-driven approach, how does this affect access to modern energy for women- and men-owned informal food enterprises? Would improved access to credit be necessarily used for modern energy or purchasing appliances for use with modern energy services?

A key question that is largely missing from the studies on energy and gender dynamics in the informal food sector is whether the use of modern energy in the informal sector is empowering to women. The studies considered in this paper show that time-savings and improved business outcomes suggest an improved economic position for women and hence a possibility for economic empowerment. However, the analysis across the studies shows that the concept of empowerment is not clearly elaborated. Moreover, where it is implied, the empowerment notion dealt with can be considered to be vertical: i.e. how women have moved from a previous position of disadvantage to a present better position. What is not explored is the horizontal aspect of empowerment: whether their positions have changed with respect to men's positions, leading to a narrowing of the gender gap. This appears to be a common issue in gender and empowerment studies in the energy sector and comes in part from focusing on collecting data from women only.

7. Conclusions

A literature review between October 2015 and February 2016 was conducted on energy in the informal food sector, focusing on gendered impacts of modern energy use. The first key finding of this literature review is that there is a dearth of literature on gender and energy within the informal sector. Secondly, the review shows that, while women dominate the informal food sector, patterns of use of different types of energy, and especially traditional and modern forms, are gendered. Third, the review shows that modern energy such as LPG can have a positive impact on businesses by improving the quality of end-product because of enhanced capacity to control temperature, improved responsiveness to customers' need for speedy service, cleanliness of environment including the ambient air quality, and time saving. Similarly, improved cookstoves improve businesses due to improved cleanliness and time saving. Such improvements can improve the profitability of women's businesses as well as working environments. Fourth, literature on food processing businesses is even less than that on cooked food. Finally, the use of modern energy sources for the benefit of the informal food sector is impeded by unreliable supply, leading to continued use of traditional fuels.

This literature review could contribute to closing the knowledge gap of the gender impacts of modern energy on the informal food sector. There is a lack of conceptual clarity in impacts, particularly those pertaining to empowerment, in that the few studies that address gender and energy in the informal food sector do not define what is meant by empowerment. Finally, the review of the literature, as well as data emerging from our own project on the productive uses of energy in the informal food sector, suggest that the use of biomass as an energy source will continue in the informal sector for reasons including affordability, accessibility and consumer preference. Efforts to support access to modern energy services in the informal food sector must therefore include supporting sustainable (including safe) use of biomass energy.

Acknowledgement

This review is part of the research project titled 'Productive uses of energy: The informal food sector in South Africa, Rwanda and Senegal', which was commissioned under the Gender and Energy Research Programme by the International Network on Gender and Sustainable Energy and funded by the United Kingdom's Department for International Development.

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Journal of Energy in Southern Africa

Volume 29 Number 3

Novel measurement and verification of irrigation pumping energy conservation under incentive-based programmes

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Abstract

In most countries the agricultural sector, especially crop irrigation, is a considerable energy consumer. Farm irrigation studies in South Africa showed that energy and water is wasted on a large scale and there is a large potential for improving efficiency. The present study focusses on the measurement and verification (M&V) of irrigation pumping energy conservation measures (ECMs) under the Eskom Standard Product Programme funding mechanism in South Africa. A novel M&V methodology was developed to quantify ECM impacts under the Programme, which has special conditions and unique M&V requirements, which makes normal approaches inapplicable. Methods were designed to effectively determine conservative but representative impacts without continuous power demand profile measurement. The design involved unique methods to quantify operational demand reduction, annual energy consumption and annual average demand reduction impacts. The design was broadened to include pumps irrigating multiple crop areas and different kind of crops. The methodologies and techniques developed were validated and verified through establishing independent cross-check measures. The paper discusses a regional top-down M&V approach to verify the actual total energy efficiency and load reduction on the electricity grid for a specific region.

Keywords: *energy efficiency; demand side management; variable speed drive; load reduction; crop load factors*

Highlights

- *Irrigation energy conservation measures under incentivised programmes.*
- *The M&V of irrigation pumping energy efficiency under the Eskom Standard Product Programme.*
- *Instantaneous and average demand reduction with annual energy consumption reduction.*
- *Quantify impacts without continuous power demand profile measurement.*

Journal of Energy in Southern Africa 29(3): 10–21
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a3058

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Technology

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1. Introduction

Most countries use irrigation pumping to increase crop yield, to different extents depending on climate and yearly precipitation. In most of the world about 70% of freshwater demand is for irrigation, and in barren and semiarid regions the value reaches 90% (Molden, 2007). Irrigation in South Africa, compared with other sectors, is by far the biggest water user (Du Plessis, 2009). According to the Department of Water and Sanitation (DWS) 2013–2015 annual strategic overviews of the water sector in South Africa, 62% of South Africa's yearly rainfall water yield was used in those years for agricultural purposes (DWS, 2013; DWS, 2015). On the energy front, the agricultural sector in South Africa contributed 4.7% of electricity sales in 2016, according to Eskom's integrated results (Eskom IDM, 2016). Internationally, Naylor (1996) found irrigation to be the major energy consumer at farm level in other countries. On-farm irrigation pumping is responsible for 23-48% of direct energy consumption allocated for crop production (Hodges *et al.*, 1994; Singh *et al.*, 2002; Lal, 2004), with the figure highly dependent on climatic regions, farming practices, crop type and use of utility power.

The agricultural sector is prone to energy and water wastage through inefficient practices, poor irrigation systems and leaks (Standard Product Programme irrigation supplementary measurement verification and guideline, 2013). Energy and water wastage can be improved or managed by energy conservation measures (ECMs), which can be irrigation energy efficiency (EE) projects or projects which shift the irrigation pumping load away from power utility peak periods. The ECMs can be utility-driven projects or incentivised programmes such as the following:

- government- or utility-funded energy service company projects, such as the Eskom integrated demand management programme (2017);
- the EE rebates or tax rebates like those covered by Section 12L of the South African income tax act (South Africa Government Gazette 2013, 2013);
- the EE trading mechanisms such as white certificate schemes (Tyler *et al.*, 2011) or carbon-trading through schemes like the clean development mechanism (Winkler and Van Es, 2007);
- vertically integrated national appropriate mitigation actions (Dazé *et al.*, 2016); or
- the anticipated South-African carbon tax (Department of National Treasury South Africa, 2015).

Under the Eskom demand side management (DSM) programme, now known as the Eskom integrated demand management (IDM) programme, many load-shifting and EE projects were carried out in residential, commercial, industrial and mining environments. These included several farming irrigation pumping load-shifting projects (Storm *et al.*, 2008). Projects were mainly interventions that could have a large Eskom peak period demand reduction or a significant EE impact, where some projects implemented both evening peak load-shifting and EE by simultaneous application.

All projects needed to show credibility, and measurement and verification (M&V) had to be applied to evaluate attained impacts (Van der Merwe, 2011), since public funding was provided by the National Energy Regulator of South Africa (NERSA) for the Eskom projects. Intensive M&V on these projects was therefore performed to assess project impacts and report to the stakeholders. The function of M&V is to independently and objectively quantify project impacts and sustainability of impacts over an agreed contractual project life (Den Heijer, 2010). All M&V practices were based on the international performance M&V protocol (IPMVP Committee, 2012). From this, South African M&V practice guidelines (Den Heijer, 2010) were developed, culminating in the establishment of a national standard: SANS 50010:2011 (South African Bureau of Standards (SABS), 2011), recently updated to SANS 50010:2018 (SABS, 2018).

As well as large DSM projects, small-scale EE projects can also add to the national IDM energy use performance improvement and were therefore also implemented to reduce energy consumption for cost saving. The Eskom Standard Product Programme (SPP) was established to provide rebates for these small projects and fasttrack implementation and associated performance assessments at a lower overall assessment cost. A project and a programme essentially differ in that a programme is an ongoing roll-out of a fixed technology over many sites, while a project considers a set target defined over certain site(s) (Coetzee *et al.*, 2012) and is not limited to a specific technology. An energy-saving rebate under the SPP is paid to participating parties who replace a standard old, inefficient technology with a standard and proven EE technology. The technologies initially allowed under the SPP included EE lighting, heat pumps, EE showerheads and solar water heating (Van der Merwe, 2011).

An Eskom IDM energy advisor team (Scheepers *et al.*, 2013) also set out to establish an Eskom programme for irrigation demand reduction and EE. Here, some larger projects fitted under the Eskom Standard Offer Programme (Eskom IDM), which still required conventional M&V (Hibberd, 2011; Den Heijer *et al.*, 2010). The majority of potential projects needed to fit under the SPP, however. According to Van der Merwe (2011) these SPP small-scale projects require a generalised approach that gives acceptable saving impact indication. This

M&V approach recognises a deemed saving rather than a measured saving as with conventional M&V. Several projects could be implemented per site subject to a single project size, each limited to 100 kW average demand reduction during weekdays, and a maximum total of 250 kW impact per site.

Conventional M&V of irrigation projects has already proved to be exceptionally challenging (Storm *et al.*, 2016). It is difficult to determine the efficiency or inefficiency of water usage in irrigated agriculture because it is a 'multiple input – multiple output process' (Malana and Malano, 2006; Rodríguez Díaz *et al.*, 2004). The difficulty of conventional irrigation M&V called for a new and unique M&V methodology to quantify ECM impacts under the SPP and other incentive-based programmes. The focus of this study is therefore M&V on irrigation SPP projects and the novel M&V methods developed to quantify the impacts of these projects.

2. Conventional M&V methods vs SPP M&V requirements

Conventional M&V methods are normally applied on ECM projects with a large demand or EE reduction. This was common practice on large irrigation projects under the Eskom DSM programme, where the ECM intervention cost is high and the total M&V cost involved only a fraction of the total project. The large EE or demand reduction achieved relates to large incentives paid to the ECM project owners. Many implemented demand reduction projects have moved several MW from the evening peak to other times.

It is important for all stakeholders within such an environment to have very accurate M&V results with a high confidence level. Also, the exact project performance must be tracked over the entire project life to ensure that the project targets are met. Here, M&V is critical and the associated cost easily justifiable. The M&V process on these projects require the following critical components and actions (Storm *et al.*, 2008; Van der Merwe, 2011):

- properly define the baseline boundary, which include ECM intervention and all interactive effects;
- define an energy governing factor as;
- proper M&V demand profile metering (billing class in most cases) is required;
- define a functional baseline metering period to capture all project variations and circumstances – anything from a few months to several years;
- baseline model development – the baseline typically consisting of average weekday, Saturday and Sunday demand profiles;
- baseline assumptions made on project parameters and conditions where the baseline is applicable;
- a baseline service level adjustment method to adjust the baseline relevant to the operation conditions it would have experienced if the ECM was not implemented. This is done by using the referenced energy driver; and
- calculate savings over the project life. This is normally done on a monthly or quarterly year basis. The participating members in the project receive incentives based on the results of the M&V project performance reports.

This conventional M&V method requires extensive baseline development and independent M&V specialists are required throughout the project life to track ongoing savings. Metering and data gathering can be cumbersome and also very expensive.

The SPP M&V approach fundamentally differs from the traditional M&V in the following aspects:

- no profile metered baseline period and no reference energy drivers;
- no ongoing metering is performed on the ECM after implementation;
- no profile baseline development; and
- the incentive is paid to participating parties at the beginning of the project, on a projection of the savings over the following three years. There is, therefore, no ongoing tracking of the project performance.

Considering these, the SPP has unique requirements that make conventional M&V approaches inapplicable. A new M&V methodology was required to assess SPP ECMs and quantify projected impacts without conventional M&V methods, while still having an acceptable confidence level.

3. Novel integrated M&V methodology for the SPP

A novel integrated M&V methodology was developed to conservatively quantify load reduction and energy efficiency resulting from ECMs under the SPP. The scientific approach was developed through a comprehensive study of all SPP requirements, project parameters, system boundaries and approach limitations. The integrated methodology includes the key components displayed in Figure 1. Specific methodology design validation and verification parameters were set as Figure 1(a), (c) and (d).

Figure 1(b) shows the key concepts of the integrated methodology described in the present study. The ECM evaluation looked at how an evaluation criterion can be devised to assess different ECM approaches to ultimately find a sustainable and quantifiable ECM. This then considered how this ECM was applied and how it led to demand reduction and energy saving. The design of assessment/measurement procedures examined the following:

- design a measurement procedure to assess actual attainable impacts through the chosen ECM;

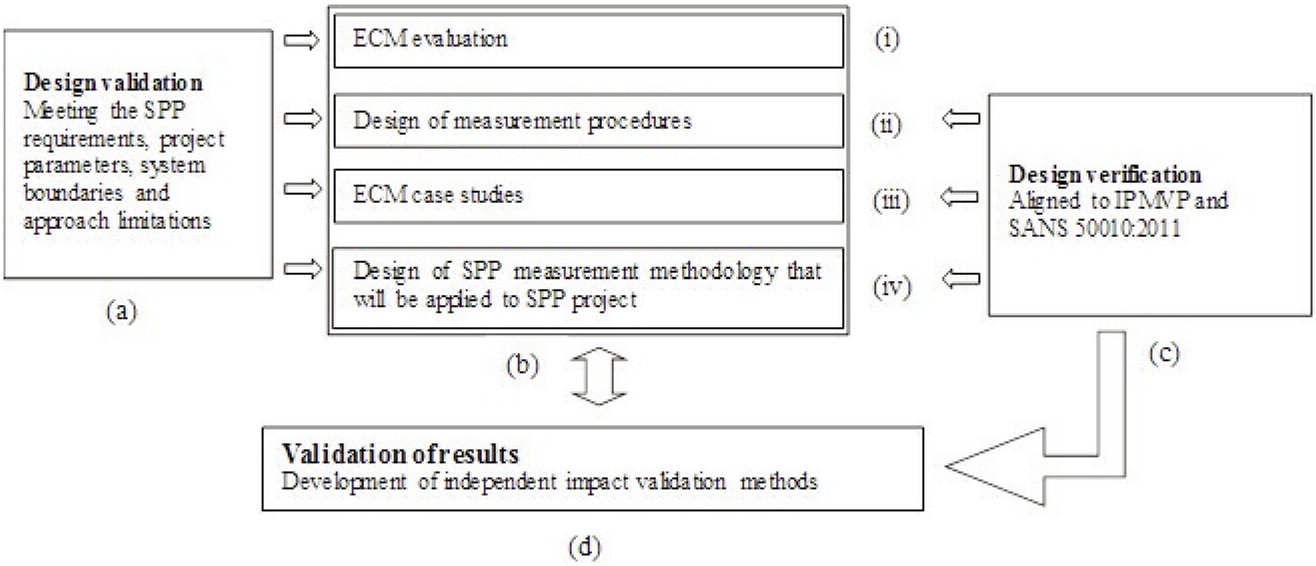

Figure 1: A novel integrated measurement and verification methodology with design validation and verification, with (a) = the design validation; (b) = key concepts of integrated methodology; (c) = the design verification; and (d) = the validation of results.

- design a measurement procedure to accurately apply the aforementioned even when the ECM was already implemented, and no baseline measurements were possible; and
- design a measurement procedure to accurately isolate and quantify the impact of the preferred ECM where other ECMs were also implemented.

Case studies following compartment (iii) of Figure 1(b) were performed to evaluate the actual attainable impacts of the chosen ECMs. Compartment (iv) shows the design of a SPP measurement methodology that includes:

- establish a measurement method to quickly and effectively quantify a conservative but representative load reduction or load shift without profile measurement. Broaden this method for an irrigation pump feeding multiple crop areas and having more than one crop type per centre pivot; and
- establish a functional method to quantify annual conservative but representative energy use impacts of an irrigation pump from the load reduction values. Then broaden the method to an irrigation pump feeding multiple crop areas and having more than one crop type per centre pivot.

Figure 1(a) shows that design validation is done by adhering to the SPP requirements, project parameters, system boundaries and approach limitations. As a design verification in Figure 1(c), all methods and procedures must be aligned with international M&V protocols and standards. Here, the IPMVP and SANS 50010:2011 was applied. Not all the steps are fully discussed in this study because of the size and complexity of the development. Figure 1(d) gives an independent method to validate the SPP M&V methodology and the actual results obtained from ECMs under the SPP. This is further disused in Section 8.

4. The ECM evaluation

Compartment (i) in Figure 1(b) presents ECM evaluation as the first key concept of the integrated M&V methodology. This section considers an ECM evaluation by discussing what ECM technologies can be implemented and how these can be applied to lead to demand reduction and energy saving.

4.1 The ECM evaluation criteria

Since no standard tried and proven irrigation EE technology had been found for the SPP, a study on inefficient irrigation practices and possible ECMs was performed (Storm *et al.*, 2008). It considered what ECMs can be implemented to give measurable and sustainable energy saving over the project life with a high confidence level. The study concluded that pump system design and setup system improvements can satisfy these requirements. The technology chosen to best fit the SPP was variable speed drives (VSDs), through which the pumping system can be optimised to achieve demand reduction and energy saving.

4.2 Application of ECM: How it leads to demand and energy saving

It is important to note that a VSD on its own will not necessarily improve EE. The VSD, however, is a ‘tool’ that enables EE, which is not possible with standard pumping equipment. Figure 2(a) shows a

(a) (b)

Figure 2: Irrigation system. (a) pre-implementation conditions with over pressured centre pivot resulting in fine mist; (b) post-implementation conditions showing significantly reduced fine mist (Storm *et al*, 2013).

centre pivot running in pre-ECM implementation conditions. Generally, it is found that centre pivots are over-pressured, resulting in ineffective irrigation.

In these conditions, the sprinklers create a fine mist, which increases evaporation, thus wasting water and subjecting the pump motor to a higher load by the higher system pressure. In South Africa, it is frequently found that irrigation engineers have overdesigned an irrigation system, especially the older ones. The system can be optimised by reducing the motor speed with a VSD so that the choking valves can be completely opened (Scheepers *et al.*, 2013). The water delivery rate is now controlled by the VSD and no more chocking is required. The pumping system is further optimised by reducing the centre pivot pressure to an optimum level. Figure 2(b) shows less mist is created since the centre pivot pressure was significantly reduced.

This optimal pressure changes the water mist to larger droplets, which have less 'in flight' evaporation (Morris and Lynne, 2006). Since the pump is not chocked anymore and the pressure is lower, a demand reduction as well as EE is realised. The lower pressure also results in less overall water being pumped and less water wasted by evaporation.

5. Design measurement procedures

Compartment (ii) in Figure 1 presents the design of measurement procedures as the next key concept. These design procedures are necessary to quantify the actual attainable impacts through SPP ECMs. The measurement procedures described relate to the conventional M&V methods given in Section 2. Although these methods will not be used in actual SPP M&V project impact projection, they are required in the present study to evaluate what real-world impacts can be achieved. Full M&V is, therefore, used to provide a sampled impact result according to certain project characteristics that can then representatively be applied to other similar projects to ascertain their likely EE impact results.

5.1 Measurement procedure to assess actual attainable impacts

The procedures involved baseline audits through independent validators and proper baseline and post-implementation profile measurements by means of reliable metering, as described below.

Baseline conditions audit

An independent validator is required to visit and assess a pump station and the irrigation system setup before any EE initiatives are considered or discussed with the farmer or any farmers in the region. This can be done through independent audits in an area well before any ECM programme. This is necessary to establish proper baseline conditions without interference. It is important that the baseline conditions may not be influenced for example, any discussion with the farmer might influence him to start operating more efficiently, thus changing the baseline operation. And the moment the typical ECM implementation procedures become available or common knowledge, 'creative savings' may surface through changing the system baseline conditions to run more inefficiently before auditors arrive. It is important during the audit that the exact operational conditions are recorded. This includes different crop areas and circles fed by a specific pump, the valve positions for each pumping scenario, and the operational pressure of each irrigation setting.

Metering installation and verification

Before the ECM is implemented, pump station operational data should be collected, through reliable meters installed on each pump in a station. The correctness of all installations must be verified through calibrated check metering. As an example, a case study of a pump irrigation system with three centre pivots is discussed with the aid of Figure 3, where in Figures 3(b) and (c) the meter installation is verified by using a calibrated handheld and a temporary Fluke power meter.

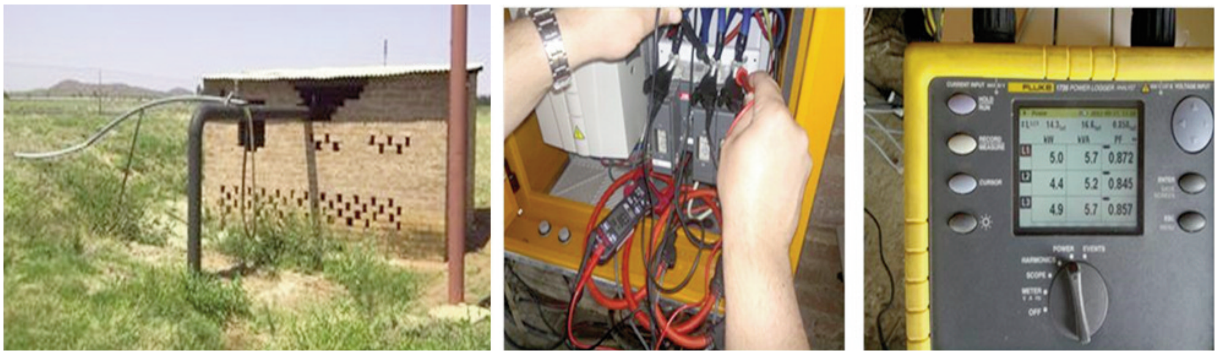

Figure 3: Pump irrigation system: where (a) = case study pump station, (b) = measurements by M&V with a calibrated handheld meter, (c) = fluke power meter measurements compared with M&V meter (Storm *et al.*, 2013).

Baseline measurements
After metering equipment installation verification, full baseline data capturing can be started. For sufficient baseline data, the centre pivots go through the full irrigation cycle. With this, all different pumping scenarios and conditions can be recorded. Figure 4 shows the full cycle pre- and post-implementation demand profiles of one of the case study pump stations. The top line shows a 53-hour full irrigation cycle energy demand profile of the irrigation pump, revealing three distinct operational scenarios: the profile starts at about 37 kW, then drops to about 29 kW for about three hours, and then stabilises to about 36 kW for the rest of the period. These three different demand conditions are caused by the pump irrigating the three different centre pivots. Water supply is moved to specific crops through supply lines by changing valves.

Post-implementation metering
After the ECM was implemented and the system optimised, the same irrigation cycle is repeated with the different pumping scenarios. Figure 4 shows the post-implementation demand profile as the bottom line on the graph, allowing a clear comparison with pre-implementation demand. For most of the irrigation cycle there was a typical 20 kW difference. The shaded area between the two profiles represents the energy demand reduction achieved over the full irrigation cycle.

5.2 Assessment where baseline measurements were not possible

In cases where it was not possible to install temporary baseline metering before the ECM, an alternative approach was required to quantify the attained impacts. A measurement procedure was established for determining impacts when the ECM was already implemented. In these cases, valid information from a proper baseline audit is required as per Section 5.1. The pumping system can be brought to pre-implementation (baseline) conditions by setting the VSD back to 50 Hz and returning pipeline valves to the pre-chocking settings and system pressures, thus essentially 'eliminating' the presence of the VSD. Now baseline measurements can be done and com-

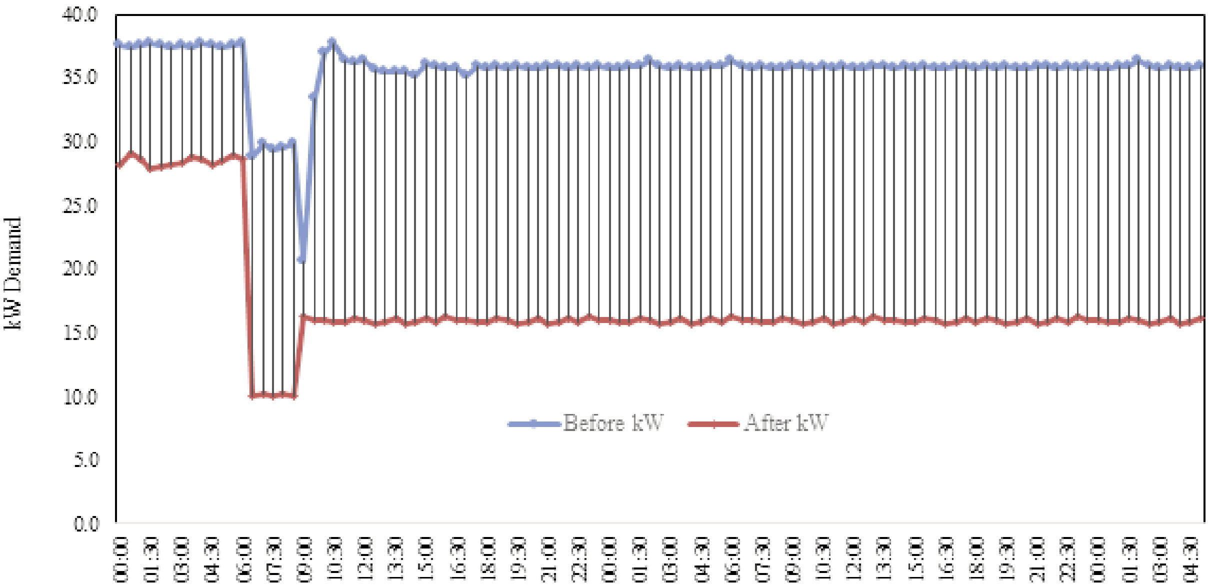

Figure 4: Full cycle pre- and post-implementation electrical demand profiles of the case study pump station (Storm *et al.*, 2013).

pared with post-implementation data to reveal the actual impact. This approach can easily be misused if proper baseline audits were not performed. If baseline audits are not possible, historical data for three months to a year is needed before any ECM implementation is required for suitable M&V. This historical data can be obtained from utility point-of-use profile power metering. From this data, the baseline conditions can be verified. Smaller utility points are, however, not always equipped with profile power meters, but rather with cumulative energy consumption disc meters in kWh. In these situations, additional baseline metering may be required.

5.3 Assessment where other ECMs were also implemented

In the case where other ECMs were implemented with the VSD, a similar approach to that described in Section 5.2 can be followed to accurately isolate and quantify the impact of the VSD. Other ECMs may include an EE pump motor or pipeline efficiency improvements. Comparing the results from proper baseline measurements with the post-implementation results gives the demand reduction due to the VSD and other ECMs. Repeating the method of Section 5.2 and comparing these results with the post-implementation results produces only the impact of the VSD, however. This essentially isolates the VSD impact and excludes the efficiency contribution of other ECMs. With some ECMs, like pipeline efficiency, the exact baseline conditions may not be achieved by applying Section 5.2's method. The pipeline efficiency may result in a lower operational demand with the same baseline valve positions and operational pressure. With both Sections 5.2 and 5.3, it should be noted that M&V is not an exact science and the aim is to quantify representative and conservative savings as prescribed by the IPMVP and SANS 50010:2018.

6. Case studies of actual attainable impact

Case studies were done on 19 VSDs installed on five farms in different areas and provinces. The aim was to quantify the actual attainable demand impacts through metering. The measurement procedures of Section 5, with other newly developed methods, were carried out at several sites to assess and verify demand impacts. Figure 3 shows some of the pump stations assessed during the case study. The line designated 'before' in Figure 4 shows the baseline profile and 'after' the post-implementation profile, where a significant demand reduction can be observed.

6.1 Operational power demand reduction results from case studies

An overall representative electrical demand reduction for the irrigation pump can be calculated from the profile measurements described in Section 5. This was done to portray a single figure of the attainable demand reduction impact of the 19 case study pumps. The profile measurement method of Section 5 was, however, too costly and impractical to use for all of the case study pumps and an alternative measurement technique was required to obtain demand reduction values for some of them. Section 7.1 describes a simple method that was designed for the irrigation SPP to establish a representative but conservative load reduction value. This technique was used to establish the instantaneous demand values given in Table 1, which summarises the pre- and post-implementation demand measured at each case study site, with the actual demand reduction.

The first column in Table 1 (overleaf) lists the test site, while the second gives the pump station name and the installed capacities of the irrigation pump motors. The next two columns show the before and after ECM instantaneous kW, while the kW and percentage demand reduction are given in the last two columns. The lowest demand reduction, 7.1%, was experienced at Farm 4 and the highest, 71.6%, at pump station P17 on Farm 1. The demand reductions measured were not related to the time of day they occurred (such as during peak periods), as the focus was solely on the attainable demand reduction. Taking all 19 sites into account, the average demand reduction achieved was 42.2%. For all measurements, the pre- and post-implementation conditions were kept the same. This is clear evidence of a definite and significant demand reduction. With project circumstances considered, it can be safely concluded that the implementation of a VSD to optimise the irrigation system can lead to real, tangible and significant demand reductions. The achieved demand reductions will directly result in energy consumption saving and, in most cases, water saving as well, as a result of water usage optimisation.

An important aspect that can be addressed in future studies, however, is to establish a method that can also determine the time of day when demand reduction occurs. This would be valuable, as the contribution the SPP irrigation ECMs demand reduction makes over the Eskom peak usage periods could also be determined.

6.2 Further assessments

The 19 pump stations were not the only pumps engaged by the energy advisors, although these were the only ones independently verified. A total of 46 farms and farm sections formed part of a large testing study over South Africa. With collaboration between M&V and the energy advisors a standard site M&V evaluation criterion, as for the 19 pump stations, was agreed upon to be used for all other farm pump stations. Very similar demand reduc-

Table 1: Achieved operational power demand reductions on 19 pump stations (Scheepers *et al.*, 2013).

Test site	*Pump station and installed pump*	*Instantaneous demand measured* *kW before*	*kW after*	*kW reduction*	% reduction
Farm 1	P36 (30 kW)	36	16	*20*	*55.6*
	E4 (30 kW)	27.5	11.3	*16.2*	*58.9*
	E40 (55 kW)	54	42	*12*	*22.2*
	E40 (30kW)	23	13	*10*	*43.5*
	P1 (30 kW)	34.4	14.7	*19.7*	*57.3*
	P1 (30 kW)	32	16.9	*15.1*	*47.2*
	P17 (22 kW)	25.7	7.3	*18.4*	*71.6*
	P17 (75 kW)	66.8	30.8	*36*	*53.9*
Farm 2	DP (110 kW)	99	53.2	*45.8*	*46.3*
Farm 3	75 kW	74.9	50.7	*24.2*	*32.4*
	75 kW	62.4	40.8	*21.6*	*34.6*
	75 kW	61.7	44.1	*17.6*	*28.5*
Farm 4	37 kW	38.1	35.4	*2.7*	*7.1*
Farm 5	P1 (30 kW)	46.8	28.8	*18*	*38.5*
	P2 (30 kW)	51	25.3	*25.7*	*50.4*
	P3 (30 kW)	68.7	33.5	*35.2*	*51.2*
	P4 (30 kW)	46.4	31.4	*15*	*32.3*
	P5D (30 kW)	45.8	33.7	*12.1*	*26.4*
	P6 (30 kW)	44.6	25	*19.6*	*43.9*

tions to those found for the 19 pump stations were obtained (Storm *et al.*, 2008).

The savings presented in Table 1, and those of the other 37 pump stations, can only be used as a guide on what can possibly be achieved and not as a national or area-specific representation. The pump stations used did not undergo proper statistical sampling (Carstens *et al.*, 2014; IPMVP Committee, 2012; Xia and Zhang, 2013; UNFCC CDM Executive Board, 2012) and were assessed as projects were implemented and evaluation sites became available. For a national or area-specific representation a thorough statistical model needs to be developed, one which considers all factors and variables. Therefore, no area representative confidence level and error margin can be tied to the findings.

In order to establish a national or area-specific representation, a proper M&V cost and accuracy model can guide decisions on how to approach this. Unfortunately, with accuracy the associated M&V cost rises significantly. With the healthy M&V practice of always reporting on conservative savings, incentive programmes can compare M&V accuracy and cost with the additional incentives that can be claimed. As with the M&V of normal irrigation projects, in some cases, even a 50% confidence level may be acceptable, depending on the overall reporting objectives and the value of the savings involved, according to Steyn (2014). Here the claimed savings will inevitably only be a conservative 50% of what was measured. Although it may not appear ideal, this approach may provide sufficient M&V for publicly funded incentive programmes, but simultaneously enable projects which may not have been possible before due to high M&V costs. Here the M&V methods described in the present study are ideal. A critical aspect of M&V that requires more attention, on any type of ECM programme, is metering and data-gathering equipment. In many cases, the costs of these are so high that it is often more than the rebate from the incentive programme. An accurate but cost-effective data-gathering system and approach is required for such projects.

7. Design of a SPP measurement methodology

Section 5 described the design of measurement procedures to quantify the actual measured impacts of SPP irrigation ECMs. In Section 6 these procedures were applied to case studies, where the focus was to assess and quantify the real world impacts resulting from the installation of VSDs on irrigation pumps. Here, measurement practices related to conventional M&V methods were applied. However, the SPP cannot financially justify such extensive measurements on all projects and a simplified standardised assessment method is required to establish attainable demand, and therefore energy consumption, reduction.

7.1 Establishing a simplified assessment method for demand reduction

A method needed to be established for the SPP to measure a conservative, but representative load reduction, without profile measurement. With centre pivots, a conservative approach is to let the centre pivot turn till it reaches the lowest elevation point on the crop circle (Steyn *et al.,* 2013), which requires measurements of a baseline instantaneous demand. This lowest point is the location where the irrigation pump demand is the lowest since the static head is effectively the lowest. These measurements are repeated after the ECM implementation and the results can be compared for the demand reduction. The impact calculated becomes the lowest possible saving that is still attainable. With centre pivots on severely angled crop circles, multiple measurement points may be considered. Crops under micro or sprinkler irrigation have a constant static head and instantaneous measurements can be taken any time after the system stabilised after pump start-up. Irrigation pumps that irrigate multiple crops, as in Figure 4, require a separate assessment for each crop type. A load reduction for each crop is determined.

7.2 Assessment method for annual average demand and energy consumption reduction

Determining the annual energy reduction under the SPP is a difficult study, since the SPP does not allow continuous measurements and the energy consumption saving needs to be determined for a specific crop in a specific area. Without continuous measurement, several other aspects may need to be considered when determining the energy and average demand reduction. These aspects can include:

- location, climatic region and typical annual rainfall;
- crop types: irrigation of summer and/or winter crops, more than one type of crop during a single season;
- irrigation methods and soil type; and
- is water allocation/registration active in the area?

The best approach found was to incorporate crop load factors (Scheepers *et al.*, 2013), through which representative irrigation requirements for a crop were established. Crop water requirement is one of the most important aspects to consider for irrigation efficiency since it is a vital part of agricultural planning (Reddy, 2015). Allen *et al.* (1998) define crop water requirement as: ‘the depth of water needed to meet the water loss through evapotranspiration (ET_{Crop}) of a disease-free crop, growing in large fields under non-restricting soil conditions, including soil water and fertility, and achieving full potential under the given growing environment’.

Crop water requirement is a well-studied field and software programmes are available to assist farmers in determining it. An example of this is CROPWAT (Banik et al, 2014) and the South-African SAPWAT (Heerden *et al.*, 2016), which is based on (Allen *et al.*, 1998) using the CLIMWAT (Tegos *et al.*, 2017) weather database comprising of 3262 weather stations from 144 countries. For the SPP the software program SAPWAT was utilised; among many other aspects, it incorporates 50 years of weather data to calculate a load factor for a specific area and crop type.

From the crop load factor, irrigation system setup and ECM load reduction, the annual energy consumption saving with the annual average demand reduction can be estimated. This can be strategically broadened to an irrigation pump, feeding multiple crop areas and having more than one crop type per centre pivot. However, independent M&V assessment of these crop factors was critical to prevent biased or unrepresentative values. A whole alternative method was developed and a study performed to independently evaluate and verify crop load factors calculated for certain areas (Storm *et al.*, 2013). This study involved determining the real-world crop load factors of hundreds of irrigation pumps stations over a four-year period. This massive undertaking is beyond the scope of the present study, but the results showed that the calculated crop load factors were indeed representative and conservative.

8. Validation of methodology through actual electrical grid impacts

A critical question: what is the actual reduction the electricity grid experiences due to these ECMs? Although ECMs will result in probable short-to-medium term (one to three years) representative reductions, the question is how these impacts will be sustained over longer periods. Also, from other types of EE projects evaluated, it emerged that sometimes re-appropriation effects diminished the real attained savings. An example of this is Eskom residential EE projects and CDM projects (Pandaram, 2006; UNFCCC CDM Executive Board, 2010). Once a homeowner realised that ECMs such as a SWH, geyser switch, geyser blanket or EE lighting reduce the electricity bill, the tendency is often to use more electricity on other household appliances, making up the original electricity cost budget, thus, effectively cancelling any attained savings – though with lifestyle improvements.

Normal M&V models do not actively capture this effect since the measurement boundary is only around the equipment part of the project scope and only direct interactive effects with other technologies are monitored. Here, CDM methodologies have additional methods and calculations to account for re-appropriation effects such as leaking and free riding (United Nations Framework Convention on Climate Change Clean Development Mechanism Executive Board, 2010).

It is imperative that programmes such as the SPP must have regulation to avoid re-appropriation effects. Old, ineffective equipment must be collected and destroyed or they will only be used at another place.

A method is required to quantify what the actual impact of ECMs is on the electrical grid. In 2006, there was a massive implementation of accelerated DSM initiatives in the Western Cape province because of a 400 MW supply shortfall (Storm *et al.*, 2009). A top-down M&V methodology was developed and successfully executed to assess the regional demand impact as seen on the electrical grid. Data was gathered from strategic measurement points on regional transmission and distribution power supply lines. The M&V methodology accounted for the following key aspects:

- average day type demand profiles with temperature adjustments;
- electricity sales growth and demand market participation;
- supply losses, municipality curtailment and load shedding; and
- leased generation, fuel switching, power export and open point shifts in electrical distribution networks.

Strategic measurements were made on the electrical network to isolate key areas effected by ECMs. Measurement data was collected from existing power utility grid meters. Care was taken, since electrical network configuration can chance through shifted open points, which in turn may affect measurement data at certain places (Dalgleish, 2009). A similar approach can be applied to isolate and assess the impacts of regional irrigation ECMs. Through the distribution networks, key high voltage lines than mainly feed irrigation areas or regions can be identified. Power lines which may tap off and feed industries or towns can also be measured so that these can be subtracted from the totals. The model can be refined through moving down to low voltage customer billing utility meters to remove a farm's loads that are not used for irrigation. This is limited to points with utility profile metering. Data extraction can be done in cooperation with utility grid control centres. From historic data, periodic baselines (monthly for instance) can be developed and baseline adjustments fixed.

9. Conclusions

Eskom's Standard Product Programme (SPP) has unique M&V requirements, which make normal M&V approaches inapplicable. The biggest challenge is the absence of continuous metering while still requiring representative and accurate results. A new and unique M&V methodology was designed to quantify energy conservation method impacts under the SPP and other similar incentive-based programmes. This new methodology was used on several pilot sites and proved to be functional, giving the required operation electrical demand reduction values required. These values provided clear evidence that the implementation and use of a variable speed drive to optimise the irrigation system can lead to real, tangible and significant demand reductions. By incorporating crop load factors with the demand reduction values established, representative annual energy consumption and annual average demand reduction impacts were also successfully established. These impacts were validated and verified through an independent cross-check measure which showed that the values obtained were indeed representative and conservative.

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Journal of Energy in Southern Africa

Volume 29 Number 3

Evaluating complex mine ventilation operational changes through simulations

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Abstract

Increasing the profitability of the mining industry is contingent on its ability to improve operational efficiency. Mine ventilation networks typically represent 25-50% of a mine's energy consumption and, therefore, exhibits scope for optimisation. Ventilation networks comprise numerous complex integrated airways, branches and ventilation fans. The most effective way to optimise and evaluate them is computer-aided simulations. However, no framework exists to clarify exactly how operational changes in ventilation networks should be evaluated. In this study, a scalable method was developed, implemented and analysed. The case study validation resulted in satisfying key performance indicators of both service delivery and operational energy costs, thereby increasing operational efficiency. The significance of the novel method is that it allows for improved operational decisions on mine ventilation networks. The value of the method was illustrated by the adoption of the method by the case study mining personnel to form the new norm of their procedures and standards.

Keywords: *Mining, optimisation, sustainable cost saving*

Highlights

- *Mine ventilation operational changes optimised and evaluated through simulations.*
- *Scalable method.*
- *Additional non-energy benefits.*

Journal of Energy in Southern Africa 29(3): 22–32
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a4445

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Technology

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1. Introduction

Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [1]. This is done by supplying sufficient airflow to the working areas to govern heat stress imposed on workers and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [2]. However, the dynamic nature of deep-level mining means that the engineering challenges faced include contending with ever-higher virgin rock temperatures because of increased depth, requiring more complex ventilation networks [3]. The costs associated with providing acceptable working conditions for reserves that are further and deeper away from ventilation shafts become a critical determinant of the feasibility of continued mining [2]. Operational efficiency is, therefore, the main contributing factor to increasing mine profitability, as shown by the industry's drive to improve upon the status quo [4, 5]. In modern mining, there has been a move towards adopting technological advances, to which the rapid development and increased production targets could be attributed [6]. Mines are, therefore, expanding operations vertically and horizontally to achieve these production targets in the most cost-effective manner possible. Research indicates that electricity is among the factors with the largest potential to increase operational efficiency on mines [7], so lowering the potential future cost of electricity is critically important.

Considering mine ventilation systems represent 25-50% of the energy consumed in a mining operation, large potential exists to realise electrical cost savings through optimisation [4, 8]. Typical backward-curved airfoil centrifugal fans employed on deep-level mines as main ventilation fans have installed capacities ranging from 500 kW to 2.1 MW per fan [4, 9]. Mine ventilation systems consist of hundreds of interconnected sections and applications, such as airways, raises, crosscuts, main shafts, ventilation shafts, sub-shafts, raise boreholes, ventilation doors, travelling ways, fans and regulators [8]. In view of the complexity of the system and mine development, it is easy to understand that inefficiencies such as short-circuits, insufficient air velocities, increasing temperatures and leakages will occur [1].

Mine ventilation networks are required to comply with occupational health and safety standards and regulations specified by the host country. In South Africa, two important factors affecting the operations of mine ventilation and subsequent working environments are the wet-bulb temperature (T_{wb}) and air cooling power (ACP) [10]. Legislation stipulates that work should not proceed underground when $T_{wb} \geq 32.5$ °C or the dry-bulb temperature (T_{db}) ≥ 37 °C [3, 10, 11]. Additionally, the ACP should be 300 W/m^2 as a minimum for acceptable working conditions [3, 10, 12].

Because of constrained resources, operational changes are not regularly and thoroughly evaluated on these complex systems in deep-level mines [9, 13]. Furthermore, decisions are often made with limited information, which increases both risks and likelihood of project failures. Consequently, deep-level mines require a reliable, scalable method to evaluate complex mine ventilation operational changes according to key performance indicators such as cost and service delivery [13].

1.1 Modelling and simulation of mine ventilation networks

Substantial research indicates that complex systems can only be thoroughly evaluated with the use of simulations [13, 14, 15, 16]. With the arrival of the digital age, simulation technologies have been incorporated to design large and complex mine ventilation networks [4]. To provide accurate results, these simulations nevertheless require an abundance of dedicated resources that are both labour-intensive and time-consuming [17]. Recent technological advancements coupled with innovative methods may, however, enable mines to evaluate operational changes more accurately and cost-effectively, resulting in improved decision-making capabilities. Several researchers have addressed techniques to model and optimise sections of mine ventilation networks [4, 16]. Acuna and Lowndes (2014) conducted a review of such studies, showing that there is still a knowledge deficit in addressing the effects of both cost and service delivery in ventilation optimisation techniques [16]. The techniques used in industry do not incorporate simulations, but include tedious manual calculations [16]. These techniques do not take the holistic effects of operational changes into account, but are narrowed to only consider single service delivery parameter evaluations [13].

Computational fluid dynamics simulation was used to optimise axial flow ventilation fan blade profiles [18]. This method holds promise for further research on airfoil and centrifugal ventilation fans in particular, but it is limited to component design and cannot be applied to optimise the branches of complex ventilation networks. Chatterjee developed a ventilation-on-demand (VOD) optimisation model that exploits the cyclical nature of mining to reduce ventilation fan-operating costs [19]. This model determines the optimal fan operating speeds during each hour of a day by considering the time-of-use electricity tariffs [11]. Although the premise of the model is well founded, it does not develop VOD methods that include network optimisation and inclusion of other techniques to achieve an integrated solution.

Various mine ventilation simulation packages are available for initial mine planning and design [15, 16], but none of them are used for optimisation or evaluation studies [16, 20]. Many mines in the private sector do not optimise or evaluate operational changes at all [11]. These mines typically implement operational changes to continue with mine development without regard to ventilation, until stopped by law or ventilation-related accidents [20]. This emphasises the need to optimise and evaluate operational changes through simulations. New methods to lower the costs associated with analysing mine ventilation networks (such as simulation and optimisation) could encourage adoption within these mines.

In the 1960s, ventilation simulation packages incorporated the simple laws of incompressible flow for Newtonian fluids [20]. However, with the large variation in air density experienced in underground mines, these packages became obsolete. In the 1970s, mine ventilation simulation packages were developed to include the thermodynamic relationships for Newtonian fluids [21]. This principle forms the basis of most modern ventilation simulation packages, which utilise the thermodynamic principles, fluid dynamic properties and network mass balances, typically of fluids such as air, to simulate actual ventilation networks [13, 20].

Modern simulation packages have varying degrees of complexity and accuracy [16], which should make a flexible, cost-effective simulation package based on the nature of work desirable [13]. The scalable technique used in the present study satisfied this need by providing a means to select and use a ventilation simulation package to optimise and evaluate operational changes. This method has the potential of allowing for decisions that can improve operational efficiency and safety, while ensuring legal compliance.

1.2 Mine ventilation optimisation

Typically, in hard-rock mining, there are two critical mining shifts to be considered in ventilation optimisation [22]. The first is the drilling, charge-up and blasting shift and the second the loading shift (when broken rock is removed from production faces) [17]. The complex ventilation network is used to ventilate the underground working areas during these shifts, in order to ensure compliance with health and safety standards [3]. There is also a shaft clearance period between shifts, during which the hazardous particulates (toxic blasting gases and dust) are diluted and exhausted by the ventilation network.

Conventionally, after the drilling shift, miners retreat from the production face to the main shaft haulage area where fresh air intakes are available until the clearance period has subsided or the miners have left the mine [9, 17]. Even though mining is conducted on a cyclical basis, maximum ventilation is typically supplied during all operating hours [9]. Only in recent studies have techniques such as ventilation on demand prompted crucial questions regarding true ventilation requirements during each hour of a day, exploiting the cyclical nature to lower operational costs [9, 11].

It is clear from literature that simulation is a viable technique to optimise and evaluate complex mine ventilation networks [8, 13, 16], but most packages are only used to evaluate either cost or service delivery during initial mine planning [9]. These key performance indicators are seldom considered simultaneously, especially when operational changes are to be implemented on a mine ventilation network. Simulation packages are therefore not used to optimise or evaluate operational changes [20]. Other techniques have been presented in literature to optimise mine ventilation networks [4, 16]. Conversely, none of the reviewed techniques provided a single framework or method that describes the process of optimising and evaluating operational changes through simulations. The present study aims to satisfy this deficit by developing an innovative scalable method to describe how operational changes should be evaluated and optimised through simulations.

2. Methodology

In this section, the newly developed scalable method, as shown in Figure 1, was applied to a mining complex. Please refer to the supplementary information for model development.[1] The method is shown in a step-by-step manner to show the significance of each step from A to I.

The ventilation network of a typical deep-level South African mining complex was selected as a case study. Due to confidentiality agreements the complex is referred to as DK. At DK, narrow-reef conventional mining is conducted at a depth of ± 1.9 km, focussing on the south reef ore body. The operation has one production shaft, which acts as the main downcast intake shaft (fresh air enters the ventilation network), and one up cast vent shaft (return air is exhausted after ventilating the working areas). DK also has a sub-vent shaft on the northern side and is interconnected with another mine, CK on two levels namely, 90L and 106L with twin airways. Next to DK's main downcast intake shaft, is an up cast vent shaft, DK1A. This illustrates the complexity of mine ventilation systems.

DK vent shaft is installed with two 2.1 MW Fantecnic (Howden) WBF-390 main surface ventilation fans. Currently, both of these ventilation fans are operating to ensure that conditions are conducive to safe and legal mining. DK1A vent shaft is installed with three Artec Davidson main surface ventilation fans, two having an installed capacity of 1.01 MW and the other 1.3 MW. Currently, only one of the 1.01 MW rated ventilation fans is operational at DK1A vent shaft.

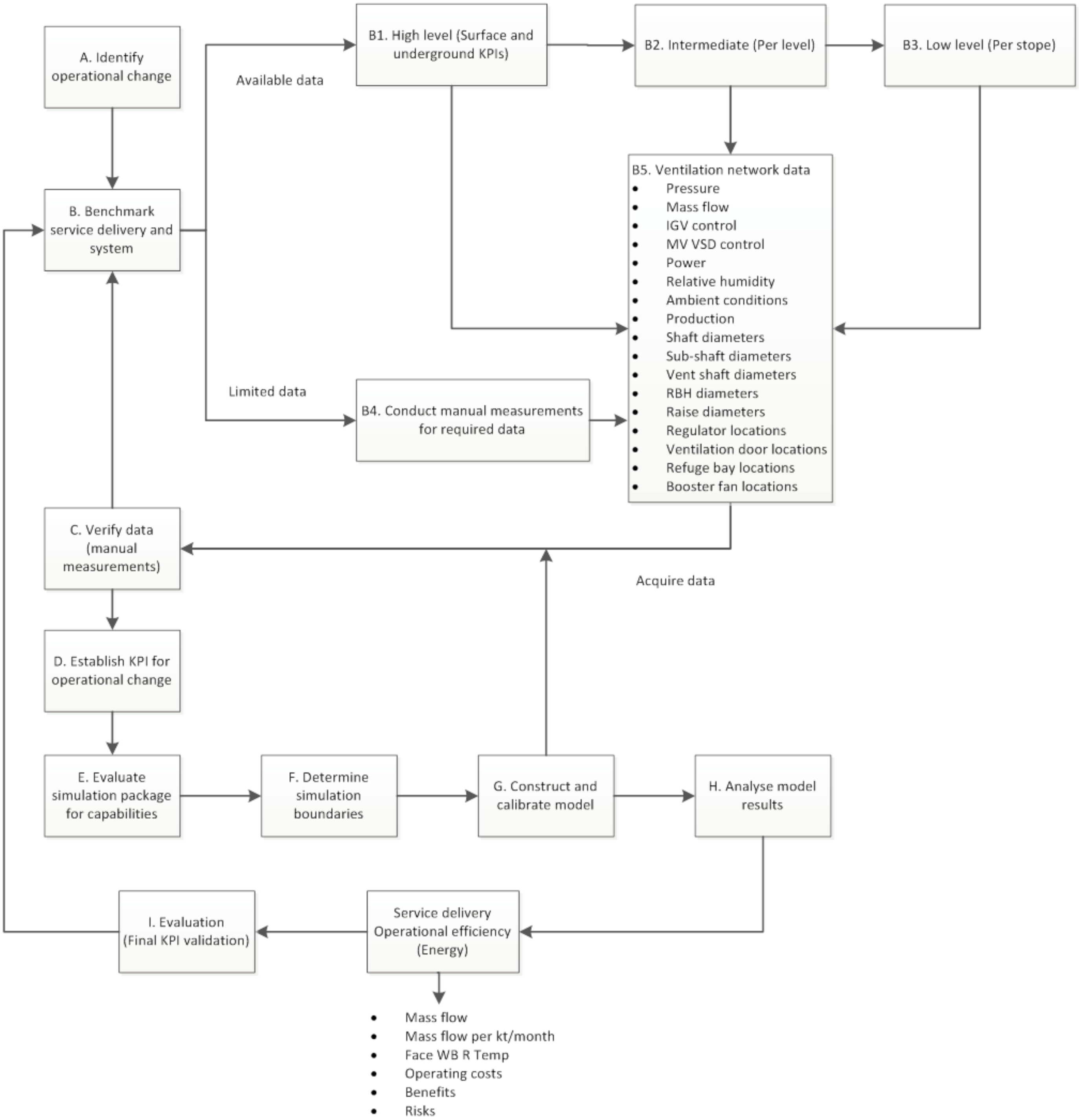


Figure1: Newly developed scalable method for mine ventilation networks.

The case study mining complex started to experience temperature constraints on the main production levels, 192L, 197L and 202L, which comprises the south reef section. The increasing temperatures were as a result of mine development. Mine personnel had to mitigate the increasing temperatures by implementing an operational change on the ventilation network. However, there were many operational changes available for implementation and mine personnel were challenged to determine the most feasible option. As a result, there was a need to apply the scalable method to address their problem and determine the most feasible option.

2.1 Operational changes (A)

As part of the scalable method (**A**), nine operational change scenarios were identified to be optimised and evaluated. Each operational change was simulated separately, but the simulations have similarities and three groups were considered, namely group 1 (scenario A to C), group 2 (scenario D to H) and group 3 (scenario I). The different operational change scenario groups are displayed in Figure 2. The operational changes were different for each scenario, and these differences are highlighted in the discussion below.

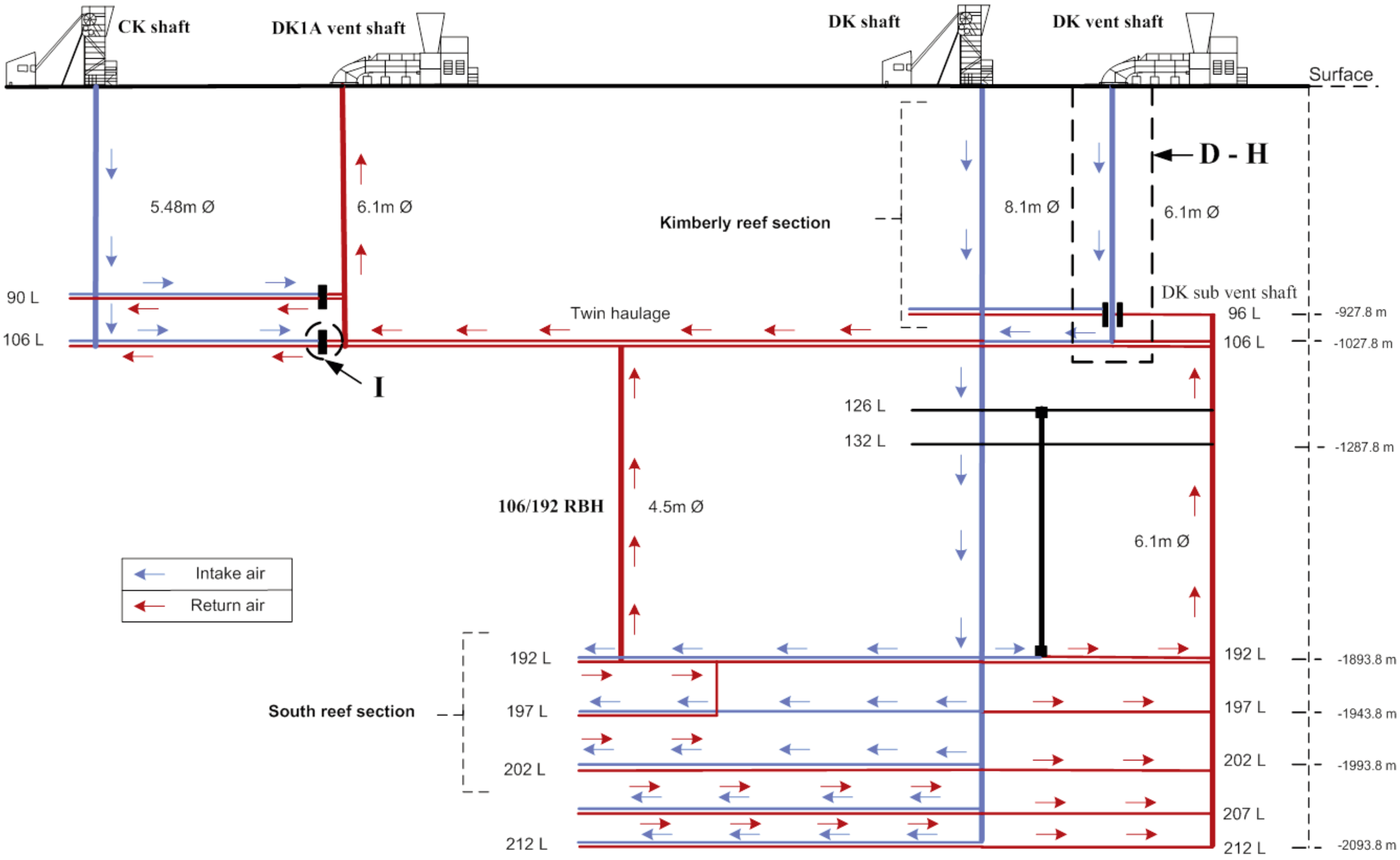
Group 1 (scenario A to C), DK vent shaft was converted to a down cast shaft and the return from CK to DK1A closed off, converting DK1A to the main up cast shaft. In scenario A, both the 1.01 MW ventilation fans and the larger 1.3 MW ventilation fans were operating at DK1A, with no fans operating at DK vent shaft. In scenario B, the two 2.1 MW ventilation fans originally situated at DK vent shaft were moved to operate at DK1A. In scenario C, the operating fan configuration was the same as in scenario B but the airway between DK and the 106/192 RBH was enlarged.

Group 2 (scenario D to H), DK vent shaft was kept as the main up cast shaft while only operating one of the 2.1 MW ventilation fans. This operational difference is indicated by the dotted rectangle in Figure 2. The fresh air intake for group 1 therefore changes to a return airway for group 2. Additionally, the returns from CK to DK1A were closed and DK1A utilised as the second up cast shaft for DK operations. In scenario D to H, one 1.01 MW ventilation fan and the larger 1.3 MW ventilation fan were operating at DK1A. In scenario E, the RBH diameter was enlarged from 4.1 m to 4.5 m. In scenario F, one of the twin airways between the RBH and DK1A was enlarged on 106L from 11.25 m^2 to 20 m^2. In scenario G, two 1.01 MW ventilation fans were operating at DK1A, and one of the twin airways was enlarged (as discussed for scenario F). In scenario H, both 2.1 MW ventilation fans were operating at DK vent shaft, with only the 1.3 MW ventilation fan operating at DK1A.

Group 3 (scenario I) is shown in Figure 2. DK vent shaft was kept as the main up cast shaft, as in the case of group 2. However, a maximum return air mass flow of 150 kg/s was maintained from CK to DK1A. The air mass flow control point is indicated by the dotted circle in Figure 2.

2.2 Benchmark (B)

The methodology was implemented on a low level for the purpose of the study to illustrate the scalability and accuracy possible with the use of simulations. As part of the methodology (B), the ventilation network operations of the mining complex were benchmarked to include detailed data on a per stope basis. This included acquiring ventilation network data from the mine such as air mass flow, temperature, relative humidity, pressure, area and tons of reef mined on a per stope basis (B3, 5). Any missing data was manually measured with calibrated measuring equipment on a per stope basis as part of the methodology (B4).



RBH = raise bore hole; Ø = diameter; L = level; D-H = group 2; I = group 3.

Figure 2: Operational change scenario A to I

2.3 Data verification (C)

The acquired data was verified (**C**) with manual measurements to ensure the accuracy of the data and subsequent simulation. Considering the latest life-of-mine plan, it was determined that the highest production rate planned for the specific mining complex was ±120 kilotons (kt) per month. In South Africa's deep-level mines, the average typical volumetric flow range is 3–6 m^3/s per kt of rock mined per month or 0.12 m^3/s per ton mined per day[17]. For this study, an average air mass flow of 4 kg/s was presumed to be sufficient in order to maintain production face wet-bulb temperatures of ±29.5°C for the south reef sections.

2.4 Key performance indicators selection (D)

The key performance indicators (KPIs) that were selected for the case study are shown below, categorised according to the data types (D):

- Service delivery KPIs – wet-bulb temperatures, air volumetric flow, air mass flow, air pressure.
- Operational KPIs – energy, maintenance.
- Technical KPI – air mass flow per kiloton production planned per month.

It was crucial to select applicable KPIs relating to the objective of the evaluation, as they form the basis on which the simulation and subsequent evaluation results were analysed. For this study, the aim was to improve the operational efficiency of the system, thereby reducing the energy costs while satisfying the service delivery requirements. Therefore, in terms of service delivery, the wet-bulb temperatures had to be within acceptable limits and the energy costs had to be kept as low as possible. Ultimately, the selected KPIs would indicate the success of the newly developed methodology, by comparing the pre- and post-implementation effects of the KPIs.

Based on this, the detailed simulation KPIs for the case study were determined and prioritised to be:

- Maintain production face return wet-bulb temperatures of ±29.5°C for the south reef sections.
- Optimise each operational change scenario for increased operational efficiency.
- Determine the suitability of existing infrastructures. Referring to existing main ventilation fans situated at DK vent shaft and DK1A vent shaft, minimum and maximum intake and return airway dimensions as well as the 106/192 RBH dimensions.

2.5 Software selection (E)

Commercially available simulation packages were evaluated (E) and a package incorporating a thermal hydraulic solver was selected to meet the detailed, per stope, simulation capabilities. Vuma 3D, a simulation package specifically designed to model complex mine ventilation networks, was already available on site and proved adequate.

2.6 Simulation boundaries (F)

The next step in the methodology was to determine the ventilation network boundaries per KPI, as defined per data type category (F). At that time, the air handling capacity of DK was limited by the main down cast shaft for a maximum down cast volume of 600 m^3/s, at an air velocity of 12 m/s. The collective up cast volume capacity of DK vent shaft and DK1A vent shaft was estimated at 1000 m^3/s. Previous studies indicated that a minimum airflow volume of 470 m^3/s was required to effectively ventilate the south reef sections. Since no mining was planned for the Kimberly reef sections, above 106L, it was excluded from the critical KPI simulation boundaries. The most critical simulation boundaries were established from the acquired data, as shown in Table 1.

Table 1: Critical KPI simulation boundaries.

Simulation boundaries	*Parameters*
Surface temperatures [°C WB/DB]	18/28
DK main shaft diameter [m]	8.1
Main intake and return airway [m^2]	11.55 (3.5 x 3.5)
Intake airway velocities [m/s]	6 – 8
Main return airway velocities [m/s]	10 – 12
Design air density [kg/m^3]	0.95
DK vent shaft diameter [m]	6.1

WB = wet bulb; DB = dry bulb

2.7 Simulation calibration (G)

As part of the method (G), the simulation was constructed for the complex mine ventilation network by incorporating the acquired data per stope and simulation boundaries. The simulation was iteratively calibrated by comparing the actual verified dataset with the simulation results on a per stope basis. Therefore, referring to Figure 1, the actual and simulation data for 192L's stope 5 west were compared. The simulation was therefore constructed to include all nodes where actual verified data were available or measured. The actual and simulated data showed an overall resulting correlation of 8%. The identified operational change scenarios were then simulated individually, to be optimised and evaluated.

2.8 Simulating operational change analysis (H)

The different operational change scenarios were simulated and optimised. Conforming to the method (H), the results were analysed according to the KPIs of each data type category. Each operational change scenario had to satisfy the service delivery and operational efficiency KPIs. Figure 1 shows the south reef section where the temperature constraints were experienced as a result of mine development, indicated by 192L, 197L and 202L. The air mass flows were therefore critical on these levels to mitigate the effects of the increasing temperatures. The south reef air mass flow is defined as the sum of the air mass flows on the main production levels before the air is returned through the up cast sub shaft and 106/192 RBH. The simulation air mass flow results for each of the scenarios are shown in Table 2.

Table 2 indicates that all of the operational change scenarios satisfied the air mass flow requirement. However, in order to evaluate and optimise the operational change scenarios, the service delivery constraints had to be satisfied and adhered to by each for all the KPIs. Furthermore, it was critical that the ventilation network resulted in wet-bulb temperatures conducive to safe and legal mining operations as this was the most important KPI [3]. All the simulation scenarios were therefore analysed to satisfy and maintain production face return wet-bulb temperatures of ±29.5°C.

The average production face wet-bulb return temperatures of the simulation scenarios are illustrated in Figure 3. The average standard deviation between the nine simulation scenarios was calculated as. As a result of this small standard deviation, one can conclude that each scenario satisfied the most critical service delivery KPI.

2.9 Evaluating operational changes (I)

Following the satisfaction of the wet-bulb temperature KPI, the evaluation of the individual operational change scenarios commenced (I). The evaluation was done according to the specified KPI categories. The individual operational change scenario's average face wet-bulb return temperatures, indicated by the bar chart, and air mass flows, indicated by the line chart, are illustrated in Figure. 4.

On first inspection, the results of the operational change scenarios showed that scenarios A, B, C and G had the lowest average face return temperatures displayed in the bar chart. The simulation results thus indicated that these scenarios were the most sensible operational changes for future mine development to contend with the increasing rock-face temperatures experienced on the south reef section. However, as part of the method, the other KPIs must also be satisfied and evaluated. Hence, considering the average simulation air mass flow design of 4 kg/s for a typical deep-level South African mine, scenario A, D, E and G had the closest correlation results. These scenarios therefore ensured that sufficient air mass flow was provided to satisfy future production requirements.

At that stage in the method, further analysis was required for the ventilation network to evaluate the operational change simulations in an integrated comprehensive manner. The next step in the method was to consider the KPI of operational efficiency, by evaluating the operational change scenario energy costs indicated by the bar chart, and total air mass flow indicated by the line chart, as illustrated in Figure 5. The energy cost for the case study was determined for each operational change scenario by multiplying the ventilation fans' energy consumption in kilowatt-hours for each scenario

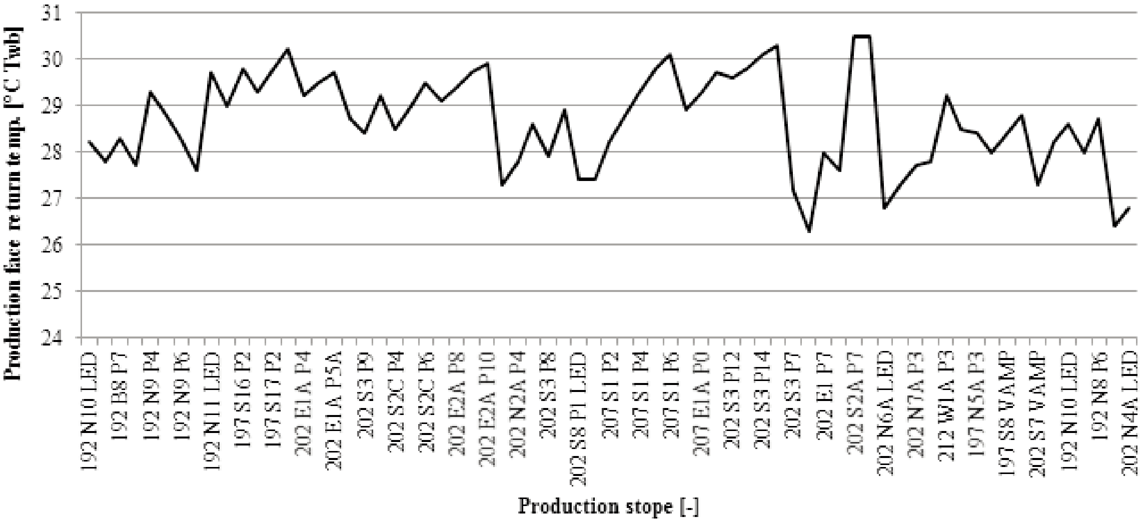


Figure 3: Average production face return wet-bulb temperatures per stope.

Table 2: Operational change scenario south reef air mass flow simulation results

Scenario	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
Mass flow [kg/s]	455.3	509.5	532.6	470.6	475.9	491.2	473.8	533.0	480.5
Air flow [kg/s per kiloton/month]	3.94	4.41	4.61	4.07	4.12	4.25	4.10	4.61	4.16

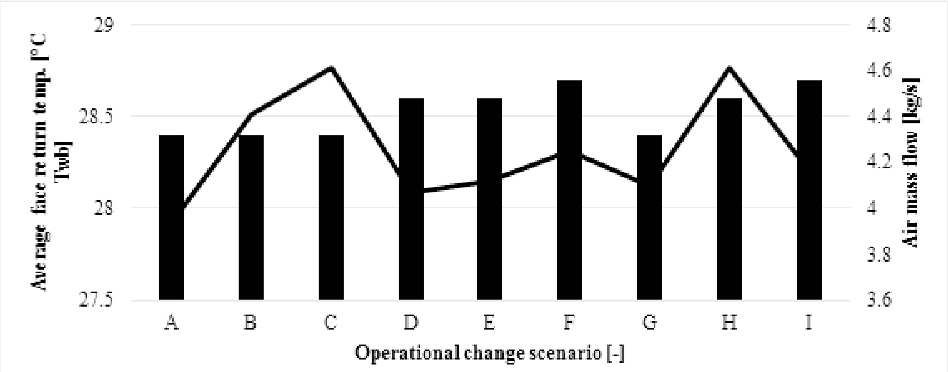


Figure 4: Average production face wet-bulb return temperatures (bar) and average air mass flow rates (line) per operational change scenario.

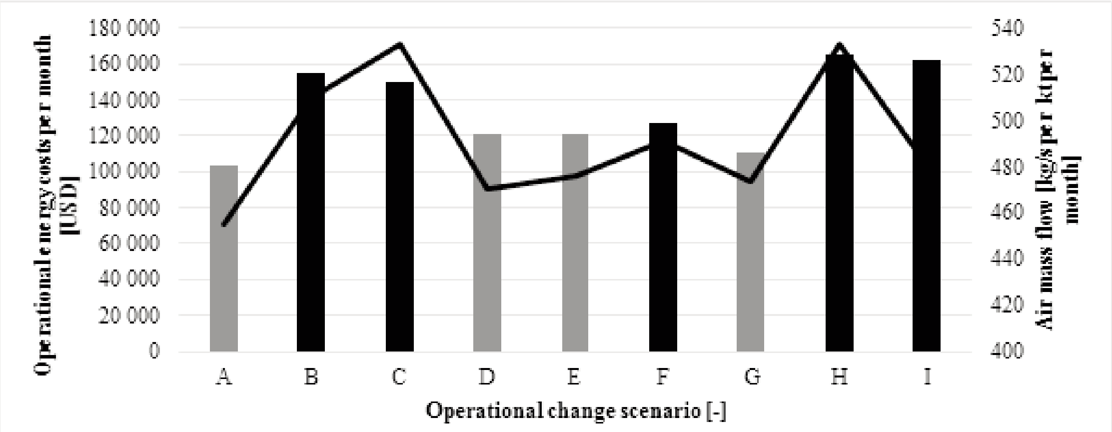


Figure 5: Operational costs per month in US dollars (bar) and total air mass flow rates (line) per operational change scenario.

per month, with the power utility's 2015/2016 electricity tariff.

Operational change scenarios A, D, E and G resulted in the lowest operational energy costs, as shown by Figure 5. This correlated to the average air mass flow utilised by the south reef section, as the operating costs were directly proportional to the up cast ventilation fans' electricity usage. Only two operational change scenarios, A and G, resulted in the lowest energy costs, thereby increasing the operational efficiency and satisfying the KPIs of the second data category.

The other operational change scenarios, in contrast, had shortcomings in at least one KPI. Therefore, only operational change scenarios A and G satisfied the KPIs of all three data categories. However, in order to proceed with the scalable methodology, the benefits and risks had to be analysed. The inclusion of the benefits and risks of each operational change scenario was incorporated in the method to make provision for a comprehensive, thorough evaluation. Although most benefits or risks cannot necessarily be quantified to a monetary value, they should still form part of the final evaluation [23].

Benefits

Scenario A had the lowest operating costs by only operating the DK1A ventilation fans. Scenario A also provided a means to convert the DK vent shaft to a second escape route for shaft egress. Scenario B provided flexibility to the network in the form of different ventilation fan operating configurations, flexibility in the up cast airflow capacities and a means to ventilate the old Kimberly reef section if required in future.

Risks

Scenario A had no flexibility or redundancy in the ventilation fans. If any of the DK1A ventilation fans experienced a breakdown, work in the south reef must be halted, according to legal standards and compliance. In scenario A, the DK1A vent shaft limited the total up cast airflow capacity. There was also no flexibility to ventilate the old Kimberly reef section in future. In scenario G, the DK vent shafts limited the down cast airflow capacity.

As mentioned previously, the only operational change scenarios which satisfied the KPIs of the three categories were A and G. Although scenario A had the lowest operational energy cost, the risks involved could have dire consequences for the mining complex and underground miners. Not all benefits and risks could be quantified to a monetary value, but should be included in the final evaluation of the operational changes. Therefore, following the evaluation and simulation analysis, operational change scenario G was implemented to achieve the desired results (**I**). The final simulation results for scenario G showed, by applying the methodology, that scenario G satisfied the most critical service delivery KPIs. The operational energy saving would therefore be realised by operating a 1.01 MW ventilation fan at DK1A vent shaft, instead of the 2.1 MW ventilation fan at DK vent shaft. This would result in a cumulative energy efficiency saving of ±9.64 GWh per annum. This figure was determined by multiplying the average energy saving per hour in kWh with 24 hours over a one-year period.

3. Validation

The operational change scenario G was implemented on the mining complex and was monitored for a period of 12 months. During this period, the cumulative energy efficiency saving measured through calibrated Schneider-Electric Powerlogic ION7330 power meters amounted to 8.50 GWh. This resulted in an energy saving of 23% on the ventilation network through implementing the most appropriate operational change identified by the scalable method. However, the total energy saving achieved was less than the simulation results indicated. The difference was attributed to the sealing of the return from CK shaft to DK shaft, which failed as a result of a temporary wooden seal. This was solved by the installation of a permanent seal, constructed from vermiculite bricks and cement packing.

As part of the method's final KPI validation, the simulated and actual results were compared. This provided an indication of the accuracy and success of the newly developed method. For that reason, the most important KPIs of the main production levels on the south reef section were analysed, as reported in Table 3. The average daily simulation KPI results were compared to the actual average daily KPI values, measured over the 12-month period. This indicated the accuracy of the calibrated simulation to forecast the effects of implementing an operational change. The average standard deviation of the daily wet-bulb temperatures was calculated to be,.

The most important objective of implementing the operational change was to ensure acceptable working conditions conducive to safe and productive mining at the highest operational efficiency, thereby lowest operational energy costs. From Table 3, the actual and simulated average daily wet-bulb temperatures correlate to within 9%. Moreover, the average daily airflow to each production level was sufficient to ensure acceptable working conditions and, in some cases, to supply supplementary airflow capacity. The service delivery KPIs were therefore satisfied for the main production levels.

Additionally, to accurately compare the results, other average daily KPIs for the integrated complex ventilation network were considered, as shown in Table 4. The average daily simulation air mass flows were compared to the actual average daily air mass flows, measured over the 12 month period. The absolute error of the average daily air mass flows are presented in Table 4 to indicate the level of simulation accuracy. Considering the average daily air mass flow results comparison in the table, the difference in air mass flow for each of the service delivery KPIs could be ascribed to variations in the data used to construct the simulations, as well as external factors such as air leaks and underground configuration changes that had an influence on the network. Due to the complexity of the ventilation network, these small differences between the simulated and actual results were negligible and the method was validated in terms of service delivery.

Another factor to consider as part of the KPI validation was operational efficiency. It was extremely important to illustrate the energy cost benefit realised as a result of implementation. Moreover,

Table 3: Post-implementation average daily KPI validation for main production levels

Level	*Simulated temp.*	*Actual temp*	*Temp error*	*Simulated airflow*	*Actual airflow*	*Airflow error*
	T_{wb}^* [°C]	T_{wb} [°C]	*Absolute* [%]	*Mass flow* [kg/s]	*Mass flow* [kg/s]	*Absolute* [%]
192	29.5	29.2	1	47.5	51	7
197	28.5	26.5	8	9.5	11.4	17
202	25.5	23.4	9	114	104.5	9

* *wb = wet bulb.*

Table 4: Post-implementation average daily KPI validation for the integrated, complex mine ventilation network.

Section	*Simulated mass flow* [kg/s]	*Actual mass flow* [kg/s]	*Absolute error* [%]
South Reef	473.8	478.0	1
192/106 Raise bore hole	185.0	165.0	12
DK vent surface fans	298.6	340.0	12
DK1A vent surface fans	299.9	313.0	4

the implementation costs were also included in the analysis. Therefore, the costs to install and close the return from CK shaft to DK shaft amounted to USD 3 312 (ZAR:USD exchange rate as on 13 November 2017). The costs to reduce the RBH and seal the old Kimberly reef sections amounted to USD 3 450. The cost to increase one of the return airways on 106L amounted to USD 2 070. The total cost of implementing operational change scenario G, amounted to USD 8 832. The time taken to complete the operational change was 1.5 months – it would have been much shorter had it not been for extended lead times for constructing the underground seals.

4. Results and discussion

The operational change was implemented and active for a period of 18 months during the time this study was compiled. The total energy savings, measured by the calibrated meters for this period amounted to 13.32 GWh which, if converted to costs according to the tariffs as mentioned earlier, resulted in an energy cost saving of ±USD 0.7 million.

The significance of this method lies in that it enables mine personnel to make improved decisions regarding operational changes on mine ventilation networks through simulations. The importance of this method was emphasised by the validation, in which scenarios A, B, C and G satisfied one KPI. However, if scenario B or C had been implemented, the operational costs would have been much higher than for scenario G. Likewise, the resulting air mass flow of scenario B and C would have proved to be unnecessary for this project. Furthermore, if scenario A had been implemented, the mine would have had a much larger risk of losing production or experiencing an underground working fatality as a result.

This method was easily implemented and was specifically developed to be scalable. This scalability is extremely important in successfully implementing and utilising it. The versatility of the method to conduct high, medium and low level evaluation studies provided mine personnel with new insights on operational changes. The author has observed a new vigour in mine personnel where the method was applied, as it was a new tool to be used for improving underground conditions and for increasing the profitability of deep-level mines. The importance of the method was underlined by its adoption by industry practising professionals as the norm of their mining standards.

This scalable method was developed according to a continuous improvement process. This enables the method to be incorporated and still be relevant in future developments such as cases where industry 4.0 and the 'internet of things' technologies are applied to the mining industry [13]. Mine personnel can develop a digital simulation twin of the entire ventilation network to be evaluated on a continuous basis, incorporating these new technologies.

5. Conclusions

This paper presented a scalable method to optimise and evaluate mine ventilation networks through simulations. Nine operational change scenarios were optimised and evaluated on a deep-level mining complex. The method was used to determine the most feasible option. The most feasible option was implemented successfully, resulting in a 23% energy saving.

Mine personnel had been challenged with making a decision of which operational change to implement, selecting from a vast array of operational changes. The method provided a means for selecting the best alternative, based on a comprehensive evaluation. The true value of the method is that it allows for improved and traceable decisions regarding operational changes – as illustrated by the adoption of the method by mining professionals as part of their own standards and procedures after successful validation.

The method promotes improved safety, better underground working conditions, legal compliance and mine productivity, as a result of a thorough evaluation which was not previously available. Its versatility and scalability makes it applicable to all ventilation networks, including future developments such as industry 4.0 or internet of things technologies.

Acknowledgements

The author thanks the personnel of the specific mining complex for their valuable inputs and data provided for the case study. This work was supported by Enermanage (Pty) Ltd.

Note

1. Supplementary material can be found at https://journals.assaf.org.za/jesa/article/view/4445.

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Journal of Energy in Southern Africa

Volume 29 Number 3

Road transport vehicles in South Africa towards 2050: Factors influencing technology choice and implications for fuel supply

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Abstract

The South African transport sector is estimated to emit 60 $MtCO_2eq$ and require 800 PJ of energy, similar in scale to industrial energy demand and emissions. The sector is forecast to potentially eclipse industry in this regard if conventional vehicle choices and travel modes persist. This paper explores scenarios of transport technology choices and demand in a future of uncertain fuel and technology costs, and the consequences for energy supply and greenhouse gas emissions. It explores the extent of electric vehicle (EV) adoption and the implication of fuel migration from petroleum products. The preference for alternative fuels such as hydrogen, liquid biofuels and natural gas is also investigated. The evolution of road transport in South Africa towards 2050 is investigated utilising the South African TIMES model, a full energy sector least-cost optimisation model that relies on a rich technological database of the entire energy supply and demand system. Hydrogen fuel cell vehicles are shown to be a viable option in freight and public transport, potentially meeting 70% of travel demand by 2045. The private passenger and light commercial sectors emerge as the main market for electric vehicles, potentially accounting for 80% of new vehicle sales by 2045. Electricity as a transport fuel could account for 30% of fuel supply and reduce transport emissions to half of present day estimates. However, the key uncertainty driving EV adoption is future vehicle costs and crude oil prices, which could dampen EV uptake. Another main finding is that petroleum-dependent vehicles remain an important vehicle class, and that re-investment in existing crude oil refineries to conform to Euro5 standards is a likely requirement. There seems to be little indication, however, that additional refining capacity would be economically viable within the planning horizon.

Keywords: *energy; electric vehicles; hydrogen; modelling; GHG emissions*

Journal of Energy in Southern Africa 29(3): 33–50
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a5596

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Technology

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1. Introduction

Transport is the primary consumer of liquid fuels in South Africa (Merven et al., 2012). Demand for energy in the sector is forecast to grow to 24–37% of total energy demand by 2050, possibly representing the largest sectoral demand for energy in South Africa (Department of Energy (DoE), 2016). The key question is how these energy needs will be met, considering the uncertainty of future fuel prices, technology costs and options, as well as efficiency gains. This question was addressed by putting significant effort into an expansion of the transport sector representation in the South African TIMES (SATIM) model.

The Integrated Energy Plan (IEP), which represents the country's key integrated energy planning strategy notes the 'lack of coordinated and integrated planning in the energy sector' that resulted in underinvestment in domestic electricity and petroleum product supply capacity (DoE, 2017). Future commodity prices, electric vehicle (EV) penetration rates,[1] a CO_2 emission constraint and refinery investments are highlighted as key uncertainties in determining the future energy supply requirements for the transport sector. Furthermore, the National Transport Master Plan 2050's (NATMAP 2050) assertion is that 'transport in South Africa will also promote a low-carbon economy by offering transport alternatives that minimise environmental harm' (Department of Transport (DoT), 2016).

Numerous sector-specific studies have been conducted in transport, but the IEP is a singular instance of a full economic sector energy supply and demand modelling study for South Africa. Transport sector studies vary from municipal to national scale, with different modelling approaches employed to address contextual objectives. Municipal studies typically require spatio-temporal models for peak traffic flows and road congestion in the context of urban planning (City of Cape Town, 2016; Nijhout et al., 2001; Perold and Anderson, 2000). Venter and Mohammed (2013) utilised survey data to construct a detailed household transport energy budget model within the Nelson Mandela Metropolitan area, Eastern Cape Province, South Africa, to assess socio-economic and land-use drivers of transport modal choices and share of household energy consumption. The NATMAP 2050 is currently the only national-scale study with a spatially disaggregated analysis of transport and future energy demand. The NATMAP 2050 discusses sectoral energy demand to contextualise the impact of transport, but besides the IEP, integrated full-sector studies are lacking. Gajjar and Mondol (2015) conducted a similar techno-economic study of alternative vehicle adoption in the country, but analysed the transport sector in isolation with a focus on passenger vehicles only.

The motivation for the analyses presented in this study was to provide a complementary perspective to the IEP and NATMAP 2050, with emphasis on the three main sectors of road transport: freight, private, and public transport. The study examined the implications for energy supply and demand and associated emissions that relate to future scenarios of national road transport and fuel supply approaching 2050. It did not consider land-use and air quality externalities associated with road transport or behavioural changes arising from technological innovation. The research questions for the study were: How might current and emerging transport technologies and fuels help South Africa transition to a low-carbon economy? What implications does this have on the upstream energy supply infrastructure outlook to 2050? What techno-economic drivers influence the adoption of EVs in South Africa?

2. Methodology

The method implemented followed closely that adopted by Merven et al. (2012) and is illustrated in Figure 1. A vehicle parc model, also described by Merven et al., and revised by Stone et al. (2018), is used to establish the characteristics of the 2000–2014 vehicle parc for South Africa. The range of vehicle technologies analysed is presented in Table 1.

The vehicle parc was estimated utilising data from the National Association of Automobile Manufacturers of South Africa (NAAMSA) and the electronic National Administration Traffic Information System (eNaTiS) registration database as illustrated in Figure 2. Scrapping factors derived from Weibull distributions were determined for each vehicle class to reconcile eNaTIS data.

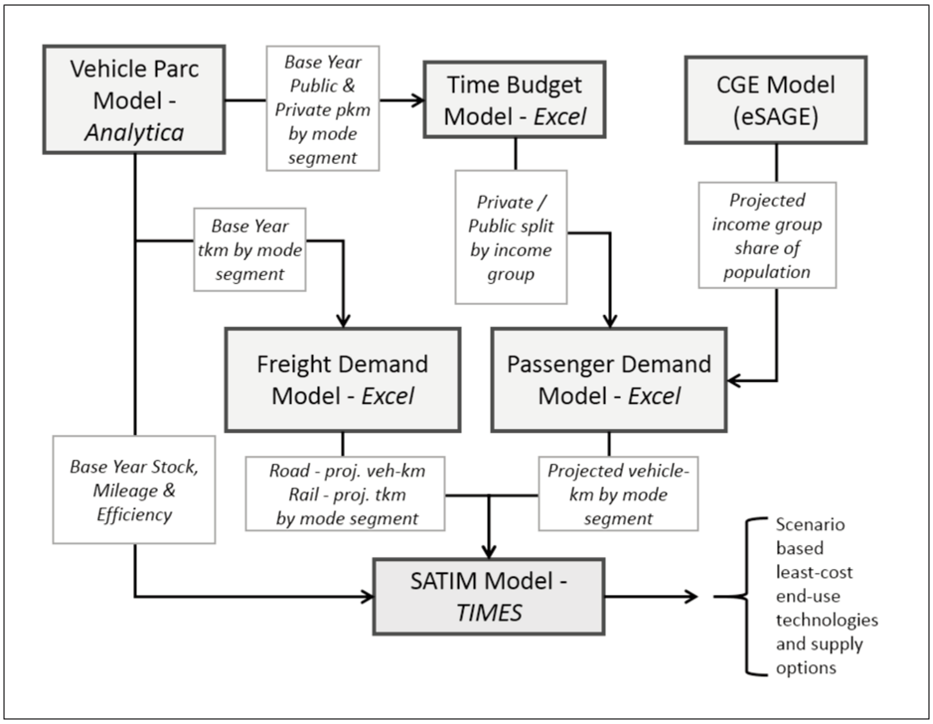
Vehicle mileage decay, which is required for vintaging the vehicle parc, fuel economy and occupancy factors (load factors for freight t-kms), were estimated from the literature for which local data is scant. The calibration process is such that the final fuel energy demand conforms to road transport fuel sales adjusted for non-road use (e.g. Eskom diesel usage). Exemplary results for fuel and vehicle model calibration are shown in Figures 3 and 4.

The model estimate of the vehicle parc is in good agreement with the national registration database for the calibration period despite a noticeable departure in fuel consumption from actual sales for the period 2013-2014. This is presumably from a reduction in vehicle activity because of a combination of fluctuating economic growth (Trading Economics, 2017) and an inflection in the rate of fuel price increases for 2013-2014 occurring at the calibration period horizon. The deviation in fuel demand highlights the inability of the model to capture historic short-run supply-demand shocks. However, since the model is employed to aid strategic planning of energy supply of 20 years or more,

Table 1: Road vehicles in the SATIM model.

Vehicle type	*Freight*				*Private passenger*			*Public transport*		
	LCV	*HCV1*	*HCV2–5*	*HCV6–9*	*Car*	*SUV*	*Motor-cycle*	*Minibus*	*Bus*	*BRT*
Petrol ICE	•	•			•	•	•	•		
Diesel ICE	•	•	•	•	•	•		•	•	•
Hybrid petrol-electric					•	•				
Hybrid diesel-electric					•	•		•		
Natural gas ICE	•	•	•	•	•	•		•	•	•
FlexFuel					•	•		•	•	•
Battery electric	•	•	•		•				•	•
Hydrogen fuel cell			•	•	•	•		•	•	•

ICE: internal combustion engine, SUV: sports utility vehicle, BRT: Bus Rapid Transit, LCV = light commercial vehicle, HCV1: medium commercial vehicle of 3 000–7 500 kg gross vehicle weight, HCV 2-5: heavy commercial vehicle of 7 501–12 000 kg gross vehicle weight; HCV 6-9: Heavy commercial vehicle of 24 001–32 000 kg gross vehicle weight.



Note: shaded blocks represent distinct models.

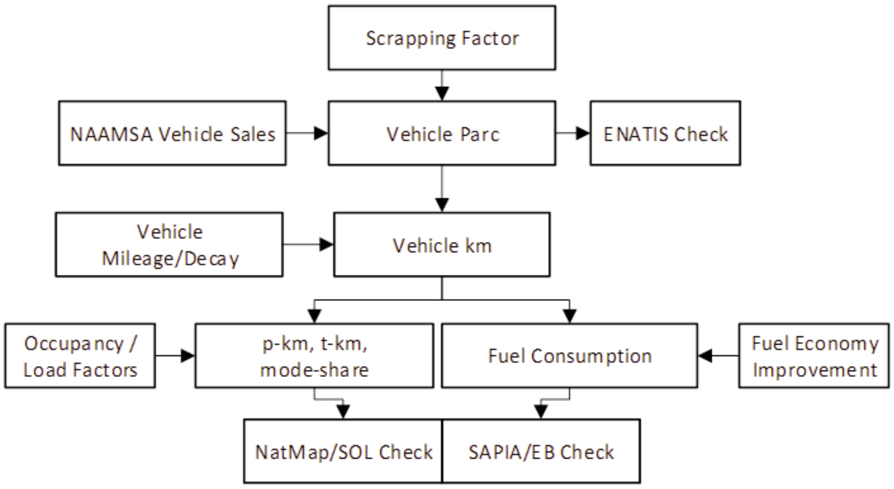
Figure 1: An overview of the SATIM transport sector model (Merven et al., 2012).

such perturbations are less consequential for long-run analyses.

A general computable equilibrium economic model, eSAGE, is used to project sectoral economic growth via gross domestic product (GDP) and household income, given certain assumptions around population growth, productivity growth and global commodity prices (Alton, 2014). The household income projections and sectoral growth projections are taken to a passenger demand projection model and to a freight demand projection model.

The ownership of passenger cars in the passenger demand projection model is split between three income groups and a miscellaneous category to accommodate commercially- and government-owned cars. With population projections for each of the income groups, the passenger demand projection model uses assumptions around private vehicle ownership by income group, vehicle mileage, vehicle occupancy, public mode shares, average mode speeds, and a travel time budget to derive vehicle-km demand by passenger vehicle class for households. This is combined with a transport-GDP linked projection of the non-household owned cars to give a total passenger vehicle-km demand projection for road vehicles. The passenger-km projections by rail are derived from assumptions around future mode shares.

The freight demand projection model takes sector GDP projections and, based on assumptions around load factors and mode shares, makes projections of vehicle-km for different freight vehicle classes. The projections for ton-km are derived from



NAAMSA = National Association of Automobile Manufacturers of South Africa, eNaTIS = electronic National Administration Traffic Information System, SAPIA = South African Petroleum Industry Association, NatMap = National Transport Master Plan, SOL = State of Logistics Survey for South Africa, EB = National Energy Supply and Demand Balance, Department of Energy.

Figure 2: Schematic representation of the vehicle parc model and its data inputs and validations.

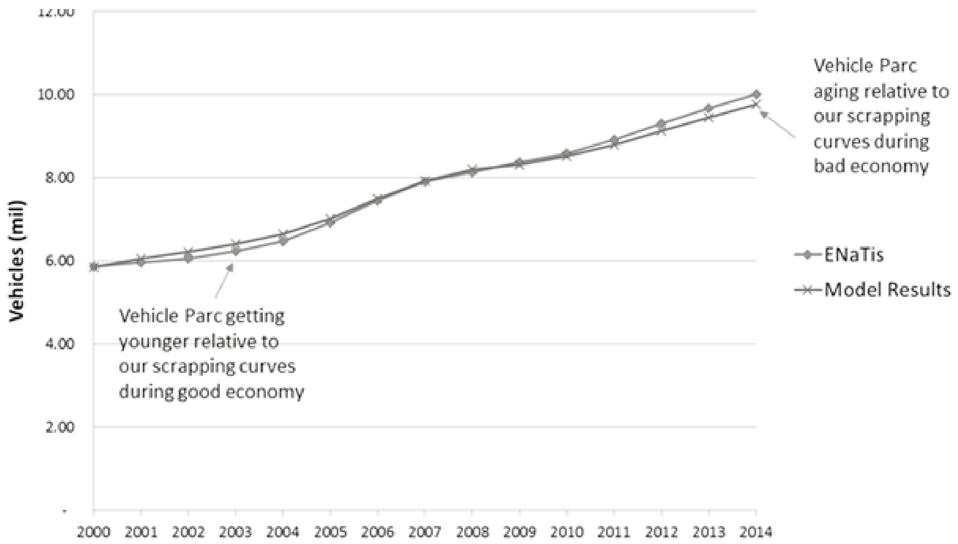


Figure 3: Calibration results of the vehicle parc model for the aggregate vehicle population compared with the registration database from the electronic National Administration Traffic Information System (eNaTIS).

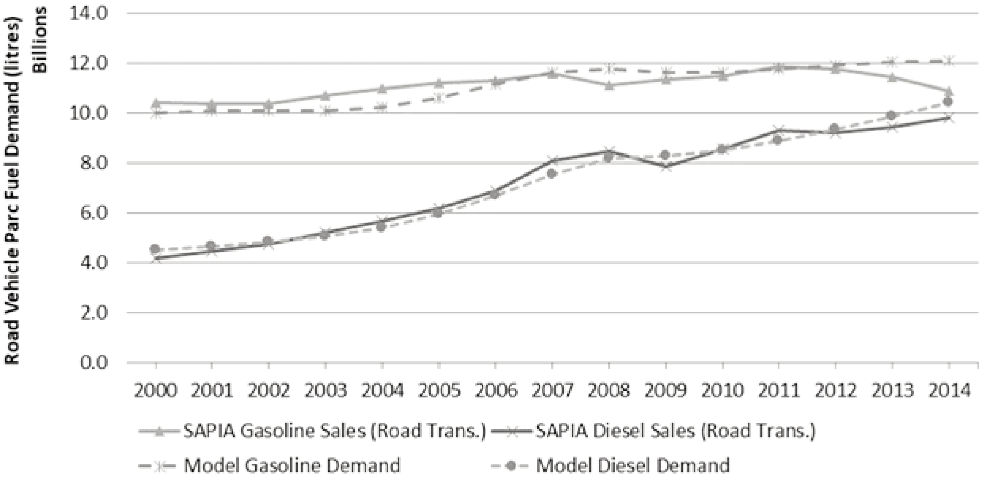


Figure 4: Model fuel demand vs actual fuel consumption for 2000–2014.

Table 2: Improvements in passenger car fuel economy in world markets: 2000–2010.

Country	*Period*	*Annual fuel economy improvement (%) (ICCT, 2011)*	*Period*	*Annual fuel economy improvement (%) (Cuenot & Fulton, 2011)*
USA	2000–2010	1.60	2005–2008	1.90
Canada	2000–2008	1.28	unavailable	unavailable
EU	2000–2010	1.90	2005–2008	1.90
Japan	2000–2009	2.81	2005–2008	2.20
South Africa	unavailable	unavailable	2005–2008	0.40

assumptions around future mode shares.

Vehicle-km projections for road vehicles are then exogenously imposed in SATIM, which is used to project the least-cost technology and fuel mix to meet the projected vehicle-km and passenger-km demands, while also meeting other goals such as national emissions constraints.

Two sets of assumptions for the demand projections are used in this analysis:

1. Reference:

- Passenger: Private vehicle ownership, annual mileage and occupancy are kept constant at the base year calibrated levels.
- Freight: Mde share between road and rail is kept constant at the base year calibration level.
- It is assumed that the efficiency of conventional internal combustion engine vehicles (ICEVs) improves annually at a rate of 0.5%.

2. Efficiency improvements and mode switching (EMS):

- Passenger: Private vehicle ownership decreases, annual mileage decreases and occupancy increases relative to the base year calibration level over time, resulting in an increase in public transport share;
- Freight: The share of rail corridor transportation increases as migration of road-to-rail freight is promoted.
- It is assumed that the efficiency of conventional ICE vehicles improves annually at a rate of 0.75%.

Fuel efficiency and future assumptions are based on data summarised in Table 2. These two sets are combined with variations in other SATIM parameters to generate the set of scenarios presented and discussed in this paper. The scenario development section describes the full matrix of scenario parameters. The demand projections generic to all scenarios and model assumptions are further described in Merven et al. (2017).

The demand forecasts for both freight and passenger transport are shown in Figure 2. In the freight sector, as indicated in Figure 3, the forecast demand for ton-kms is unchanged, with the primary reduction in road transport demand attributed to an increase in road-to-rail migration. In the Reference scenario, the share of rail freight remains constant at 15%, but grows to approximately 30% by 2050 in the EMS case. The reduction in passenger-kms in the EMS case is considered to occur as occupancy rates increase, private car ownership (high trip length) decreases and private car activity decreases.

3. Scenario development for the energy model

The state of road transport in South Africa in 2050 is subject to a multitude of interacting factors, which, by their inherent uncertainty, requires the formulation of a coherent set of scenarios describing feasible futures for the transport sector. Table 3 presents assumptions on key drivers that apply to all scenarios.

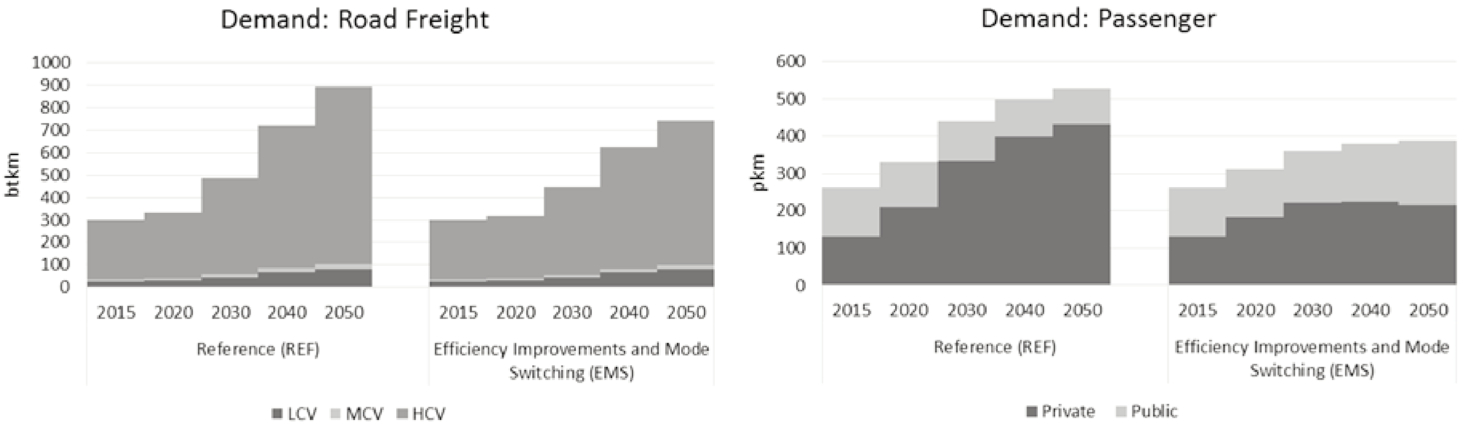


Figure 5: Road transport demand for the Reference and EMS scenarios.

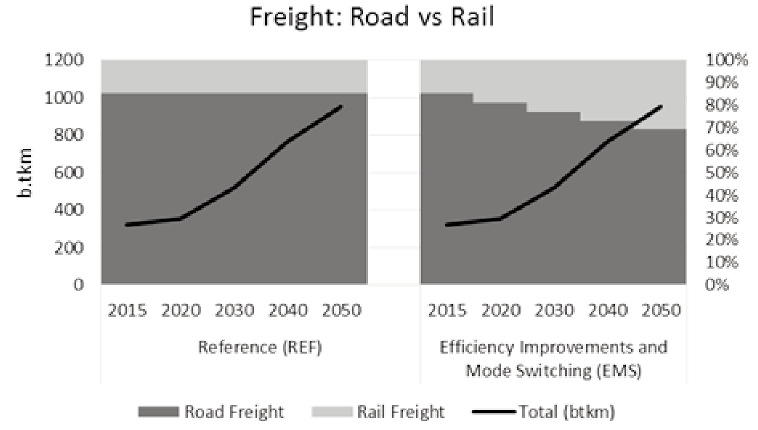


Figure 6: The road-to-rail modal shift incorporated in the EMS scenario.

Table 3: Key model assumptions.

Assumption	*Description*
Discount rate	The cost of capital for future investments is assumed to remain at 8% and apply globally to all model investments.
GDP growth (Merven et al., 2017)	An average annual GDP growth rate of 3.1% over the planning horizon (2015–2050) is assumed.
Cleaner Fuels Phase 2 (DoE, 2011; SAPIA, 2017)	The tabled *Cleaner fuels Phase 2* regulations are presumed to be implemented by 2025 with existing crude oil refineries allowed to invest to comply with the fuel specifications or retire. Includes the cost of flue-gas desulphurisation (FGD) fitment to new coal-to-liquids (CTL) plants.
Biofuels blending* (DoE, 2014)	Mandatory blending of bioethanol and biodiesel is presumed to occur from 2020 at the minimum blend levels of 2% and 5% for petrol and diesel respectively. A maximum blend level of 10% is set for petrol while biodiesel blend ratios are unrestricted. Higher blend ratios for bioethanol are included with the addition of E85 vehicles.

**Potential revenue associated with the production of biofuels (e.g. animal cake) is not included.*

3.1 Scenario matrix and descriptions

The portfolio of scenarios modelled for this study is summarised in Table 4, which details the four most important factors driving the evolution of transport considered: the national carbon budget, the level of progression to be achieved in mode switching and efficiency improvement, the investment cost of new and emerging technologies (vehicle CAPEX), and the oil price. It is anticipated that a carbon budget of 14 Gt of CO_2eq is imposed for the country and juxtaposed with the case of unconstrained emissions (Burton et al., 2016). As discussed earlier, the EMS case presents an alternative growth pathway for demand and technological progress. Despite disruptions to the conventional model of private vehicle ownership from market entrants such as Uber and the Bus Rapid Transit system, private vehicle ownership remains an aspirational goal for most households as it enables a high degree of personal mobility (Naughton, 2014; Williams, 2016).

The future choice of private vehicle is thought to be largely influenced by the initial purchase cost, with alternative technology choice a secondary consideration (Deloitte, 2014). The Ricardo-AEA (2012) ‘Review of the efficiency and cost assumptions for road transport vehicles to 2050’ forms the basis of comparative vehicle costs and on-road efficiency in SATIM. Given the inherent high uncertainty in forecasting long-term future investment costs (Wolfram and Lutsey, 2016; Pelletier et al., 2014), an optimistic case of vehicle purchase cost parity is included to gauge the sensitivity of technological adoption rates to purchase price. Bevis et al. (2013) suggested 2015–2020 as an EV parity date in the study of EV adoption drivers. For this study 2020 and 2030 are modelled as tentative years for purchase cost convergence (USA DoE, 2017; Carrington, 2016). It is assumed that both freight and passenger EVs would incur lower maintenance costs, which, including the cost of battery replacement over the vehicle life, would be 20% less than a conventional ICE vehicle that represents the lower value of reported and calculated ranges (Stone, 2017; Pelletier et al., 2015; e-Mobility NSR, 2013).

3.2 Refuelling and charging infrastructure costs

The prevalence of a particular vehicle technology is influenced by the availability of refuelling (or recharging) options (ESAA, 2014; 2013; van den Bulk, 2009). The extent of fuel distribution is, in turn, driven by comparative investment costs,

Table 4: An overview of the scenarios included in the modelling analyses.

Scenario	*Description*	*Carbon budget (Gt)*	*EMS*	*Vehicle capex parity by 2030*	*Oil price (USD/bbl (2050))*
Reference	Reference scenario	14		✓	125#
RefTech2020	Reference with vehicle capex parity by 2020 and market share limits of 50% in 2030 and 100% in 2050	14		✓ by 2020 125	
RefLoOil	Reference with a lower future oil price	14		✓	80 (2020-2050)
RefHiTech	Reference with higher EV costs	14		×	125
RefHiTechLoOil	Reference with higher EV costs and a lower future oil price	14		×	80 (2020-2050)
RefHiTech-UCE	Reference with higher EV costs and unconstrained emissions (UCE)	UCE		×	125
RefTech2020-UCE	RefTech2020 scenario with UCE	UCE		✓ by 2020	125
Ref-UCE	Reference with UCE	UCE		✓	125
Ref10Gt	Reference with a 10 Gt carbon budget	10		✓	125
eMode	Efficiency improvements and mode switching	14	✓	✓	125
eModeLoOil	EMS with a lower future oil price	14	✓	✓	80 (2020-2050)
eModeHiTech	EMS with higher future EV costs	14	✓	×	125
eMode10Gt	EMS with a 10 Gt carbon budget	10	✓	✓	125

✓ included in scenario, ×: Ricardo-AEA (2012) forecasted vehicle costs implemented instead, #: IEA (2016)

which ultimately affect the cost of fuel. Distribution costs for competing fuels are shown in Table 5. The utility costs refer to the expansion of the centralised transmission and distribution network. The EV charging costs and efficiencies assume Level 2 charging for both residential and commercial premises and is adapted from USA data (Smith and Castellano, 2015; Snyder, 2012; Forward et al., 2013).

Table 5: Investment cost estimated for the distribution of fuels in the SATIM model.

Description	*Distribution infrastructure cost (ZAR million/petajoule) (2015 rands)*
Utility electricity	20 210
Commercial EV charging (5 cars per charger)*	19
Residential EV charging (2 vehicles per charger)*	10
Gas	453
Hydrogen	1 360
Diesel and petrol	34

** Assumed*

4. Results and discussion

The results of the optimisation modelling are presented and discussed according to themes of future transport technologies in the vehicle fleet, the impact on local refineries and the impact on the power sector. For the modelling horizon of 2050, the results are shown for the transitionary years 2030 and 2045. These milestone years provide an indication of a potential inflection and consequent transformation of the transport sector.

4.1 Demand and technology preference

It was found that oil-based vehicles in 2015 dominate in the transport fleet and comprise petrol and diesel vehicles. Although in the model this class of vehicle includes hybrid range-extended and E85 vehicles, which depend on petroleum products, these vehicles are negligible in 2015. Table 6 lists the total fleet population for 2015 and for the selected milestone years. The private and freight vehicle fleet in SATIM is projected to grow by 260% in 2045 in the Reference scenario. The EMS scenario reduces the private vehicle fleet by approximately half as occupancy rates increase and public transport is promoted, resulting in about 25% increase in the public transport fleet in 2045. The public transport sector fleet in 2015 is dominated by minibuses. In both the Reference and EMS cases, public transport is migrated to larger buses, which explains the decline in the public vehicle fleet in all the scenarios.

Table 7 displays the SATIM-projected share of new EVs in road transport. A preference for private and light duty freight EVs is observed, with EVs potentially accounting for 80% of new vehicles in 2045. Public transport EVs are less favoured, potentially accounting 5% of new vehicles in 2045.

Tables 8–10 present the share of transport demand for each class of road transport vehicle: freight, private and public. Common to all three tables is the continued preference for oil product vehicles should the future oil price level at approximately USD 80/bbl rather than the IEA (2016) fore-

Table 6: Total road vehicles for indicated years.

	Total vehicles (x1000)								
	2015			2030			2045		
Scenario	*Freight*	*Private*	*Public*	*Freight*	*Private*	*Public*	*Freight*	*Private*	*Public*
Reference	2728	7073	316	4487	10745	228	7574	17233	135
RefTech2020	2728	7073	316	4548	10745	229	7603	17233	135
Ref-LoOil	2728	7073	316	4452	10745	229	7477	17233	135
RefHiTech	2728	7073	316	4450	10745	228	7005	17233	132
RefHiTech_LoOil	2728	7073	316	4433	10745	229	6974	17233	135
RefHiTech-UCE	2728	7073	316	4449	10745	228	7005	17233	133
RefTech2020-UCE	2728	7073	316	4548	10745	229	7606	17233	134
Ref-UCE	2728	7073	316	4486	10745	228	7575	17233	133
Ref10Gt	2728	7073	316	4486	10745	227	7552	17233	135
eMode	2722	6900	311	4388	8582	221	7435	8472	170
eModeLoOil	2722	6900	311	4387	8582	226	7349	8472	173
eModeHiTech	2722	6900	311	4387	8582	221	6880	8472	170
eMode10Gt	2722	6900	311	4439	8582	222	7415	8472	168

Table 7: The projected share of new electric road vehicles in 2030 and 2045.

	2030			2045		
Scenario	*Freight*	*Private*	*Public*	*Freight*	*Private*	*Public*
Reference	32%	35%	11%	80%	80%	5%
RefTech2020	46%	46%	10%	80%	80%	5%
Ref-LoOil	32%	0%	10%	78%	80%	5%
RefHiTech	31%	0%	10%	1%	0%	6%
RefHiTech_LoOil	31%	0%	10%	1%	0%	0%
RefHiTech-UCE	32%	0%	11%	1%	0%	0%
RefTech2020-UCE	46%	46%	10%	77%	80%	5%
Ref-UCE	32%	14%	11%	77%	80%	5%
Ref10Gt	32%	46%	10%	81%	80%	0%
eMode	32%	0%	7%	79%	79%	0%
eModeLoOil	32%	0%	10%	80%	79%	0%
eModeHiTech	30%	0%	7%	1%	0%	0%
eMode10Gt	32%	33%	7%	82%	79%	0%

cast of USD 125/bbl by 2050. This delays the economic preference for alternative vehicles towards the latter half of the planning horizon (2045). In particular, the penetration of EVs appears to be sensitive to future projected costs, with minimal uptake if vehicle purchase parity is not realised during the period.

The ICEV shares in freight are less than in the passenger sector, ranging from 40–70%. This is largely because of the higher scrappage rates (capacity decay curves) attributed to freight vehicles resulting in a higher rate of fleet replenishment (Supplement, Table 4[2]). In the interim period, 2015–2030, natural gas vehicles (NGVs) and hydrogen fuel cell vehicles (HFCVs) emerge as alternatives, with freight EVs contributing a minor role. Figure 7 illustrates the EV preference in freight vehicles for three scenarios typifying the transport scenario paths in the present study. The figure depicts vehicle technology preference by disaggregated freight class. It is observed that EVs by capacity are largely confined to light commercial vehicles, for which the tkm share grows to about 10% in 2045. The HCV6–9 category, which is larger by load class, is responsible for the bulk of road traffic, and a preference for HFCVs is noted, displacing oil and gas vehicles in the later period. The incurred additional cost of hydrogen production relative to diesel and natural gas is offset by the lower MJ per km of HCFVs (Supplement, Tables 3 and 5).

Table 9 shows that private EVs remain economically unattractive when there is about 30% premium relative to a petrol ICEV (Supplement, Table 3). In the absence of tariff distortion, a purchase cost premium appears to be the main barrier. A smaller 10 Gt carbon budget does not appear to influence an earlier migration to EVs as the results are comparable to the 14 Gt Reference scenario. Similarly,

Table 8: Freight t-km share by vehicle technology share.

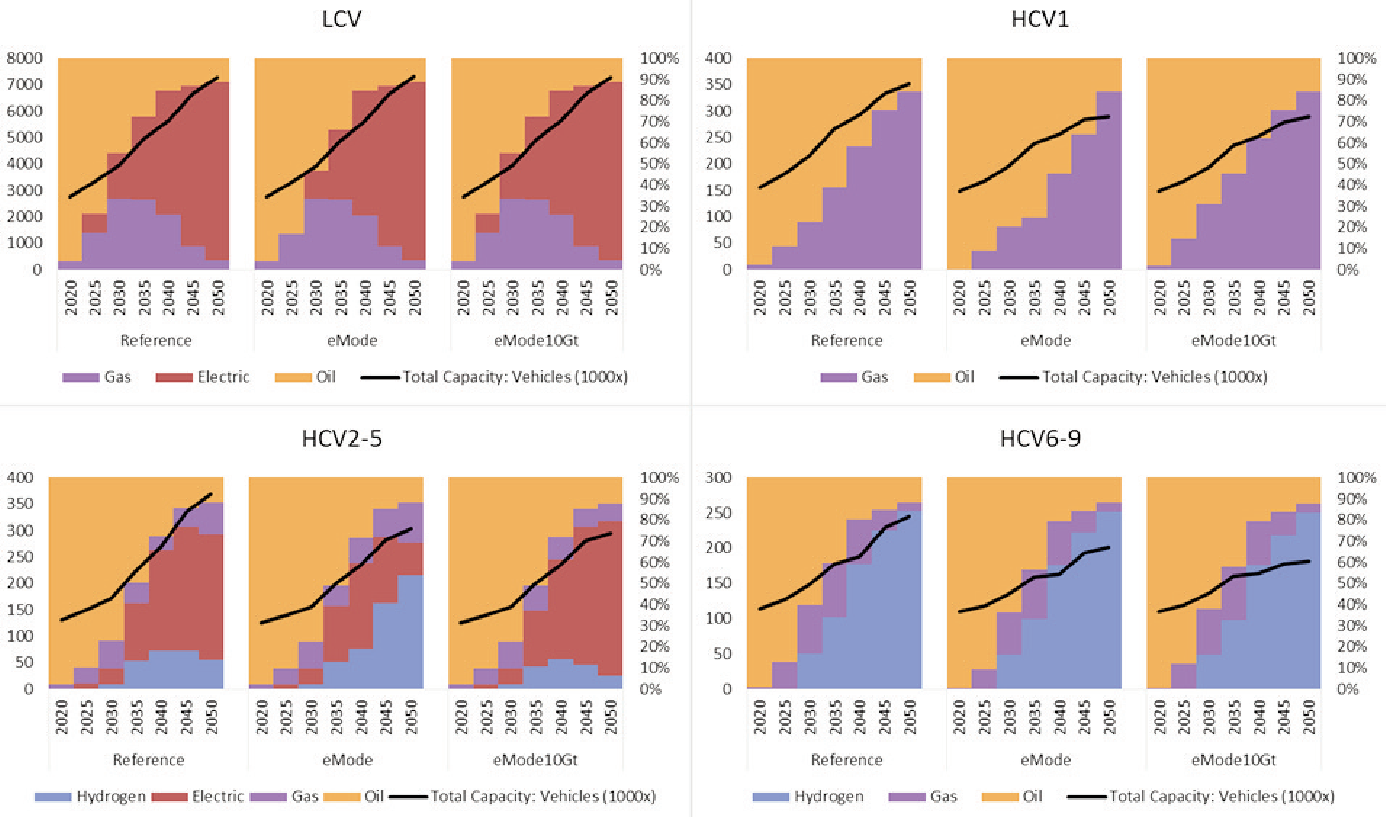
						2030	*2045*	
Scenario	*Oil*	*Electric*	*Hydrogen*	*Gas*	*Oil*	*Electric*	*Hydrogen*	*Gas*
Reference	49%	3%	20%	28%	5%	16%	68%	10%
RefTech2020	40%	7%	29%	24%	5%	16%	68%	10%
Ref-LoOil	68%	3%	16%	13%	26%	10%	59%	6%
RefHiTech	49%	3%	20%	28%	13%	1%	68%	18%
RefHiTech_LoOil	72%	2%	16%	11%	29%	1%	60%	10%
RefHiTech-UCE	50%	3%	20%	27%	13%	1%	67%	18%
RefTech2020-UCE	40%	7%	29%	24%	5%	11%	75%	9%
Ref-UCE	50%	3%	20%	26%	5%	11%	75%	10%
Ref10Gt	48%	3%	20%	28%	14%	17%	57%	12%
eMode	52%	3%	20%	26%	5%	13%	71%	10%
eModeLoOil	73%	3%	16%	8%	26%	11%	57%	6%
eModeHiTech	52%	3%	20%	26%	13%	1%	67%	19%
eMode10Gt	49%	4%	20%	28%	14%	18%	55%	12%

Table 9: Private pkm by vehicle technology share.

		2030				*2045*		
Scenario	*Oil*	*Electric*	*Hydrogen*	*Gas*	*Oil*	*Electric*	*Hydrogen*	*Gas*
Reference	80%	17%	0%	2%	23%	72%	0%	5%
RefTech2020	65%	33%	0%	2%	23%	72%	0%	5%
Ref-LoOil	98%	0%	0%	2%	23%	72%	0%	5%
RefHiTech	98%	0%	0%	2%	95%	0%	0%	5%
RefHiTech_LoOil	98%	0%	0%	2%	95%	0%	0%	5%
RefHiTech-UCE	98%	0%	0%	2%	95%	0%	0%	5%
RefTech2020-UCE	65%	33%	0%	2%	23%	72%	0%	5%
Ref-UCE	91%	7%	0%	2%	23%	72%	0%	5%
Ref10Gt	75%	22%	0%	2%	23%	72%	0%	5%
eMode	96%	0%	0%	4%	24%	69%	0%	7%
eModeLoOil	96%	0%	0%	4%	24%	69%	0%	7%
eModeHiTech	96%	0%	0%	4%	93%	0%	0%	7%
eMode10Gt	81%	15%	0%	4%	24%	69%	0%	7%

Table 10: Public pkm by vehicle technology share.

			2030					*2045*		
Scenario	*Rail*	*Oil*	*Electric*	*Hydrogen*	*Gas*	*Rail*	*Oil*	*Electric*	*Hydrogen*	*Gas*
Reference	9%	63%	4%	15%	8%	11%	68%	5%	10%	6%
RefTech2020	9%	65%	4%	13%	8%	11%	35%	5%	40%	9%
Ref-LoOil	9%	61%	4%	18%	8%	11%	81%	5%	3%	0%
RefHiTech	9%	62%	4%	17%	8%	11%	81%	4%	4%	0%
RefHiTech_LoOil	9%	62%	4%	17%	8%	11%	84%	2%	3%	0%
RefHiTech-UCE	9%	60%	4%	18%	8%	11%	45%	3%	41%	0%
RefTech2020-UCE	9%	64%	4%	14%	8%	11%	32%	5%	52%	0%
Ref-UCE	9%	61%	4%	18%	8%	11%	34%	4%	51%	0%
Ref10Gt	9%	76%	4%	3%	8%	11%	83%	3%	3%	0%
eMode	10%	63%	3%	18%	6%	14%	35%	2%	45%	5%
eModeLoOil	10%	63%	4%	16%	6%	14%	72%	2%	13%	0%
eModeHiTech	10%	62%	3%	18%	6%	14%	56%	1%	30%	0%
eMode10Gt	10%	77%	3%	3%	6%	14%	82%	1%	3%	0%



LCV: light commercial vehicle, HCV1: medium commercial vehicle of 3 000–7 500 kg gross vehicle weight, HCV 2-5: heavy comm-ercial vehicle of 7 501–12 000 kg gross vehicle weight; HCV 6-9: heavy commercial vehicle of 24 001–32 000 kg gross vehicle weight.

Figure 7: Freight vehicle disaggregation by capacity class and main vehicle technology for the two exemplar transport scenarios and a stricter 10 Gt carbon budget.

efficiency gains in ICEs as incorporated in the EMS (*eMode*) scenarios do not impact the preference for private EVs. The EVs also appear as the main alternative to oil ICEs, with the choice of gas ICEs having minimal impact.

Results for the public transport sector are more varied relative to the freight and private sectors. Table 10 shows that, generally, hydrogen vehicles in public transport are advantaged when emissions are unconstrained (UCE) or an increasing share of passenger travel is met by public transport (eMode). A higher share of public passenger travel demand is met by HFCVs if vehicle costs are comparable by 2020. Lower future oil prices (LoOil) advantages oil-fuelled vehicles. These include minibuses, comprising hybrid and e85 fuel vehicles. Gas vehicles that meet close to 10% of demand are preferred over EVs, which have a minimal footprint in the fleet, providing less than 5% of public passenger travel demand. The travel mode shift to rail remains constant during this time at about 10%. Gas vehicles appear less likely to meet passenger demand towards 2050 as HFCVs are generally preferred. The future price of oil is a determinant in vehicle choice, as a lower future oil price (LoOil) favours diesel vehicles. The Ricardo-AEA (2012) paper suggested marginal price variation for HFCVs and NGVs compared with diesel vehicle; and main trade-offs are fuel cost and vehicle efficiencies. Ignoring distribution losses, which are minimal compared with production efficiency, HFCVs are in the order of 30–40% more efficient than ICEs (diesel and gas) and therefore fuel cost appears the driver of choice in the LoOil scenarios, which favour oil vehicles in 2045. The cost advantage of diesel fuel over hydrogen gas lies in the range of 5–80% (Supplement, Table 5). For the UCE scenario, hydrogen fuel, via the favoured steam methane reformation (SMR) process, enjoys approximately 10% advantage over diesel and it is in the Reference UCE scenarios that HFCVs are most favoured in public transport with 50% of passenger travel met in 2045. Conversely the LoOil and 10 Gt scenarios markedly reduce the share of HFCVs as hydrogen fuel becomes up to 80% more costly. Hydrogen production is curtailed because of the CO_2-eq emissions associated with the SMR process, which is preferred over the more carbon-intensive coal-gasification and energy intensive electrolysis processes.

The generation portfolio in the power sector that would promote electrification of transport is further discussed in Section 4.3 along with the impacts on refinery capacity and production.

Table 11: Fuel supply in PJ for road transport.

	Base year Diesel 361; Petrol 414; Gas 0; Biofuels 0; Hydrogen 0; Electricity 3											
	2030	*2045*										
Scenario	*Diesel*	*Petrol*	*Biofuels*	*Hydrogen*	*Gas*	*Electricity*	*Diesel*	*Petrol*	*Biofuels*	*Hydrogen*	*Gas*	*Electricity*
Reference	329	361	20	15	111	34	182	156	26	55	83	186
RefTech2020	279	316	18	24	88	59	182	156	26	59	81	186
Ref-LoOil	383	409	23	14	90	14	228	197	17	46	56	173
RefHiTech	378	405	21	16	114	13	378	335	67	63	243	8
RefHiTech_LoOil	412	429	23	12	83	12	423	380	26	50	208	7
RefHiTech-UCE	378	405	21	16	114	13	375	332	54	69	243	8
RefTech2020-UCE	280	316	18	24	88	60	221	160	25	79	75	175
Ref-UCE	367	394	20	16	111	23	220	159	26	79	76	175
Ref10Gt	352	309	44	13	114	39	159	143	109	43	83	188
eMode	314	348	19	14	107	13	150	128	26	61	68	116
eModeLoOil	348	350	20	12	83	13	193	166	17	41	41	112
eModeHiTech	318	351	19	14	106	12	243	210	26	59	213	10
eMode10Gt	319	276	21	11	110	28	141	123	91	36	69	125

**Values for gas represent total imports including, for example, gas for electricity generation; 1 PJ ~ 0.16 mil.bbl of crude oil (6.12 GJ/bbl LHV)*

4.2 Fuel production and supply

Table 11 provides an indication of the extent of domestic fuel supply and the reliance on imported finished product. The values shown are in petajoules for ease of comparison of energy utility of fuels and include estimated 2015 fuel supply values as a reference. Fuel consumption by road transport in 2015 is estimated to be about 365 PJ of diesel and 422 PJ of petrol. Electricity as a fuel for passenger travel amounts to 3 PJ. Crude oil dependency for road transport, relative to 2015, decreases by about 85% in 2030 to about 55% in 2045 for the scenarios favouring higher market shares of EVs. A purchase cost premium of 20–30% in 2050 for EVs would see crude oil imports at similar levels to 2015 during 2030–2045. The importation of crude oil potentially increases at greater than 30% of present day levels by 2045 if future prices are less than USD 80/bbl.

The prevalence of oil product vehicles in 2030 results in diesel and petrol remaining important fuels and together accounting for 75–90% of fuel supply. Supply of finished oil product, including imports, varies between approximately 50 and 75% by 2045. The petrol:diesel supply ratio in 2015 is about 1.15, indicating a preference for petrol ICE vehicles that remains until 2030 with the ratio exceeding 1. The ratio by 2045 exceeds 1, as diesel vehicles dominate in the ICE fleet. These results do not reflect externalities associated with diesel ICE emissions, which future regulations may limit (SAPIA, 2008). Liquid biofuels as a share of total liquid fuel supply remains low at 3% in 2030 and up to 8% in 2045 and is mainly utilised in the public transport sector in the minibus taxi fleet. The tabled mandatory fuel blend regulation is the primary driver of supply, except for the 10 Gt scenarios for which a 25% share of total liquid fuel supply is achieved, of which biodiesel is the preferred fuel. The minibus public transport fleet is the primary consumer of bioethanol, with E85 vehicles accounting for 40–50% of the total fleet; followed by HFCVs with 30–40%; and conventional diesel and petrol vehicles (Other oil) accounting for 20% in2045 (Figure 8).

A high level of oil product supply in 2045 results if EV vehicles do not achieve purchase parity and lower crude oil prices occur during the planning period. The scenarios that realise a high level of EVs in the vehicle fleet would reduce oil product supply from about 90 to 75% of total supply in 2030. Electricity as a transport fuel ranges from 1–7% of supply in 2030 to 1–30% of supply in 2045. The higher values reflect optimistic EV vehicle purchase costs, which results in a reduction in overall transport energy supply requirements from approximately 1 100–700 PJ for the Reference demand scenarios and 800–500 PJ for the EMS demand scenarios.

Freight road transport is the main consumer of natural gas. Natural gas as a transport fuel appears to stabilise at 10–20% of fuel supply from 2030 to 2045. Higher levels of supply of 20–30% in 2045 are reached for the pessimistic EV cost scenarios. The 10 Gt scenarios increase gas imports by about 25% (200–230 PJ), which is primarily required for electricity generation.

A lower level of liquid fuel supply occurs under a stricter carbon budget, given the reliance on domestic coal-to-liquids (CTL) for 20–30% of fuel supply. This, which represents 20% of existing domestic refinery capacity (Table 12), accounts for about 10% of national emissions (excluding land use) with emissions of about 47 Mt CO_2-eq/annum, compared with 3 Mt CO_2-eq/annum for total crude

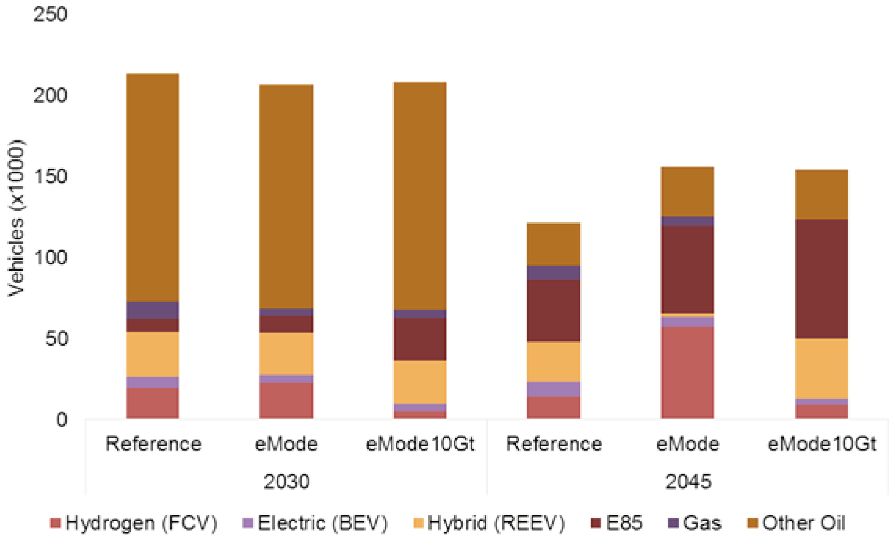


Figure 8: Total public passenger fleet by technology type.

oil refinery activity (Lozynskyy et al., 2014). A 10 Gt carbon budget scenario would require a cessation of CTL production before the technical retirement date in 2040, as indicated in Table 12. No new investment in CTL occurs except in the UCE scenarios. The UCE scenarios, which represent both pessimistic and optimistic EV adoption, would invest in new CTL capacity in the order of 25% of the existing CTL capacity. This amounts to about 40 000 bbl/day, or the equivalent of the existing gas-to-liquids plant in Mossel Bay. Gas-to-liquids is not discussed in the research presented here, as direct combustion ICE vehicles are preferred because of higher well-to-wheel fuel efficiencies, hence no new investment in GTL occurs.

The decision on the upgrade of existing crude-oil refineries to Euro5 fuel standard in 2025 is modelled as previously introduced (Table 3). Referring to Table 12, investment in the refurbishment of existing refineries occurs to meet fuel supply demand rather resort to imported product (Table 11). The pessimistic EV adoption scenario RefHiTech_LoOil, comprising higher EV costs and lower oil prices, would favour additional investment in new crude oil refinery capacity in the order of 25% of existing capacity or about 130 000 bbl/day (the Natref inland refinery has a reported capacity of 108 000 bbl/day).

Although the capacity of crude oil refineries remain fairly constant across the scenarios, their utilisation varies from 70–90% in 2030 to 40–90% in 2045. The low utilisation results from either the impost of a stricter 10 Gt carbon budget or high levels of EV shares in the road vehicle fleet, particularly private passenger vehicles, which comprise the bulk of road vehicles.

Table 12: Domestic refinery capacity.

	Refinery capacity (PJ/a) Crude oil 1001; CTL 246				*Refinery production (PJ/a) Crude oil 862; CTL 208*			
Base year	*2030*		*2045*		*2030*		*2045*	
Scenario	*Crude oil*	*CTL*	*Crude oil*	*CTL*	*Crude Oil*	*CTL*	*Crude oil*	*CTL*
Reference	1001	246	1001	0	775	212	502	0
RefTech2020	902	246	902	0	630	208	501	0
Ref-LoOil	1031	246	1031	0	930	211	634	0
RefHiTech	1018	246	1175	0	917	212	1068	0
RefHiTech_LoOil	1137	246	1307	0	1031	184	1195	0
RefHiTech-UCE	1018	246	1168	0	918	212	1061	0
RefTech2020-UCE	902	246	903	67	631	208	477	59
Ref-UCE	1001	246	1002	68	885	212	473	61
Ref10Gt	1101	246	1101	0	997	0	462	0
eMode	986	246	992	0	728	213	406	0
eModeLoOil	1001	246	1001	0	885	138	535	0
eModeHiTech	986	246	986	0	739	212	682	0
eMode10Gt	1005	246	1005	0	904	0	407	0

4.3 Electricity supply and emissions

The electrification of road transport would shift fuel demand to the power sector, and the imposition of a carbon budget allows the model to optimise the carbon budget across the supply and demand sectors. Liquid biofuels was introduced as an option and RE for electricity supply presents another opportunity for low-carbon transport. Table 13 contrasts the generation capacity across the scenarios. Table 13 includes the disaggregated capacity of sSolar-PV generation by type, i.e., utility generation transmitted via the centralised transmission network; or roof-top distributed generation (without storage). The UCE scenarios represent the counterfactual generation capacity.

The optimistic EV scenario RefTech2020 requires an additional 10–20 GW of capacity compared with the pessimistic RefHiTech-UCE and RefHiTech_LoOil scenarios, which require about 75–150 GW of capacity in 2030–2045. The HiTech costs and LoOil price scenarios, which increase the reliance on refinery oil product and gas, have the effect of reducing the capacity required by the power sector. Since EVs are ∼50% more fuel efficient than ICE equivalents, 20 GW of additional capacity reduces the total energy supply to transport by approximately 30% (Table 11).

New nuclear capacity of 6 GW is required to meet the 10 Gt scenario by 2045. An additional 5 GW of rooftop PV in the Reference 10 Gt case results in a marginal increase in total capacity of 4 GW such that the total power sector capacity of 192 GW represents the largest power sector build.

Figure 9 displays the electricity supplied to private passenger vehicles for the RefTech2020 scenario and its counterfactual UCE case. Private passenger fleet in 2030 consumes 70% of the 10 TWh supplied to road transport. The bulk of electricity supplied is utility-generated. Electricity is supplied in similar proportion via residential and utility-based supply in the initial phase of an earlier EV deployment (2020–2025).

In 2025, residential electricity is favoured with a supply ratio of 1.4 for the reference 14 Gt scenario compared to a supply ratio of 0.5 for the UCE scenario where utility-based supply is preferred. As the EV fleet grows to reach 45% of new vehicles in 2030 and meet 33% of passenger private travel, utility-based electricity becomes the predominant supply. The modelling period 2035–2045 suggests a convergence of supply preference towards residential and commercial electricity as rooftop PV capacity grows.

Although Table 14 suggests an economic preference for distributed PV throughout the period, PV supply is assumed to incorporate nil storage and thus only generates during daytime, with peak generation occurring around midday. The EVs in the national fleet are currently assumed to be charged on average constantly and therefore exhibit a uniform profile.

Improvement of the current EV model to incorporate and gauge the effects of driver behaviour with higher resolution time-of-use charging profiles and battery degradation effects is planned for future research (Nicholas et al., 2016; Pellettier et al., 2015; Wietschel et al., 2013).

Road transport electrification appears to have little impact on electricity prices, as the generation cost trajectory exhibits little variation across the scenarios except for the 10 Gt carbon budget scenarios, which act as the primary stimulus of an increase in generation cost (Figure 10). A general trend of increasing generation cost from 0.60 ZAR/kWh to

Table 13: Capacity in GW of the power sector with solar-PV capacity by generation class.

	Base year total: 53 GW											
	2030						*2045*					
Scenario Name	*Total*	*PV rooftop*	*PV utility*	*Gas*	*Coal*	*Nuclear*	*Total*	*PV rooftop*	*PV utility*	*Gas*	*Coal*	*Nuclear*
Reference	83	6	15	0.39	34	1.86	179	33	47	29	19	0
RefTech2020	85	6	17	0.39	34	1.86	180	30	49	30	19	0
Ref-LoOil	79	6	15	0.39	34	1.86	174	29	50	30	19	0
RefHiTech	85	6	16	0.39	34	1.86	164	29	42	25	18	0
RefHiTech_LoOil	80	6	16	0.39	34	1.86	159	28	41	24	19	0
RefHiTech-UCE	77	5	15	0.39	36	1.86	152	21	43	24	22	0
RefTech2020-UCE	82	6	16	0.39	36	1.86	170	26	47	28	22	0
Ref-UCE	78	6	15	0.39	36	1.86	169	26	49	29	22	0
Ref10Gt	107	7	22	1.1	34	1.86	192	50	42	17	13	6
eMode	80	6	13	0.39	34	1.86	169	22	48	29	21	0
eModeLoOil	76	6	15	0.39	35	1.86	161	21	47	27	22	0
eModeHiTech	81	6	15	0.39	34	1.86	162	25	44	26	19	0
eMode10Gt	104	7	21	0.78	34	1.86	188	45	44	18	13	6

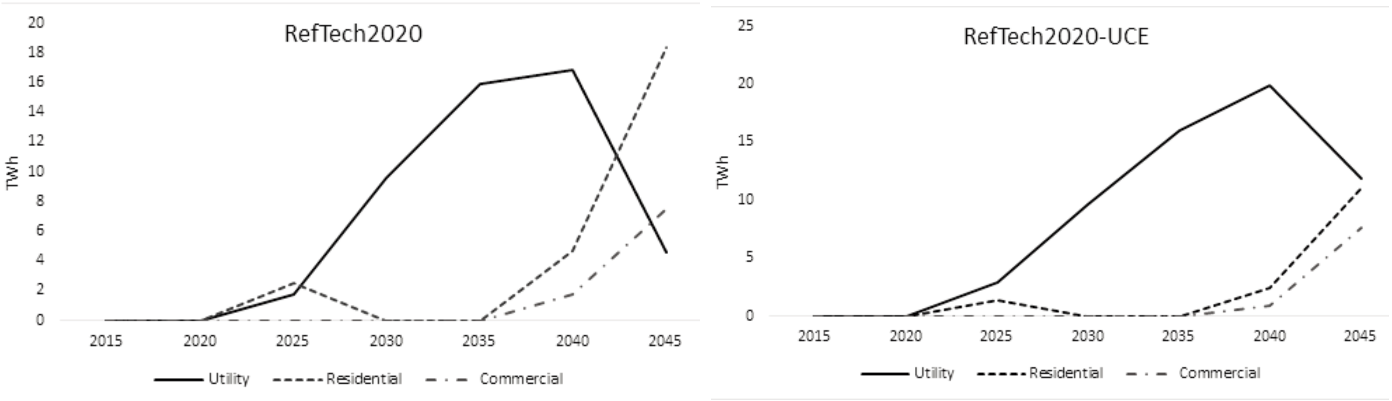


Figure 9: Electricity supply sources for private passenger electric vehicles.

Table 14: Projected LCOE for PV supply and average utility price (ZAR/kWh).

Scenario	Supply	2025	2030	2045
RefTech2020	Commercial-PV	0.73	0.90	0.77
RefTech2020-UCE	Commercial-PV	0.73	0.90	0.77
RefTech2020	Residential-PV	0.99	1.25	1.08
RefTech2020-UCE	Residential-PV	0.99	1.25	1.08
RefTech2020	Utility	1.34	1.51	1.70
RefTech2020-UCE	Utility	1.32	1.50	1.63

Note: LCOE values include the cost of distribution.

0.85 ZAR/kWh is observed, with the 10 Gt scenario approaching 1.10 ZAR/kWh, which is largely due to earlier investment in solar-PV (Table 13).

The subsequent GHG emissions associated with the transport sector and its share of the national budget is summarised in Table 15. Also included for comparison are the estimated values for 2015. In terms of magnitude, transport emissions generally appear to plateau at their 2015 levels by 2030. Optimistic EV purchase costs would result in a decline in relative emissions by 2030 and result in a 50% reduction in present day emissions by 2045 from 60 to 30 Mt CO_2-eq. A lower future oil price and EV cost premium of up to 20–30% would

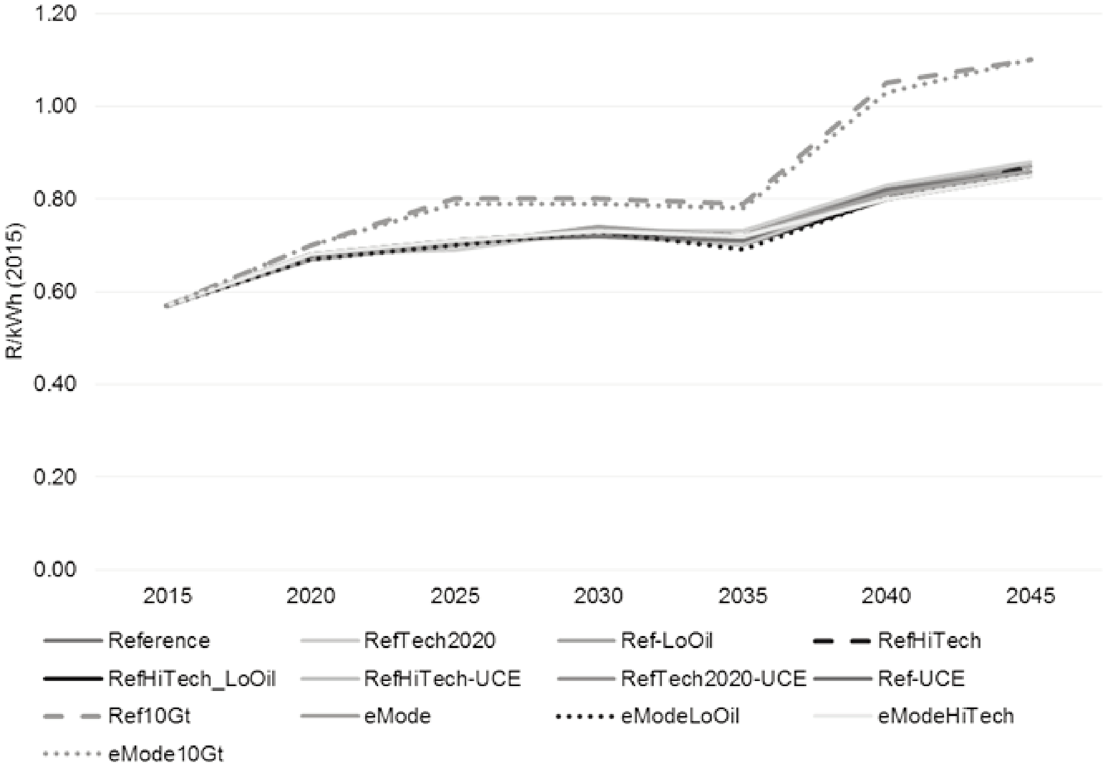


Figure 10: Average lectricity generation cost by scenario (2015 rands).

plateau transport emissions across the planning period at 60 Mt CO_2-eq, which is largely caused by the reliance on hybrid vehicles in the private passenger sector.

The EMS scenario with optimistic future vehicle cost exhibits the lowest emission trajectory, with a value of 27 Mt CO_2-eq in 2045. The EMS scenarios are, however, not distinguished by their overall transport emissions as values occur in a similar range as the other scenarios.

The transport sector emissions, as a share of the national GHG emissions, would remain at current levels of about 14%, with high markets shares of oil product hybrid vehicles. This potentially decreases to less than 10% should there be a large uptake of EVs. The GHG emissions from the power sector appear to plateau across the planning period at their present-day level of approximately 235 $MtCO_2eq$ for all scenarios except the Reference and 10 Gt scenarios.

5. Conclusions

The South Africa TIMES model was used to examine how the transport sector would help South Africa transition to a low-carbon economy; how new and emerging technologies – more specifically electric vehicles – could play a role; and what would be the implications for the supply of transport fuels in the medium-to-long-term future. Oil product vehicles, which include hybrid and E85 vehicles, remain an important vehicle class until at least 2030. In all three road transport sectors (freight, private and public), lower forecast crude oil prices – USD 80/bbl from 2020 rather than USD 125/bbl by 2050 (IEA, 2016) – would encourage petroleum product consumption, increasing the share of internal combustion engine (ICE) vehicles during the interim horizon (2030). Crude oil dependency for road transport could plateau or increase to greater than 30%, relative to present day levels, should the price of oil reach less than USD 80 /bbl. Such a scenario effectively forestalls the emergence of electric vehicles (EVs) until the latter half of the planning horizon (2045), where EV preference is insensitive to oil price.

The results, however, suggest that uncertainty in vehicle purchase cost is the primary determinant of the rate and level of penetration of EVs into the vehicle fleet. Should vehicle cost parity be realised, EVs could account for a high share of in the future fleet, accounting for approximately 80% of new light vehicle sales in 2045 for both freight and private transport. Electricity would account for ~30% of transport fuels and reduce transport energy supply requirements by about 30% in 2045.

The power sector would consequently require an additional 10–20 GW of capacity during the later period, 2030–2045, increasing the importance of electricity as a road transport fuel. Emissions from transport would plateau in 2030 at their current estimated 60 $MtCO_2$-eq in 2015 and decline to 30 $MtCO_2$-eq by 2045, equating to less than 10% of national greenhouse gas emissions (excluding land use) present and future, as emissions from the power sector are expected to plateau at present-day levels with increased investment in renewable energy, specifically solar-PV (both utility and distributed) and gas.

Hydrogen fuel also emerges as an important alternative fuel for public transport and freight in the future. Within the freight sector, light commercials are the predominant adopters of bEV technology, whereas hydrogen fuel cell vehicles (HFCVs) are preferred for the bulk of the heavy vehicle fleet

Table 15: Full economic sector CO_2-eq emissions contrasted with the power and transport sectors.

	Emissions $MtCO_2$-eq							
	Base year emissions: Total: 426 Power: 234 Transport: 60 14%							
		2030			*2045*		*2030*	*2045*
Scenario	*Total*	*Power*	*Transport*	*Total*	*Power*	*Transport*	*Transport share*	
Reference	437	223	56	379	161	33	13%	9%
RefTech2020	432	223	49	432	223	33	11%	8%
Ref-LoOil	442	223	62	442	223	39	14%	9%
RefHiTech	429	209	60	429	209	63	14%	15%
RefHiTech_LoOil	431	215	63	431	215	67	15%	15%
RefHiTech-UCE	459	240	60	459	240	63	13%	14%
RefTech2020-UCE	449	241	49	449	241	32	11%	7%
Ref-UCE	458	241	59	458	241	32	13%	7%
Ref10Gt	308	137	54	308	137	34	18%	11%
eMode	435	223	53	435	223	27	12%	6%
eModeLoOil	427	231	55	427	231	32	13%	8%
eModeHiTech	435	223	54	435	223	45	12%	10%
eMode10Gt	307	142	49	307	142	29	16%	9%

(>24 ton capacity) due to their extended range and higher well-to-wheel fuel efficiencies compared to diesel and gas. Diesel and gas remain important fuels. Uncertainty over future oil prices and EV costs could result in diesel and gas ICE vehicles respectively contributing 30% and 20% of freight demand in 2045.

A stricter carbon budget deters investment in HFCVs, due to the emissions associated with production, and instead favours biodiesel. Excepting the 10 Gt scenarios, a limited preference for biofuels exists in the transport fleet and features mainly in the minibus public transport fleet.

Furthermore, the modelling indicates that investment in the refurbishment of crude-oil refineries to meet revised regulations for cleaner fuel standards is economically preferred over imported finished product.

The exploration of a number of scenarios with the SATIM model demonstrates the importance of a holistic, full-sector assessment encompassing technology preference, emissions, fuel consumption and supply options, as was noted in the results presented. However, when considering the transformation of transport, price distortions and policies such as fuel taxes and vehicle tariffs can act powerfully in the long term to either hinder or promote sustainable transport.

A limitation of this paper was the response in energy demand to driver behaviour and charging habits, research which requires a more granular temporal demand profile for EVs by driver profile. Also, at present the SATIM model does not incorporate distributed solar-PV with storage and its effects on the supply sector and transport vehicle choice. This remains the subject of further research including further detailed transport sector-specific analyses.

Notes

1. Electric vehicle in this paper refers to battery electric vehicles.
2. Supplementary material can be found at https://journals.assaf.org.za/jesa/article/view/5596.

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Journal of Energy in Southern Africa

Volume 29 Number 3

The impact of energy fuel choice determinants on sustainable energy consumption of selected South African households

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Abstract

The erratic nature of electricity supply in South Africa combines with other factors continuous to affect household electricity demand, leading to increasing reliance on other fuels. This dependence is characterised by the use of traditional fuels by mostly low-income households, contributing significantly to environmentally harmful emissions. This study assessed the primary determinants of energy fuel choice in selected South African households, to alert policymakers to important energy consumption behavioural tendencies that can inform policies and that can assist sustainable energy growth and reduction of biomass use in households. The investigation was primarily based on energy consumption models and used a quantitative research design. Gauteng and North West were considered for data collection. Households, in general, tended to practice energy stacking. The results suggest policy measures that could promote sustainable energy use by households.

Journal of Energy in Southern Africa 29(3): 51–65
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a4714

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Technology

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1. Introduction

Andrew (2015:1) asserted that the most important need in life is the availability of energy to drive social development and industrial competitiveness. Elias and Victor (2005:4) argued that human behaviour has been changing constantly towards the utilisation of energy because of the influence of technological developments. However, despite the need for improved access to sustainable energy, Ellingsen (2010:3) stated that there is still a constant growth in energy inequality, as most rural households across the world continue to struggle to access modern energy services, leading to increasing reliance on traditional biofuels. Pachauri and Rao (2014:1) highlighted that energy inequality was commonly analysed on the following bases:

- income or some related monetary measure, as prevailing disparities in income would closely mirror inequalities in energy accessed and consumed; and
- disparities in energy quantities consumed and types of energy sources predominantly used.

The authors argued that the distribution of modern energy sources remained highly unequal, with a much higher dependence on environmentally unfriendly energy fuels by most people, especially in developing countries. A massive study conducted by the International Energy Agency (IEA) (2006:40) on households' use of biofuels, reflected the following findings;

- over 2.5 billion people around the world still primarily rely on traditional energy sources such as fuelwood, charcoal, agricultural and animal waste to meet their daily energy demand for cooking and heating yearly. A total of 1.6 billion people of are still without complete electricity access;
- in developing countries over 90% of most household daily energy consumption comes from biofuels; and
- one-third of the world's population (2.7 billion people) will still primarily depend on biofuels in 2030.

Oparinde (2010:3) found that biomass fuels could be regarded as combustible renewables such as vegetable materials that can be converted into vegetable oil, landfill gas and bio-additives. Biomass can also be traditional energy fuels such as wood and animal waste, and intermediate biomass sources such as charcoal and coal. Biomass use in the present study was taken to refer to traditional energy fuels. Gallachóir (2007) recommended that energy research was primary for developing robust policies and initiating a change towards increased energy sustainability. Such empirical research significantly contributes to understanding energy poverty in South Africa. The IEA (2002:376) found that only 23% of the sub-Saharan population is electrified, with about 500 million people still unconnected to an electricity source, making the least electrified region in the world. Winkler (2006:34) cited recent estimates showing that a significant proportion of South Africa's households would remain unelectrified. Treiber *et al.* (2015) noted that improvement towards the consumption of cleaner fuels would reduce energy poverty. Linear model investigations such as that of Ismail and Khembo (2015) predict a positive relationship between socio-economic development and energy fuels transition in South Africa. Howells *et al.* (2005) noted that a primary hindrance to facilitating energy transition in the country is the knowledge deficit in policymaking on factors that govern energy choices by households.

2. Conceptual framework development

This study, following the models discussed in the supplementary file,[1] took into consideration both the energy ladder and the energy stacking hypotheses. Concerns on biomass fuels use and its effect on clean energy use have not been adequately analysed in the South African context (Howells *et al.*, 2005), with very little empirical research exploring the appropriateness of energy choice models in the country's household sector. It is, however, noteworthy much empirical research has been conducted here with regard to the energy ladder (Alberts *et al.*, 1997; Davis, 1998; Howells *et al.*, 2006; Louw *et al.*, 2008). There is limited research advancing the applicability of the energy stacking hypothesis, despite the work of Madubansi and Shackleton (2006); and Musango (2014), with objectives related to this hypothesis. The present study, therefore, comprehensively explored both the energy ladder and the energy stacking guidelines in the South African context. Uhunamure *et al.* (2017) can be recognised as one of the first researchers to consider both models for such a study. Households' fuel choice classification criteria of endogenous factors (household characteristics) and exogenous factors (external conditions) in Kowsari and Zerriffi (2011) guided the development of the conceptual framework for the empirical research (see Table 1).

The present study considered only the endogenous category. Two factors were considered from the economic characteristics and four factors from the non-economic characteristics.

2.1 Economic characteristics

The economic category was generally considered to be a primary influence on households' energy choice. The income and expenditure factor were sampled in the empirical research. Overemphasising income or expenditure as a measurement of wealth in determining a household's fuel choice is unclear, as in countries such as South Africa, a sig-

Table 1: Household fuel choice factors (Kowsari and Zerriffi, 2011).

Categories	*Factors*	*Measuring aspect*
	Endogenous factors	
Economic characteristics	Income, expenditure and landholding	Endogenous characteristics reflect the capabilities of households, behavioural attitudes, preferences and experiences of households
Non-economic characteristics	Household size, gender, age, household composition, education, labour and information	
Behavioural and cultural characteristics	Preferences(e.g food taste), practices, lifestyle, social status and ethnicity	
	Exogenous factors	
Physical environment	Geographic location and climatic condition	Exogenous factors influence household decisions about their energy system by affecting available choices and incentives to choose one energy technology or fuel over another.
Policies	Energy policy, subsidies and market and trade policies.	
Energy supply element	Affordability, availability, accessibility and reliability of energy supplies	
Energy device characteristics	Conversion efficiency, cost and payment method and complexity of operation	

nificant proportion of households depend on free, government-subsidised energy. Research can choose to use either income or expenditure as a measurement of wealth, but appplication should be relative to its context (Elias *et al*., 2005).

2.1.1 Income and setting

Income was the first factor studied in as a significant determinant of energy fuel choice, through the energy ladder model. Early findings concurred that there is a significant association between income and households energy choice (Barnes *et al*., 1994, 1996; Pachauri & Spreng, 2004; Wuyuan *et al*., 2008). Even though new findings emerged exploring more comprehensive approaches to factors influencing household fuel choice pattern, Whitfield (2006:143) pointed out the shortcomings in energy research to advance the understanding of household fuel choice significantly beyond the influence of incomes. Van der Kroon *et al*. (2013) found that the placement of a household in the environment would typically determine the level of opportunity and possible income level.

2.1.2 Expenditure

Davis (1998) and Heltberg (2005) used expenditure instead of income in measuring economic influence on households' energy fuel choice. Low- and high-income households differ in energy spending as:

- the price of modern fuels, as well as their transaction cost, is usually high;
- income for low-income households is typically too low to accommodate payments associated with modern energy systems; and
- low-income households have an uncertain income source to accommodate regular spending required by modern energy sources.

A household's expenditure of fuel will depend on the unit price of the fuel demanded (Schlag & Zuzarte, 2008:10). As a rise in a household income will enable its capacity to switch to more sustainable fuels, primary and useful energy consumption will also increase as well (Mestl & Eskeland, 2009). Link *et al.* (2012) highlighted that minimum wages influence reliance on biomass energy fuels. Rao and Reddy (2013) maintained that household incomes derived from wages or salaries had a positive impact on the probability of using cleaner fuels. Van der Kroon (2013) found that a household's capital determined the fuel type relied on.

2.2 Non-economic characteristics

In early household fuel choice studies, the economic factor was the only one used to capture patterns of household fuel-switching through the aid of the energy ladder. However, non-economic elements later gained momentum, based on the concept of energy transition. Campbell *et al.* (2003) determined that income continued to be the most recommended determinant of fuel choice and the world is gradually heading to a dichotomy in which norms such as wealthier households being able to adopt modern fuels while poorer oness are increasingly forced to choose biomass will be irrelevant. The present empirical study considered the following household categories: size, education and gender.

2.2.1 Household size

Kowsari and Zerriffi (2011) pointed out that household size determined the amount of energy consumed by a household. Household size indirectly influences households to practise both energy switching and energy stacking behaviours. Ado (2016) articulates household size to significantly affect the use of energy fuel types. The size of a household will influence fuel transition because large ones tend to practise energy stacking more than smaller ones.

2.2.2 Education

Link *et al.* (2012) asserted that education influenced energy fuel transition in two ways. Firstly, schooling limits the labour force for fuel acquisition activities such as wood collection, possibly leading to a tendency to adopt fuels requiring no acquisition efforts, such as paraffin and gas. Secondly, education can initiate change by providing knowledge about the dangers that biomass energy pose to health and the environment. Schlag and Zuzarte (2008:14) highlight that a large proportion of the global population, especially sub-Saharan Africans, lack significant tutelage on consumers fuel choice theory. Thus, some informal education on fuels will greatly impact on households' fuel preferences. Prasad (2008) highlighted the need for people to be well informed, and thus empowered, at household level about the advantages of cleaner energy and the shortcomings of biomass fuels. According to the theory of cognitive dissonance, individuals strive for consistency between their knowledge and behavioural attitudes (Kowsari & Zerriffi, 2011). Whitfield (2006:143) mentioned that information education and social learning could be used to influence households energy fuels adoption significantly. Educational level will affect households' disposition to adopt modern fuels (Musango, 2014).

2.2.3 Gender

Patriarchal societies generally expect women to perform the majority of household tasks, such as cooking and washing. Gender can immensely influence fuel choice. A household where a male is the primary income earner and the main decision-maker might neglect the importance of the costs and benefit of clean cooking fuels (Schlag & Zuzarte, 2008:13-15). Treiber (2015) concurred that culture and tradition can influence women ignoring modern energy technologies. It was found that women preferred preparing chapattis using charcoal and fuelwood as this was less time consuming, given constant and controllable heat. The cooking process involved traditional pots and biomass fuel, which influenced the taste (Treiber, 2015). Van der Kroon *et al*. (2013) found that women and children are most involved in collecting wood in most South East Asian countries. Balmer (2007) maintained that gender roles referred to the different tasks individuals performed; in households it means a division of labour in which different obligations are assigned to men and women.

2.3 Household activities and energy use in the South African context

The empirical research considered that certain fuels are mostly utilised for a particular household activity in the South African context. Electricity was the only energy type that households universally used for various activities such as cooking, lighting and heating. Use of LPG is mainly limited to cooking, solar energy to water heating. Direct utilisation of biomass fuel types (coal, wood and charcoal) by households includes for heating and cooking (Musango, 2014). Research on energy transition shows that most households' basic energy demand is for heating, cooking and lighting and fuel choice mostly relates to these (IEA, 2006:369). It is necessary to address these together for a realistic approach to household energy analysis (Kowsari & Zerriffi, 2011) and they were what the present study focused on.

3. Methodology

The study considered households in the North West and Gauteng provinces of South Africa. Gauteng because of its level of urban growth and being the country's nucleus of social development. North West province was selected as a developing are, to represent the country's spatial geography. Pretoria and Johannesburg were the target sample cities in Gauteng, and Mafikeng and Potchefstroom in the North West.

A purposive-convenience sampling technique was used. Actual data gathering utilised the quota sampling guidelines. Purposive-convenience sampling involves targeting participants at random. Purposive targeting was employed to find mostly income earners considered to be the financial nucleus in providing households' day-to-day needs. Convenience sampling meant gathering data from households based on their availability and willingness to participate in the study. The quota sampling guideline was used to target households from identified zones from sample cities. The demographics are mostly in clusters where an urban city has an outskirt settlement – usually referred to as a township. These townships reflect underdeveloped characteristics as compared with central city settlements with more sustainable development tendencies. The aim was to identify low-income and high-income residential groups, ensure that enough participants from both groups were considered. Table 2 presents a description of sampled groups, Table 3 shows the income brackets.

This paper is part of a larger project aimed at developing a framework for sustainable energy

Table 2: A description of sampled groups.

City	*Quotas*	*Income rank status*
Mafikeng quota (A)	Riviera Park	High
Mafikeng quota (B)	Extension 36	Low
Potchefstroom quota (A)	Potchefstroom	High
Potchefstroom quota (B)	Ikageng	Low
Pretoria (A)	Pretoria North	High
Pretoria (B)	Soshanguve	Low
Johannesburg (A)	Auckland Park	High
Johannesburg (B)	Soweto	Low

development in South Africa. The data collection employed closed-ended questionnaires with defined categories for examining the effect of electricity supply and consumption in the domestic sector and related electricity consumer behaviours. Questions were strictly dichotomous, with participants ticking “yes” or “no” on the options that relate to their practised fuel choice behaviours. In total, 400 households were given questionnaires, but just 323 responded.

4. Data analysis and results

The International Business Machines (IBM) Statistical Package for Social Sciences (SPSS) statistics version 24.0.0 was used in analysing data (IBM SPSS, 2016). A test for reliability was conducted on the data by estimating the Cronbach Alpha, which measures the internal consistency of responses and indicates the level to which participants’ opinions are relative on scale. For an exploratory study, reliability measured by Cronbach’s Alpha of >0.5 and <0.7 is good, and >0.7 gives excellent reliability. The Cronbach Alpha obtained was 0.74, implying that there was a sufficient internal consistency from acquired data. The Chi-square test was used to identify if an association existed between sampled groups through the Cramer’s V. The aim was to determine the existence of equality between the two categorical (groups). A Cramer value >0.1 <0.3 indicates small, $>0.3<0.5$ medium and >0.5 large associations between groups. The p values are also presented to confirm the validity of results. It is, however, not relevant for this paper as the research aimed at establishing practical significant differences among sample groups, rather than statistical differences.

4.1 Influence of income on energy fuel choice

The criteria used in this factor determinant involved sampling participants based on quotas within the target sample demographics. The investigation also reflected that groups’ income status was relative to sampled income brackets similar to Makonese *et al.* (2018). The income profile of sampled groups is shown in Table 3.

The results indicate that sampled areas from townships on average comprised households with lower income brackets compared with those from main town zones. Analysis considered grouping all settlements with similar income status to perform a general analysis based on each of the classified income ranks (high- and low-income groups).

Table 4 shows the results for income groups’ use of electricity for lighting, cooking and heating. The Cramer’s V differs only marginally within income groups in the use of electricity for cooking of 0.13 and heating of 0.21. Results indicate that 95.8% of households from the high-income group and 94.3% of low-income group used electricity for lighting in general. Furthermore, results indicate that income influences household’s use of electricity for cooking and heating. Most high-income earners use electricity for cooking at 95.8% and heating at 79.1%. Low-income earners use electricity less for cooking at 77.6% and heating at 71.5%.

Table 5 reflects the results for income groups’ use of LPG. The Cramer’s V of 0.21 indicates a zero difference within income groups for the use of LPG for cooking and heating. Results reveal that high-income households tended to use gas at 35.2% as an alternative cooking fuel compared with 16.5% of low-income groups. Low-income groups tend to use paraffin for cooking at 15.2% compared with high-income households at 3%.

Table 6 presents results for solar water heating. High-income households tended to utilise solar

Table 3: A description of the income profile of sampled groups.

Groups	*Total participants*	*Brackets (ZAR/month)*				
		>15 000	*15 001–25 000*	*25 001–34 000*	*34 001–46 000*	*>46 000*
Soweto	49	38	5	6	0	0
Extension 36	50	43	7	0	0	0
Ikageng	9	7	3	0	0	0
Soshanguve	50	33	8	9	0	0
Rivira Park	49	0	11	33	5	0
Potcheftroom	15	0	3	6	6	0
Auckland Park	50	0	0	8	24	18
Pretoria North	51	0	0	14	29	8

Table 4: Use of electricity by income (ZAR/month).

Description	*High-income*		*Low-income*		*Cramer's V*	
	Yes	*No*	*Yes*	*No*	*P values*	*Effect*
Electricity use for lighting						
Frequency	158	7	149	9	0.05	0.03
Percentage	95.8	4.2	94.3	5.7		
Electricity use for cooking						
Frequency	139	19	128	37	0.01	0.13
Percentage	95.8	5.7	77.6	22.4		
Electricity use for heating						
Frequency	125	33	118	47	0.05	0.21
Percentage	79.1	20.9	71.5	28.5		

Table 5: Use of liquefied petroleum gas and paraffin by income.

Description	*High-income*		*Low-income*		*Cramer's V*	
	Yes	*No*	*Yes*	*No*	*P values*	*Effect*
Gas use for cooking						
Frequency	58	107	26	132	<0.001	0.21
Percentage	35.2	64.8	16.5	83.5		
Paraffin use for cooking						
Frequency	5	160	24	134	<0.001	0.21
Percentage	3	97	15.2	84.4		

Table 6: The use of solar water heater by income.

Description	*High-income*		*Low-income*		*Cramer's V*	
	Yes	*No*	*Yes*	*No*	*P values*	*Effect*
Frequency	40	125	16	142	0.001	0.26
Percentage	24.2	75.8	10.1	89.9		

Table 7: Use of traditional fuels (biomass) by income.

Description	*High-income*		*Low-income*		*Cramer's V*	
	Yes	*No*	*Yes*	*No*	*P values*	*Effect*
Use of wood for cooking						
Frequency	9	156	65	93	□0.001	0.34
Percentage	5.5	94.5	42	58		
Use of wood for heating						
Frequency	20	145	28	130	0.05	0.07
Percentage	12.1	87.9	17.7	82.3		
Use of coal for cooking						
Frequency	6	152	118	47	0.05	0.53
Percentage	4	96	72	28		
Use of coal for heating						
Frequency	12	146	15	150	0.05	0.02
Percentage	7.6	92.4	9.1	90.9		

water heaters at 24.2% as an alternative energy source for heating compared with 10.1% of low-income groups. The use of solar within the income groups had an effect size of 0.26 tending towards medium. Cramer's V indicate that there is a small association between income and the use of solar water heaters.

Table 7 presents results on households' use of energy fuels with biomass. In general, Cramer's V reflect that there were medium differences within income groups for the use of wood for cooking at 0.34 and large differences for the use of coal for cooking at 0.53. The results reflect that low-income households tended to use wood more for cooking at

42% compared with high-income households at 5.5%. Low-income groups also used coal significantly for cooking at 72%. High-income groups tended to not use coal for cooking, at only 4%.

4.2 Expenditure

Expenditure on energy was also tested to determine the influence of spending power on households' energy choice. Participating households from the two sampled groups had to indicate their monthly spending on electricity on a scale ranging from below ZAR 200 to above ZAR 300. The aim was to determine the spending disparity on electricity within the sampled household groups. Table 8 presents the results for households spending on electricity, showing that high-income households spent most, with a larger proportion of them at 81.1% spending above ZAR 300 for electricity monthly. Low-income households at 27.8% spent less than ZAR 300, while 52.5% spent less than ZAR 200. This implies that the proportion of income devoted for electricity spending was small for low income households compared with high-income households.

Table 8: Expenditure per income groups in rands.

Description	*<200*	*<300*	*>300*	*Total*
		High income group		
Frequency	11	20	133	164
Percentage	6.7	12.2	81.1	100
		Low income group		
Frequency	83	31	44	158
Percentage	52.5	19.6	27.9	100

4.3 Household size

Household size was a significant influence on energy choice. Table 9 presents results for household size effect on electricity for lighting, cooking and heating. Cramer's V reflect small differences for household size and use of electricity for cooking (0.15) and heating (0.18) but not lighting (0.08).

Table 10 presents the influence of household size on the use of LPG for cooking. Households with more members tended to utilise LPG for cooking. Cramer's V reflected small differences between household size and household use of paraffin (0.14); and gas fuel (0.13) for cooking. Families with 1 to 3 members used paraffin less for cooking (4.5%), compared with households with 4 to 6 members (13.1%), and 7 and more members (11.8%). Households with 1 to 3 members also used less gas fuel for cooking (22.3%) compared with households with 4 to 6 members (26.3%) and at least 7 members (41.8%).

Table 11 presents results for household size influence on the use of coal and wood for cooking and heating, indicating that household size was not significant here. For instance, the use of wood for heating when the frequency of participants and percentages obtained are compared reflected that household size with 1 to 3 members (14.1%) and 4

Table 9: Household size influence on the use of electricity for lighting, cooking and heating.

No. of members	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
			Use of electricity for lighting			
1 – 3	Frequency	128	2	130	0.05	0.18
	Percentage	98.5	1.5	100		
4 – 6	Frequency	148	8	156		
	Percentage	94.9	5.1	100		
>7	Frequency	29	5	34		
	Percentage	85.3	14.7	100		
			Use of electricity for cooking			
1 – 3	Frequency	47	78	125	0.021	0.15
	Percentage	37.6	62.4	10		
4 – 6	Frequency	61	94	155		
	Percentage	39.4	60.6	100		
>7	Frequency	19	12	31		
	Percentage	61.3	38.70	100		
			Use of electricity for heating			
1 – 3	Frequency	102	28	130	0.03	0.08
	Percentage	78.5	21.5	100		
4 – 6	Frequency	116	40	156		
	Percentage	74.40	25.60	100		
>7	Frequency	23	11	34		
	Percentage	67.60	32.40	100		

Table 10: Household size influence on the use of liquefied petroleum gas and paraffin for cooking.

No. of members	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of paraffin for cooking						
1 – 3	Frequency	7	149	130	0.03	0.14
	Percentage	4.5	95.5	100		
4 – 6	Frequency	17	113	156		
	Percentage	13.1	86.9	100		
>7	Frequency	4	30	34		
	Percentage	11.8	88.2	100		
Use of gas for cooking						
1 – 3	Frequency	29	101	130	0.06	0.13
	Percentage	22.3	77.7	100		
4 – 6	Frequency	41	115	156		
	Percentage	26.3	73.7	100		
>7	Frequency	14	20	34		
	Percentage	41.2	58.8	100		

Table 11: Household size influence on the use of biomass for cooking and heating.

No. of members	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of wood for cooking						
1 – 3	Frequency	22	134	156	0.05	0.09
	Percentage	14.1	85.9	100		
4 – 6	Frequency	17	113	130		
	Percentage	13.1	86.9	10		
7	Frequency	8	26	34		
	Percentage	23.50	76.50	100		
Use of coal for cooking						
1 – 3	Frequency	6	150	156	0.29	0.09
	Percentage	3.80	96.20	100		
4 – 6	Frequency	8	122	130		
	Percentage	6.20	93.80	100		
>7	Frequency	2	32	34		
	Percentage	5.90	94.10	100		
Use of wood for heating						
1 – 3	Frequency	22	134	156	0.13	0.11
	Percentage	14.10	85.90	100		
4 – 6	Frequency	17	113	130		
	Percentage	13.10	86.90	100		
>7	Frequency	9	25	34		
	Percentage	26.50	73.50	100		
Use of coal for heating						
1 – 3	Frequency	10	146	156	0.26	0.09
	Percentage	6.4	93.6	100		
4 – 6	Frequency	12	118	130		
	Percentage	9.2	90.8	100		
>7	Frequency	5	29	43		
	Percentage	14.7	85.3	100		

to 6 (13.1%) displayed a similar pattern of wood use for heating.

Table 12 presents results for solar water heating. Cramer's V indicate that there is no association between household size and the use of solar water heaters.

Table 12: Household size influence on the use of solar water heating.

No. of members	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
1 – 3	Frequency	12	118	130	0.26	0.09
	Percentage	9.20	90.8	100		
4 – 6	Frequency	10	146	156		
	Percentage	6.40	93.6	100		
>7	Frequency	5	29	34		
	Percentage	14.7	85.3	320		

Table 13: Education's influence on the use of electricity for lighting, cooking and heating.

Qualification level	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
		Use of electricity for lighting				
Grade 12 and below	Frequency	52	2	54	0.5	0.07
	Percentage	96.3	3.7	100		
Diploma	Frequency	57	1	58		
	Percentage	98.3	1.7	100		
Degree	Frequency	86	5	91		
	Percentage	95.5	5.5	100		
Postgraduate	Frequency	106	7	113		
	Percentage	93.8	6.2	100		
		Use of electricity for cooking				
Grade 12 and below	Frequency	37	17	34	0.18	0.12
	Percentage	68.5	31.5	100		
Diploma	Frequency	48	10	58		
	Percentage	82.8	17.2	100		
Degree	Frequency	81	10	91		
	Percentage	89	11	100		
Postgraduate	Frequency	96	17	113		
	Percentage	85	15	100		
		Use of electricity for heating				
Grade 12 and below	Frequency	37	17	54	0.03	0.15
	Percentage	68.50	31.50	100		
Diploma	Frequency	48	10	58		
	Percentage	82.8	17.2	100		
Degree	Frequency	86	5	91		
	Percentage	95.5	5.5	100		
Postgraduate	Frequency	96	17	113		
	Percentage	85	15	100		

4.4 Education

The opinions of participants were assessed by evaluating the influence of primary income earners' educational levels on the household's fuel choice. Table 13 presents results for electricity use for lighting, cooking and heating. Cramer's V reflected small differences for cooking (0.12) and heating (0.15). Participants with higher qualifications such as postgraduates (85%) and degrees (89%) used electricity mostly for cooking in comparison with participants who possessed a diploma (82.8%) and grade 12 and below (68.5%). Participants with higher qualifications, postgraduates (85%) and degrees (95%) used electricity mostly for heating compared with participants in possession of a diploma (82.8%) and grade 12 and below (68.5%).

Table 14 reflects results on the influence of educational level on the use of LPG and paraffin for cooking. It was found that there was an influence. Cramer's V indicated small-to-medium differences for the use of paraffin (0.19) and of gas (0.18). Participants with lower educational levels such as grade 12 and below (15.9%) and diploma (11.1%) used paraffin mostly for cooking compared with participants at higher educational levels: degree (3.3%) and postgraduate (3.4%). Participants with

Table 14: Education's influence on the use of liquefied petroleum gas and paraffin for cooking.

Qualification level	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of paraffin for cooking						
Grade 12 and below	Frequency	18	95	113	0.01	0.19
	Percentage	15.9	84.10	100		
Diploma	Frequency	6	48	54		
	Percentage	11.1	88.80	100		
Degree	Frequency	3	88	91		
	Percentage	3.3	96.7	100		
Post-graduate	Frequency	2	56	58		
	Percentage	3.4	96.6	100		
Use of gas for cooking						
Grade 12 and below	Frequency	19	94	113	0.02	0.18
	Percentage	16.8	83.2	100		
Diploma	Frequency	15	43	58		
	Percentage	25.9	74.1	100		
Degree	Frequency	25	66	91		
	Percentage	27.5	72.5	100		
Post-graduate	Frequency	21	33	54		
	Percentage	38.9	61.10	100		

higher qualifications postgraduate (38.9%) and degrees (27.5%), used gas more than those with lower qualifications: diploma (25.9%) and grade 12 and below (16.8%).

Table 15 reflects results on the influence of educational level on the use of biomass for cooking and heating. The Cramer's V reflect that medium differences existed for educational level and household use of wood for cooking (0.29) and heating (0.20). Participants with lower qualifications: grade 12 and below (27.4%) and diploma (7.4%), used wood for cooking than participants with higher qualifications: degree (7.7%) and post-graduate (3.4%). Results also reflect that participants with lower qualifications: grade 12 and below (23.9%) and diploma (14.8%), used wood for heating more than participants with higher qualifications: degree (8.8%) and postgraduates (6.9%).

These tendencies might follow these patterns because higher educational levels will tend to deter-

Table 15: Education's influence on biomass use for cooking and heating.

Qualification level	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of wood for cooking						
Grade 12 and below	Frequency	31	82	113	<0.001	0.29
	Percentage	27.4	72.6	100		
Diploma	Frequency	4	50	54		
	Percentage	7.40	92.60	100		
Degree	Frequency	7	84	91		\
	Percentage	7.7	92.3	100		
Post-graduate	Frequency	2	56	58		
	Percentage	3.4	96.6	100		
Use of coal for cooking						
Grade 12 and below	Frequency	6	107	113	0.52	0.08
	Percentage	5.3	94.7	100		
Diploma	Frequency	4	50	54		
	Percentage	7.4	92.6	100		
Degree	Frequency	3	55	58		
	Percentage	5.2	94.8	100		
Post-graduate	Frequency	2	89	91		
	Percentage	2.2	97.8	100		

Continued on next page

Table 15: Education's influence on biomass use for cooking and heating.

continued from previous page

Qualification level	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
			Use of wood for heating			
Grade 12 and below	Frequency	27	86	113	<0.001	0.20
	Percentage	23.9	76.1	100		
Diploma	Frequency	8	46	54		
	Percentage	14.8	85.2	100		
Degree	Frequency	8	83	92		
	Percentage	8.8	91.2	100		
Post-graduate	Frequency	4	54	58		
	Percentage	6.9	93.1	100		
			Use of coal for heating			
Grade 12 and below	Frequency	6	102	108	0.31	0.09
	Percentage	5.3	90.1	100		
Diploma	Frequency	9	82	101		
	Percentage	9.9	90.1	100		
Degree	Frequency	6	48	50		
	Percentage	11.1	88.9	100		
Post-graduate	Frequency	3	55	58		
	Percentage	5.2	94.8	100		
			Use of coal for heating			
Grade 12 and below	Frequency	6	102	108	0.31	0.09
	Percentage	5.3	90.1	100		
Diploma	Frequency	9	82	101		
	Percentage	9.9	90.1	100		
Degree	Frequency	6	48	50		
	Percentage	11.1	88.9	100		
Post-graduate	Frequency	3	55	58		
	Percentage	5.2	94.8	100		

Table 16: Education's influence on solar water heating.

Qualification level	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Grade 12 and below	Frequency	2	111	113	0.05	0.16
	Percentage	1.8	98.2	100		
Diploma	Frequency	1	90	100		
	Percentage	1.1	98.9	100		
Degree	Frequency	3	51	54		
	Percentage	5.6	94.4	100		
Post-graduate	Frequency	5	53	58		
	Percentage	8.6	91.40	100		

mine income, levels of comfort, and lifestyle.

The relationship between educational qualifications and the use of solar water heaters is presented in Table 16. The Cramer's V confirmed small differences for educational level and household use of solar water heaters (0.16). Participants with higher qualification: postgraduate (8.6%) and degree (5.6%) used more solar energy than those with lower qualifications: diploma (1.1%) and grade 12 and below (1.8%).

4.5 Gender

Gender assessment was made of the male and female participants' usage of different energy sources for domestic activities. Table 17 presents the results for lighting, cooking and heating. The Cramer's V reflects small differences for gender and the use of electricity for lighting (0.14) and cooking (0.16). Results indicate that male participants use electricity mostly for lighting (98.1%), compared to females (92.2). Results also reflect that male partic-

Table 17: The influence of gender on electricity use for lighting, cooking and heating.

Gender	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of electricity for lighting						
Male	Frequency	153	3	156	0.01	0.14
	Percentage	98.10%	1.90%	100%		
Female	Frequency	154	13	167		
	Percentage	92.20%	7.80%	100%		
Use of electricity for cooking						
Male	Frequency	65	91	156	0.01	0.16
	Percentage	41.60%	58.40%	100%		
Female	Frequency	63	104	167		
	Percentage	37.70%	62.3%%	100		
Use of electricity for heating						
Male	Frequency	121	35	156	0.34	0.05
	Percentage	77.60%	22.40%	100%		
Female	Frequency	122	45	167		
	Percentage	73.10%	26.90%	100%		

Table 18: The influence of gender on liquefied petroleum gas and paraffin use for cooking.

Gender	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of paraffin for cooking						
Male	Frequency	39	117	156	0.27	0.1
	Percentage	25	75	100		
Female	Frequency	47	120	167		
	Percentage	28.1	71.9	100		
Use of gas for cooking						
Male	Frequency	45	111	156	0.26	0.11
	Percentage	28.8	71.2	100		
Female	Frequency	39	128	167		
	Percentage	23.4	76.6	100		

ipants' use electricity most for cooking (41.6%), compared to females (37.7%).

Table 18 reflects the influence of gender on the use of LPG. The Cramer's V showed small differences for gender and the use of paraffin for cooking (0.1) and gas for cooking (0.1). Paraffin was more used for cooking by females (28.1%) than males (25%). Gas was used for cooking mostly by men (28.8%) than by females (23.4%). Inconsequential effect sizes were, however, reflected for gender influence on LPG use.

Table 19 presents the influence of gender on the use of biomass for cooking and heating. The Cramer's V indicated small differences for gender and the use of wood for cooking (0.14) and coal for cooking (0.12). Wood was used more for cooking by females (30.5%) than by males (12.2%). A noteworthy difference was recorded in the use of coal for cooking for female (10.8%) and male (5.8%).

Table 20 reflects results on the influence of gender on renewable energy use for heating. The Cramer's V reflect no significant differences for gender and the use of solar water heaters.

6. Conclusions

The research aimed to assess determinants of energy fuel choice in the South African household context by utilising the guidelines of the energy ladder and energy stacking hypotheses. Results were consistent with those of some previous studies, but some are unique to the South African context.

Findings reflected that high-income households tend to use more advanced energy sources of energy fuels than low-income ones in general. High-income groups used more electricity for cooking and heating. However, electricity is used by all income groups primarily for lighting. Low-income households tend to use paraffin for cooking, compared with high-income households that tend to use more LP gas. Solar water heaters are more used by high-income households for heating. Low-income households tend to use wood fuel significantly for cooking and heating. Coal tends to be used by low-income groups for cooking. Findings also reflect that monthly electricity expenditure above ZAR 300 is commoner with high-income households (81.1%) than low-income ones (27.8%).

Table 19: The influence of gender on biomass use for cooking and heating.

Gender	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Use of wood for cooking						
Male	Frequency	19	137	156	0.06	0.14
	Percentage	12.2	87.8	100		
Female	Frequency	51	116	167		
	Percentage	30.50	69.50	100		
Use of coal for cooking						
Male	Frequency	6	161	167	0.26	0.12
	Percentage	3.60	96.4	100		
Female	Frequency	56	100	156		
	Percentage	36.	64	100		
Use of wood for heating						
Male	Frequency	23	144	167	0.05	0.03
	Percentage	13.8	86.2	100		
Female	Frequency	25	131	156		
	Percentage	16	84	100		
Use of coal for heating						
Male	Frequency	9	147	156	0.10	0.09
	Percentage	5.8	94.2	100		
Female	Frequency	18	149	167		
	Percentage	10.8	89.2	100		

Table 20: The influence of gender on solar water heating.

Gender	*Measurements*	*Yes*	*No*	*Total*	*P value*	*Effect size*
Male	Frequency	19	137	156	0.42	0.07
	Percentage	12.1	87.9	100		
Female	Frequency	4	120	167		
	Percentage	2.6	97.4	100		

Results reflect that household size will influence the use of energy for lighting, cooking and heating. Larger households tend to use LPG for cooking more than smaller ones. Household size has a limited influence on biomass use, except for wood for heating, and no influence on the use of solar energy for water heating. Results reflect that educational level correlate to household energy fuel choice. Household participants with higher educational qualification levels (postgraduates and degreed) have a greater tendency to use electricity for lighting, cooking and heating. Participants with lower academic qualifications (Diploma and grade 12 and below) use more paraffin for cooking while participants with higher qualifications tend more to use gas. For biomass, education greatly influences the use of woodfuel for both heating and cooking. Education has little impact on the use of solar energy for water heating.

As regards the influence of gender on energy choice, more male participants use electricity for lighting, cooking and heating than female ones. Males use gas fuel more for cooking while females use more paraffin. There were insignificant differences in biomass use between females and men, except for wood in cooking. The results also showed that more male participants utilise solar energy for heating than female participants.

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Journal of Energy in Southern Africa

Volume 29 Number 3

Perceived success of energy strategies for South Africa's financial services industry

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Abstract

Energy strategies have become a global focal point involving both individuals and organisations. These strategies are implemented widely by developed countries to address greenhouse gas emissions. Developing countries are, on the other hand, lagging behind with this important global objective of reducing emissions. South Africa is one of these countries because of its rapid industrialisation along with its increasing use of coal to produce energy. It is therefore imperative for the country to develop and implement energy strategies supported by a culture and awareness of energy management. The purpose of the present study is to create an awareness of the current state of energy strategies in terms of energy conservation, efficiency and sustainability. A quantitative research design was followed, using a questionnaire to evaluate the energy management strategies implemented by the South African financial services industry. The results indicated that there are two main barriers against their implementation: their cost, and limited awareness and knowledge of the various strategies available. The results show that renewable energy strategies are not exploited to a beneficial degree. One way to enhance the development and efficiency of renewable energy strategies is to improve communication about the benefits through training and education programmes.

Keywords: renewable energy; energy strategies; energy conservation; energy efficiency; energy risks

Highlights:

- *Energy conservation and efficiency strategies assist with reducing energy costs.*
- *Barriers against implementation include the cost of the strategies and lack of knowledge.*
- *Communication improves reductions in energy costs.*

Journal of Energy in Southern Africa 29(3): 66–74
DOI: http://dx.doi.org/10.17159/2413-3051/2018/v29i3a5273

Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa

Sponsored by the Department of Science and Technology

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1. Introduction

Energy conservation and efficiency as well as renewable energy have become focal points in the everyday lives of individuals and organisations. Some organisations' motivations to implement energy strategies include becoming more sustainable and reducing their carbon footprints and operational costs. According to the U.S. Energy Information Administration (2013), the total consumption of marketable energy worldwide was predicted to increase by 56% between 2010 and 2040. Keho (2016) confirmed the predictions by, indicating that the biggest increase, 46–58%, would take place in developing countries from 2004 to 2040. This study further indicated that developing countries' energy consumption would grow at a rate of 3% per year in comparison with 0.9% for industrialised countries. Davidson et al. (2002) pointed out that South Africa was the most industrialised country in Africa and produced the most greenhouse gas (GHG) emissions, through its dependence on coal-produced energy. The U.S. Energy Information Administration (2016) indicated that Africa's total coal consumption increased by 40% for the period 2012 to 2040, with South Africa accounting for more than 90% of Africa's total consumption of energy. The primary energy supply for South Africa is shown in Figure 1. Figure 1 shows that South Africa's primary energy supply source is coal, at 67.9%, with renewable energy sources only accounting for 0.3% of the total energy supply in 2015.

Figure 2 illustrates the country's energy usage per sector in 2015, indicating that the three major consumption sectors were industrial, residential and transport, which together accounted for 90% of the total energy available. The balance was consumed by commerce, agriculture and other sectors. The country prioritised the energy, transport, mining and industrial sectors for moderating actions regarding climate change and the implementation of alternative energy sources (Department of Energy, 2015), the commerce sector still showed opportunities for the implementation of additional energy management strategies to reduce energy costs and greenhouse gas (GHG) emissions.

The commerce sector's energy usage was still quite low, at 6% in 2015, but with a potential to take the lead in energy management through energy conservation and efficiency as well as the introduction of renewable energy sources to the energy mix. These changes to the energy mix within organisations were promoted by the government through fiscal and financial incentives as well as a robust regulatory and legal framework (Department of Energy, 2016). Currently, the commerce sector's main use of energy is in the form of lighting, heating and air-conditioning, which could prove costly for large buildings especially. It is, therefore, important for organisations operating in this sector to manage energy in a way that will reduce costs, increase sustainability and lower carbon emissions.

The increase in marketable energy and the costs associated with energy create a need for organisations to implement and manage energy strategies to decrease the possible negative impact that increasing energy costs can have on them. The research question for this article was: To what extent can the energy strategies implemented by the financial services industry in South Africa ensure effective reductions in energy cost? The aim was to evaluate the country's energy strategies with respect to their efficiency and perceived success in the financial sector.

2. Literature review

Esty and Simmons (2011) found that organisations' interest in having a green business has increased over the last decade and the top management in most large organisations have realised that sustainable environmental issues needed to be part of an organisational strategy. Energy management can be

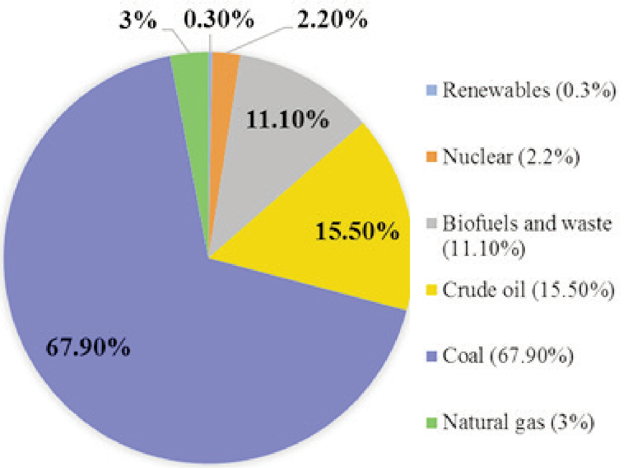

Figure 1: Primary energy supply in South Africa in 2015 (International Energy Agency, 2015).

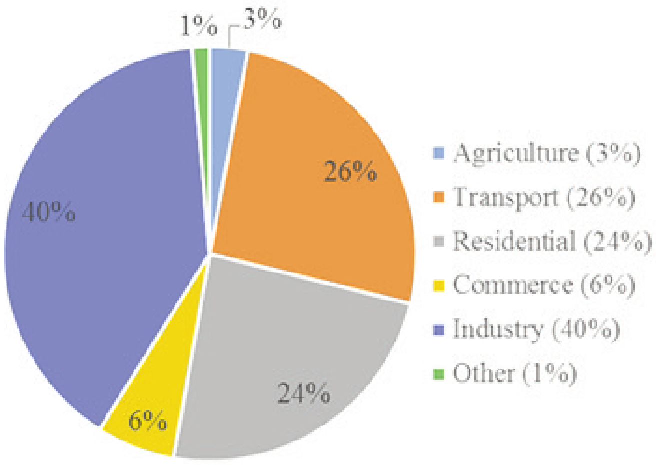

Figure 2: Energy usage by sector in 2015 (International Energy Agency, 2015).

defined as a combination of systematic techniques, energy activities and organisational management processes in order to improve an organisation's energy performance through lower energy costs and GHG emissions (Ates and Durakbasa, 2012). The implementation of energy management can help organisations reduce the risks and costs associated with energy, to enhance their reputation and improve their level of compliance with the legislation (Energy Lens, 2014). Winkler (2005) mentioned that energy risk management could be regarded as a critical factor in both the social and economic development of South Africa.

Lund (2007) classified energy strategies into three aspects: energy conservation, energy efficiency, and renewable energy. It is imperative for organisations to consider implementing all three to develop a holistic energy management framework. In this regard, Fox (2009) stated that the primary objective of energy management within organisations was to provide a comfortable working environment by regulating temperature and humidity, to provide electricity for infrastructure and operations, and to provide a productive work environment using technology and various available tools.

Energy management has become a vital task of organisations because of increasing energy prices, carbon emissions targets, and legislative and regulatory requirements. Energy management incorporates three energy strategies: energy conservation, energy efficiency, and using renewable energy. Organisations reduce their GHG emissions and operational costs by developing a culture and awareness of managing energy. Successful energy management within organisations involves all three strategies.

Strategy 1: Energy conservation. This is the easiest to implement. Organisations can reduce their energy use by such actions as switching off electrical equipment not in use, and using less electricity in peak periods, therefore decreasing the demand for electricity.

Strategy 2: Energy efficiency. Energy efficiency is defined as the ratio of energy input to energy output within an organisation (Herring and Roy, 2007) and it is inversely proportional to energy consumption (Hsu, Chang and Hsiung, 2011). Energy efficiency is still seen as a low-cost solution for organisations to reduce their operational energy costs. This strategy involves both demand-side and supply-side management. The former encourages energy users to use less electricity during peak periods, although it does not always decrease energy consumption, while supply-side management, involves an organisation's energy supply, which can be managed and reduced through the introduction of a sustainable energy management system. Ways to achieve energy efficiency include (Winkler and Van Es, 2007):

- efficient lighting systems, including compact florescent lamp and light-emitting diode devices;
- lighting retrofits, including motion sensors;
- smart metering, which tracks energy consumption;
- unplugging and switching off electronics when not in use;
- programmable control systems which monitor consumption; and
- computer-intelligent software programmes to assist with the management of computer systems when not in use.

Strategy 3: Renewable energy. As the final level of the energy management pyramid, this is also the costliest of the three. Most energy supplied worldwide is produced by fossil fuels (Johansson and Thollander, 2018), which include coal, crude oil, natural gas and turf, and which are all produced from animal and plant remains under enabling conditions over an extended period (Quaschning, 2009). The use of these energy sources damages the environment by producing harmful toxins and carbon dioxide, increasing the amount of GHG emissions (Dresselhaus and Thomas, 2001).

Renewable energy means using any sustainable energy source such as solar, wind, waves and tides, hydropower or biomass, with a potential to reduce dependence on fossil fuels and with no or lower carbon emissions (Botha, 2017). Renewable energy incurs lower operating costs (Fox, 2009). It also ensures increased production of clean energy and diversification of the energy supply (Winkler, 2005). Most countries are increasing the use of renewable energy sources. In Africa, for example, Morocco, Egypt, Algeria and Nigeria plan to increase the proportion of energy generated by renewable energy sources to between 15% to 40% of their total energy use by 2030 (Cassell, 2013). South Africa's 2030 target for renewable energy sources ranges between 15% and 29% (Edkins et al., 2010).

Energy management strategies can assist organisations to reduce their GHG emissions by implementing renewable energy as well as energy conservation and efficiency strategies. The key benefits of all energy management strategies are to enhance energy security, protect the environment and reduce GHG emissions (Small, 2012; Russian Sustainable Energy Financing Facility, 2011). Additional benefits include possible tax rebates, lower operating costs, and an improvement in an organisation's corporate social responsibility. There are, however, also barriers to implementing such strategies, including high capital implementation costs; limited knowledge, education and awareness; limited incentives and finance; a weak services market; and a lack of technological support (Botha, 2017).

It is important that, in terms of the potential benefits, organisations include energy conservation, energy efficiency and renewable energy within their energy management strategies. It is also essential that organisations mitigate and control the potential barriers to energy management strategies by executing sound management decisions.

3. Methodology

A quantitative, non-experimental research design was followed using a questionnaire to evaluate energy management strategies implemented by South Africa's financial services industry. The target population for this research included managers involved in operations and strategic decisions in the sector. A non-probability sampling method was used that focused on the number of respondents that needed to be evaluated in order to get an in-depth understanding of the research problem. There were 144 participants and 78 respondents. A response rate of 54% was achieved, which was considered to be representative and to yield reliable findings and conclusions. The data were analysed by means of descriptive and inferential statistics.

4. Results and discussion

The study analysed the attitudes and opinions of managers in the financial services industry represented by the banking industry, insurance companies, investment organisations, asset management entities and other related industries, including financial consulting, government, non-profit organisations, research and general financial services, as shown in Figure 3.

The focus was on the energy management strategies implemented by organisations to reduce their operating costs. It also investigated the perceived effectiveness of strategies to communicate energy management strategies to employees. Figure 4 shows the basic activities used by most respondents as part of their energy conservation strategies. It was found that 87% of respondents switched off lights when not in use, 85.9% used energy-saving light bulbs; 84.6% re-set their central heating and cooling systems; and 79.5% restricted their employees' use of portable heating and cooling systems.

The high proportions of these activities did not prevent improvement on other basic energy conservation activities such as the use of light-timing devices, which were used by less than 50% of the respondents. This could be attributed to cost implications of this activity or a lack of awareness. Out of the five energy conservation activities, the use of energy-saving light bulbs; resetting heating and cooling systems; and the restriction of portable heating and cooling systems were, respectively,

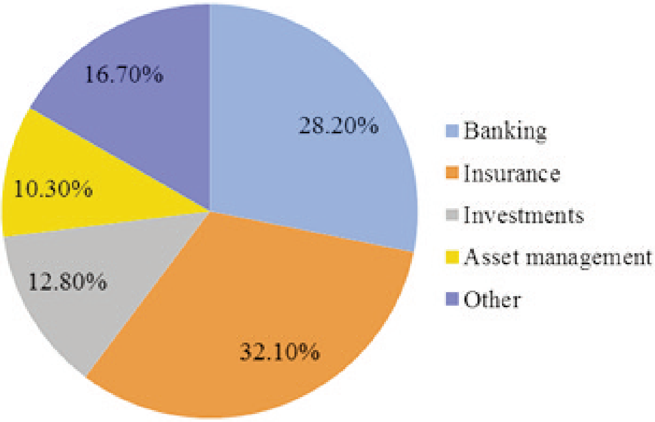

Figure 3: Industries involved in the financial services industry based on response rate.

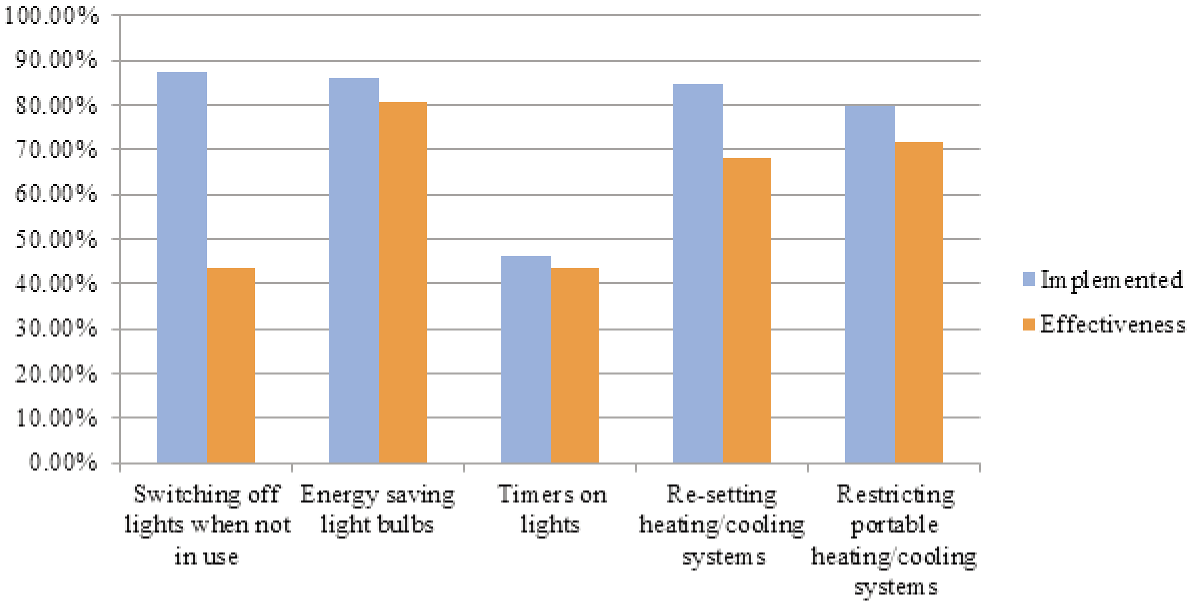

Figure 4: Energy conservation and efficiency implementation and effectiveness.

found to be the most effective energy-saving strategies within the various organisations at 80.8, 68.0, 71.8%. Switching off lights when not in use accounted for only 43.6%, which could be one of the most basic energy conservation activities. The low exploitation of this energy conservation activity could be caused by the employees' lack of awareness within organisations, poor communication, or by a low appetite of employees to change.

A renewable energy strategy, as the last strategy within energy management which should form part of the organisations' overall strategy. Most of the respondents (65.3%) did not make use of renewable energy sources. Although the reasons for not implementing renewable energy strategies did not form part of the study, possible cause for this could include the costs and finance options involved in renewable projects as well as a general lack of knowledge and awareness of these strategies. Figure 5 shows that 24.4% of the respondents used solar energy, 6.4% wind energy and 3.9% biomass. Although fewer than 35% of the organisations were implementing the various available renewable energy strategies, these were still seen as being effective in energy management and in reducing energy costs within the organisation (solar energy 21.8%, wind turbines 9% and biomass 6.4%).

Communication is a vital part of any process within an organisation. The results shown in Figure 6 show more emphasis on the communication of energy conservation and efficiency strategies than on renewable energy strategies. More than 70% indicated that communication existed with regard to energy conservation and efficiency strategies, while less than 30% indicated that these strategies were not communicated or that they were not aware of the communication attempts. With regard to renewable energy strategies, only 55% indicated that they were communicated within their organisations; 33% indicated that there was no communication of these strategies; while the balance indicated no awareness to any communication at all.

Research by Winkler and Van Es (2007) and Fox (2009) showed that funding is a barrier against the implementation of energy management strategies, but that it can assist organisations in reducing their overall operating costs. Figure 7 shows that most of the respondents (80%) found that implementing energy conservation and efficiency strategies assisted in reducing energy costs, while 49.9% indicated that renewable energy strategies had the same effect. Only 12% indicated that their energy conservation and efficiency strategies had no influence on their costs, with 38.5% indicating that renewable energy strategies had no influence on the costs within their organisations. Nine percent indicated that they did not know whether energy conservation and efficiency strategies had a possible influence on their costs, while 12% did not know about renewable energy strategies.

The present study showed a positive attitude towards implementing energy strategies and their effectiveness within organisations. One aspect, however, that could be improved to increase cost saving for the organisations is communication with employees about the various energy strategies that the organisations are implementing. A correlation analysis was conducted to examine the potential of energy conservation and efficiency strategies; and renewable energy strategies to predict a reduction in energy costs. Existence of a strong positive correlation of $p = 0.627$, $n = 71$, $\mathrm{p} < 0.001$ (were p is the correlation and n the number of respondents) was found among implementing energy conservation and efficiency strategies and a reduction in energy costs. It was also found that a positive correlation of $p = 0.370$, $n = 71$, $\mathrm{p} < 0.002$ between implementing renewable energy strategies and a reduction in energy costs existed. Although the correlation for the renewable energy strategies was lower than for

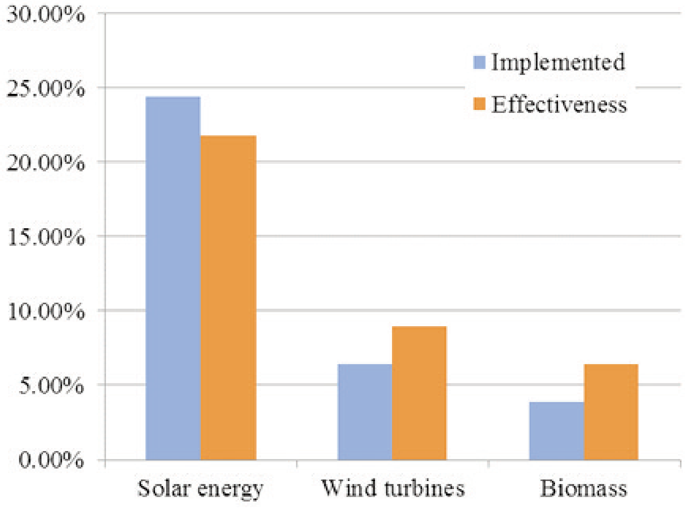

Figure 5: Renewable energy implementation and effectiveness.

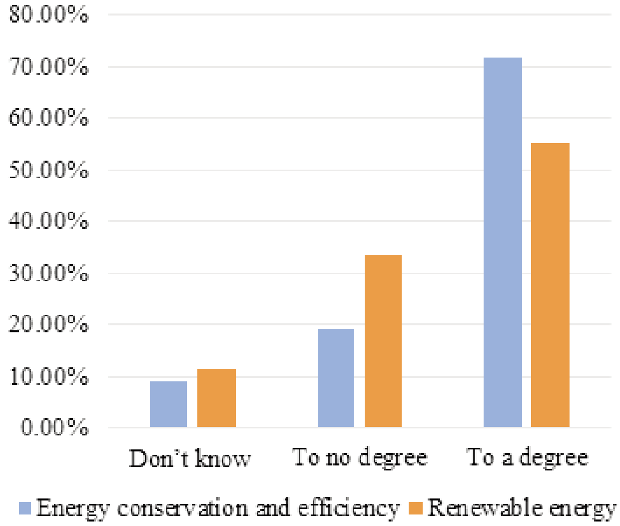

Figure 6: Communication of energy strategies.

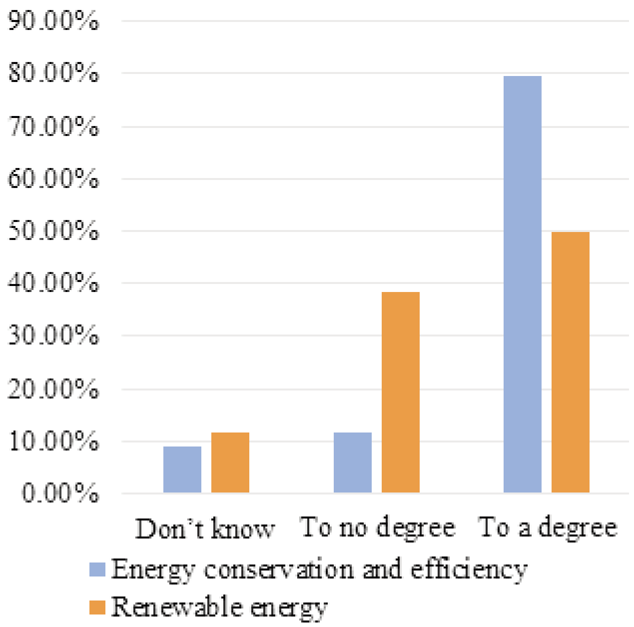

Figure 7: Reducing energy costs through implementing energy strategies

the energy conservation and efficiency strategies, both showed an increased probability of a decrease in energy costs if these strategies were implemented, as summarised in Table 1.

The results corroborated a reduction in energy costs within organisations with an increased implementation of energy strategies. The literature has also shown that implementing energy strategies not only promotes energy security, it also assists organisations to decrease their energy costs and overall carbon emissions (Russian Sustainable Energy Financing Facility 2011; Small 2012).

Multiple regression analyses were conducted to examine the relationship among the decrease in energy costs and implementing energy conservation and efficiency strategies; and communicating these strategies. The multiple regression model with both predictors produced $R^2 = 0.757$, as shown in Table 2, where R^2 is the proportion of variance in the dependent variable that can be explained by the independent variable. The results further indicated that the model was a significant predictor of the reduction in energy costs, where $F(2, 66) = 99.514$, $p < 0.0001$ (where F is the F-ratio and p the statistical significance) , as shown in Table 3.

Both communication, where beta = 0.694 and $p < 0.0001$; and energy conservation and efficiency

Table 1: Summary of correlations.

Parameter		*Reduction in energy cost*	*Energy conservation and efficiency strategies*	*Renewable energy strategies*
Pearson correlation	Reduction in energy costs	1.000	0.627	0.370
	Energy conservation and efficiency strategies	0.627	1.000	NA
	Renewable energy strategies	0.370	NA	1.000
Level of significance. (2-tailed at 0.01)	Reduction in energy costs	NA	0.000	0.002
	Energy conservation and efficiency strategies	0.000	NA	NA
	Renewable energy strategies	0.002	NA	NA
Number of respondents	Reduction in energy costs	71	71	71
	Energy conservation and efficiency strategies	71	71	71
	Renewable energy strategies	71	71	71

Table 2: Summary of the model on the reduction in energy costs.

Model	*R*	*R^2*	*Adjusted R^2*	*Std. error of the estimate*
1	0.870[a]	0.757	0.749	0.632

a = Predictors: (Constant), Communication of energy conservation and efficiency strategies, Energy strategies implemented; R = Multiple correlation coefficient, Std. = Standard

Table 3: The ANOVA[a] of communication, implementation of energy conservation and efficiency strategies and reduction in energy costs.

Model	*Parameter*	*Sum of squares*	*df*	*Mean square*	*F*	*Sig.*
1	Regression	79.598	2	39.799	99.514	0.000[b]
	Residual	25.596	64	0.400		
	Total	105.194	66			

a = Dependent variable: Implementation of energy strategies resulted in a decrease in energy costs; b = Predictors: (Constant), Communication of energy conservation and efficiency strategies, Energy strategies implemented; df = Degrees of freedom, F = F-ratio, Sig. = Statistical significance.

strategies, where beta = 0.278, $p < 0.0001$, contributed significantly to the model as presented in Table 4. The final predictive model was according to Equation 1.

$$\text{reduction in energy costs} = -0.178+(0.642 \text{ x commumication})+(0.375 \text{ x strategy}) \qquad (1)$$

It can therefore be concluded that communication plays a major role in energy conservation and efficiency strategies. Decision-makers will be aware of these strategies and by implementing it will lead to a reduction in energy costs.

Multiple regression analyses were conducted to examine the relationship among the decrease in energy costs and the implementation of renewable energy strategies; and communication of these strategies. The renewable energy strategies were excluded because they did not influence the reduction in energy costs. The multiple regression model with communication as predictors produced $R^2 = 0.790$, as shown in Table 5. The results further indicated that the model was a significant predictor of the reduction in energy costs, $F(1, 56) = 207.003$, $p < .0001$ as presented in Table 6.

The communication of renewable energy strategies contributed significantly to the model (beta = 0.864, $p< 0.0001$) (Table7). The final predictive model was according to Equation 2.

$$\text{reduction in energy costs} = 0.231 + (0.864 \text{ x communication}) \qquad (2)$$

It can therefore be concluded that communication plays a role in renewable energy strategies and by increasing the communication regarding the energy strategies will assist in decreasing the energy cost of the organisation.

Although most of the organisations seem to be implementing various energy conservation and efficiency strategies, renewable energy strategies are still relatively rare. The results showed that with an increase in communication regarding the various energy strategies, organisations could also increase a possible reduction in their overall energy costs.

Table 4: Coefficients of communication, energy efficiency and conservation strategies and reduction in energy costs.

Model	*Parameter*	*Unstandardised coefficients*		*Standardised coefficients*	*t*	*Sig.*
1	(Constant)	-0.178	0.326		-0.545	0.587
	Communication of energy conservation and efficiency strategies	0.642	0.067	0.694	9.644	0.000
	Energy efficiency and conservation strategies	0.375	0.097	0.278	3.861	0.000

t =T-value, sig. = Statistical significance

Table 5. Summary of the model on renewable energy and reduction in energy costs.

Model	*R*	*R^2*	*Adjusted R^2*	*Std. error of the estimate*
1	0.889^a	0.790	0.786	0.675

a = Predictors: (Constant), Communication of renewable energy strategies, R = Multiple correlation coefficient, std. = Standard.

Table 6: The ANOVA^a of communication of renewable energy strategies and reduction in energy costs.

Model	*Parameter*	*Sum of squares*	*df*	*Mean square*	*F*	*Sig.*
1	Regression	94.277	1	94.227	207.003	.000^b
	Residual	25.036	55	.455		
	Total	119.263	56			

a = dependent variable: Implementation of the energy strategies resulted in a decrease in energy costs; b = Predictors: (Constant), Communication of renewable energy strategies.

Table 7: Coefficients of the communication of renewable energy strategies and reduction in energy costs.

Model	*Parameter*	*Unstandardised coefficients*		*Standardised coefficients*	*t*	*Sig.*
1	(Constant)	0.231	0.173		1.333	0.188
	Communication of renewable energy strategies	0.864	0.060	0.889	14.388	0.000

t =T-value, sig. = Statistical significance

5. Conclusions

Energy conservation, efficiency and renewable energy strategies are a vital part of all organisational management. It is important for organisations to implement all three strategies as part of an overall energy management strategy to reduce energy costs as well as greenhouse gas emissions. Other benefits from implementing energy management strategies include increased corporate social responsibility, increased energy security, possible tax reductions and protecting the environment. The two main barriers against implementing energy strategies include the costs of the strategies, as well as limited awareness and knowledge of the various energy strategies available. Most organisations implemented energy conservation and efficiency strategies, and that most of them were effective at reducing energy costs. However, renewable energy strategies are still lagging, although it was indicated that these strategies can assist organisations in reducing their energy costs. Although there is some form of internal communication regarding these energy strategies, there is room for improvement. This could be one of the key areas that organisations could concentrate on to make employees aware of their energy management strategies, which in turn could lead to a cost-effective approach towards energy risk management. In addition, it is recommended that education and training on energy strategies should make up an integral part of an organisation's risk management process to exploit the benefits that are linked to these strategies and to ensure the involvement of all the employees and stakeholders. It could also be recommended that awareness campaigns should be launched to promote the use of renewable energy strategies, thus ensuring that South Africa positively contributes to the global objective of reducing emissions.

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Volume 29 Number 3

Journal of Energy in Southern Africa

The energy transition patterns of low-income households in South Africa: An evaluation of energy programme and policy

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Abstract

The transition to modern energy carriers like electricity is an important way to achieve to eradicate energy poverty. This study investigated energy transition patterns and trends in low-income South African households. The marginal effects of the different determinants on the probability of choosing a specific energy carrier were computed and the influence of some endogenous characteristics in transitioning to modern energy carriers was explored. It was found that energy ladder behaviour exists for cooking while energy stacking was most likely for space heating and the pattern for lighting tended towards energy stacking. Dwelling type, household size and geographical location were among the key determinants of the energy transition pattern. Policies to reduce energy poverty need a multi-pronged approach and not only a focus on electricity access.

Keywords: *energy ladder; energy stacking; energy poverty; electricity*

Journal of Energy in Southern Africa 29(3): 75–85
DOI: http://dx.doi.org/10.17159/2413-3051/2017/v29i3a3310
Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa
Sponsored by the Department of Science and Technology

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1. Introduction

Energy choices have a major impact on the energy system of a country and its economic development (Joyeux and Ripple, 2007; Lay et al., 2013). If a household relies mainly on traditional fuels for cooking, space heating or lighting, economic activities may be hindered (Lay *et al.,* 2013; Liu *et al.,* 2013; Van der Kroon *et al.,* 2013). Shifting to modern energy carriers is associated with welfare improvement and is an important developmental goal to achieve, in order to eradicate energy poverty (Kowsari and Zerriffi, 2011; Liu *et al.,* 2013). Provision of electricity in developing countries is generally recognised as a necessary foundation to eradicate energy poverty.

The South African government, in addressing the electricity imbalance in the residential sector, introduced several national programmes to widen access to electricity (Department of Energy [DoE], 2013), including the National Electrification Programme and the Integrated National Electrification Programme. The main objective of these programmes was to connect to the grid rural and urban low-income houses deprived of access to electricity during the apartheid period. The programme expected that the residents of the electrified houses would switch to electricity as the main energy source for their household needs. To address affordability problems related to electricity, the Department of Minerals and Energy (DME) in 2003 launched the Free Basic Electricity (FBE) programme. This provides 50kWh of electricity per month free of charge to poor households connected to the national electricity grid (DME 2003; Inglesi-Lotz, 2010; Ruiters, 2009).

Energy transition has been conceptualised in the form of the 'energy ladder' or 'energy stacking' models (Kowsari and Zerriffi. 2011; Lee *et al.,* 2015; Van der Kroon *et al.,* 2013). The energy ladder model aligns with the economic theory of the consumer and describes a linear transition of household energy choices from a traditional energy carrier to a transitional one and then to a modern one as income improves (Hosier and Dowd, 1987; Lee *et al.,* 2015; Van der Kroon *et al.,* 2013).

The energy stacking or multiple fuel use model, on the other hand, was developed based on findings that households choose to use a combination of energy carriers on both upper and lower stages on the energy ladder as income rises or depending on their preferences or needs (Arnold *et al.,* 2006; Davis, 1998; Kowsari and Zerriffi, 2011; Lee *et al.,* 2015; Martins, 2005).

Understanding the energy choices of low-income households is important in designing suitable policies to support the transition process and targeted measures to eliminate energy poverty. The presence of energy ladder or stacking transition patterns could lead to different sets of conclusions and policy recommendations. Moreover, the few empirical studies on household energy choice and transition in South Africa do not use panel data (Davis, 1998; Madubansi and Shackleton, 2006; Uhunamure *et al.,* 2017), which among other things, enables the control of unobserved effects and explains energy choice over time.

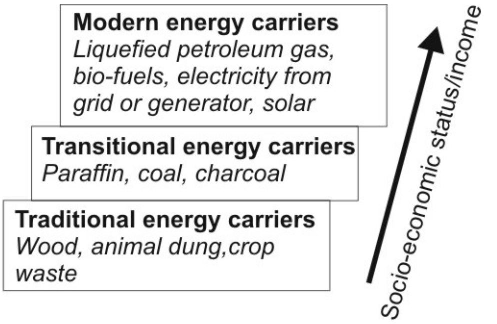


Figure 1: Energy ladder model (Nissing and Blottnitz, 2010; Van der Kroon *et al.,* 2013).

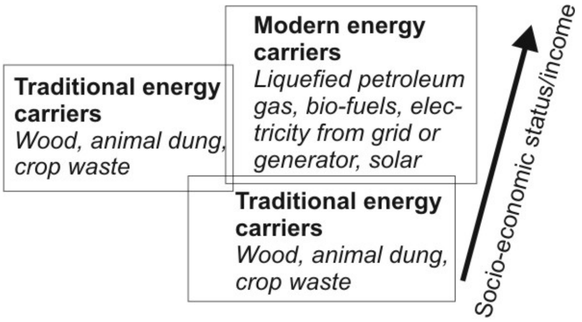


Figure 2: Energy stacking model (IEA, 2002; Van der Kroon et al., 2013).

This study aims to investigate whether the energy transition patterns by low-income households in South Africa follow the energy ladder or energy stacking models for cooking, heating and lighting energy services. If income is the major determinant of the transition to more modern energy sources, then specific energy policy may not be needed beyond providing access. The energy transition patterns in low-income households will therefore determine whether the development of an energy policy is necessary, bearing in mind that the main goal is sustainable energy use and energy poverty alleviation. Section 2 presents the data and methods while, Section 3 provides the results and discussion, and Section 4 presents conclusions.

2. Data and methods

2.1 Data description

The data employed for the analysis comes from the four waves of the National Income Dynamics Survey (NIDS). The survey began in 2008 (the baseline wave), with a nationally representative sample of 28 000 individuals in 7 300 households across the country. The survey is repeated every two years with the same group of households or individuals, using a combination of household, adult, child and proxy questionnaires (Brown *et al.,* 2012; Leibbrandt *et al.,* 2009; NIDS, 2012).

2.2 Model specification

An ordered logit model, also known as the proportional odds model, is a statistical technique that takes ordering into account and the odds ratio of the event is independent of the category *j* (Greene, 2008). An ordinal logit regression considers the probability of the event and all others above it in the ordinal ranking. In other words, an ordinal logit regression is concerned with cumulative probabilities rather than probabilities for discrete categories (Agresti, 2010).

Households face choices between traditional, transitional and modern energy carriers for cooking, heating and lighting and are assumed to maximise their utility by choosing one of the energy carriers as their main energy source for the specific end-use. Following the approach of O'Connell (2005), suppose data (Y_i, $X_{1i} \ldots X_{ki}$) for observations $i = 1, \ldots, n$, where Y is a response variable with C ordered categories: $j = 1, \ldots, C$, with probabilities, $P(Y = j) = \pi^{(j)}$ and $X_1 \ldots X_k$ are k explanatory variables and observations Y_i are statistically independent of each other. Consider the C – 1 cumulative probabilities in Equations 1 – 3.

$$\Upsilon^{(j)} = P(Y \leq j) = \pi^1 + \ldots + \pi^{(j)} \text{ for } j = 1, \ldots, C - 1 \tag{1}$$

$$\Upsilon^{(j)} = P(Y \leq j) = \pi^2 + \ldots + \pi^{(j)} \text{ for } j = 2, \ldots, C - 1 \tag{2}$$

$$\Upsilon^{(j)} = P(Y \leq j) = \pi^3 + \ldots + \pi^{(j)} \text{ for } j = 3, \ldots, C - 1 \tag{3}$$

The following holds for $\Upsilon_i^{(j)} = P(Y_i \leq j)$ for each unit i and each category $j = 1, \ldots, C\text{-}1$, giving Equation 4.

$$\log [\Upsilon_i^{(j)} / 1 - \Upsilon_i^{(j)}] = \log [P(Y_i \leq j) / P(Y_i > j] = \alpha^j - (\beta_1 X_{1i} + \ldots + \beta_k X_{ki}) \tag{4}$$

Assume that the observed ordinal variable Y_i is related to the latent variable according to Equation 5.

$$Y_i = k \text{ if } \mu_{k-1} \leq Y_i^* \leq \mu_k \text{ for } k = 1, \ldots K \tag{5}$$

The model for the cumulative probabilities is therefore given by Equation 6.

$$\Upsilon^{(j)} = P(Y \leq j) = \frac{exp[\alpha j - (\beta 1X1i + \ldots + \beta kXki)]}{1 + exp[\alpha j - (\beta 1X1i + \ldots + \beta kXki)]} \tag{6}$$

The intercept terms must be $\alpha^{(1)} < \alpha^{(2)} < \ldots < \alpha^{(C-1)}$, to guarantee that $\Upsilon^{(1)} < \Upsilon^{(2)} < \ldots < \Upsilon^{(C-1)}$. The parameters α, called thresholds are in increasing order ($\alpha^{(1)} < \alpha^{(2)} < \ldots < \alpha^{(C-1)}$), $\beta_1, \ldots, \beta_k$ are the same for each value of *j*. This is good for the parsimony of the model because it means that the effect of an explanatory variable on the ordinal response is described by one parameter (Agresti, 2010).

In the case of three ordered categories, Equation 6 simplifies to Equations 7–9.

$$P(Y = 1) = \frac{1}{1 + exp(\beta 1X1i - k1)} \tag{7}$$

$$P(Y = 2) = \frac{1}{1 + \exp(\beta 1X1i - k2)} - \frac{1}{1 + \exp(\beta 1X1i - k1)} \tag{8}$$

$$P(Y = 3) = 1 - \frac{1}{1 + \exp(\beta 1X1i - k2)} \tag{9}$$

By maximum likelihood, estimates for α and β can be obtained. The likelihood function for each i^th^ observation can be expressed as Equation 10.

$$\ell_i(\alpha, \beta) = 1[Y_i = 0]\log[\Lambda(\alpha_1 - X_1\beta)] + [Y_i = 1] \log [\Lambda(\alpha_2 - X_1\beta) - \Lambda(\alpha_1 - X_1\beta)] + [Y_i = 1]\log[1 - \Lambda(\alpha_3 - X_1\beta)] \tag{10}$$

The parameters for an ordered logit model can be difficult to interpret, therefore, reporting marginal effects after an ordered logistic regression can make the results more understandable (Greene, 2008; Long and Freese, 2014). The marginal effects for the present study were calculated at the mean values in a covariate model showing how P(Y=1) changes as the variables changes from 0 to 1, holding all other variables at their means, i.e., the marginal effect approximates how much the dependent variable is expected to increase or decrease for a unit change in an explanatory variable so that the effect is presented on an additive scale (Buis, 2010). The marginal effects are derived by taking the partial derivatives of Equations 7, 8 and 9 and Equations 11, 12 and 13 are obtained.

$$\partial \Pr(Y=0|X) / \partial X_k = - \beta_k \lambda (\alpha_1 - X\beta); \tag{11}$$

$$\partial \Pr(Y=j/X) / \partial X_k = \beta_k [\lambda (\alpha_{j-1} - X\beta) - \lambda (\alpha_3 - X\beta)], \text{ for } 0<j<3; \text{ and} \tag{12}$$

$$\partial \Pr(Y=3/X) / \partial X_k = \beta_k \lambda (\alpha_3 - X\beta \tag{13}$$

The predicted probabilities are estimated as in Equations 14, 15 and 16.

$$P(Y\_ordinal = \text{'less preferred'}) = P(S + u \leq \_cut1) \tag{14}$$

$$P(Y\_ordinal = \text{'moderately preferred'}) = P(\_cut1 < S + u \leq \_cut2) \tag{15}$$

$$P\ (Y\_ordinal = \text{'most preferred'}) = P\ (\_cut2 < S + u) \qquad (16)$$

In which the basic equation is written according to Equation 17.

$$\Pr(Y = j|X) = F\ (\hat{T}_j - X_1\hat{\beta}) - F\ (\hat{T}_{j-1} - X_1\hat{\beta}) \qquad (17)$$

Based on the assumptions of the 'energy ladder', modern energy carriers should be the source most preferred (being on top of the ladder) by the low-income households for cooking, heating and lighting. Transitional energy carriers are assumed to be moderately preferred, being in the middle of the ladder, while traditional energy carriers will be less preferred because they are at the bottom of the ladder.

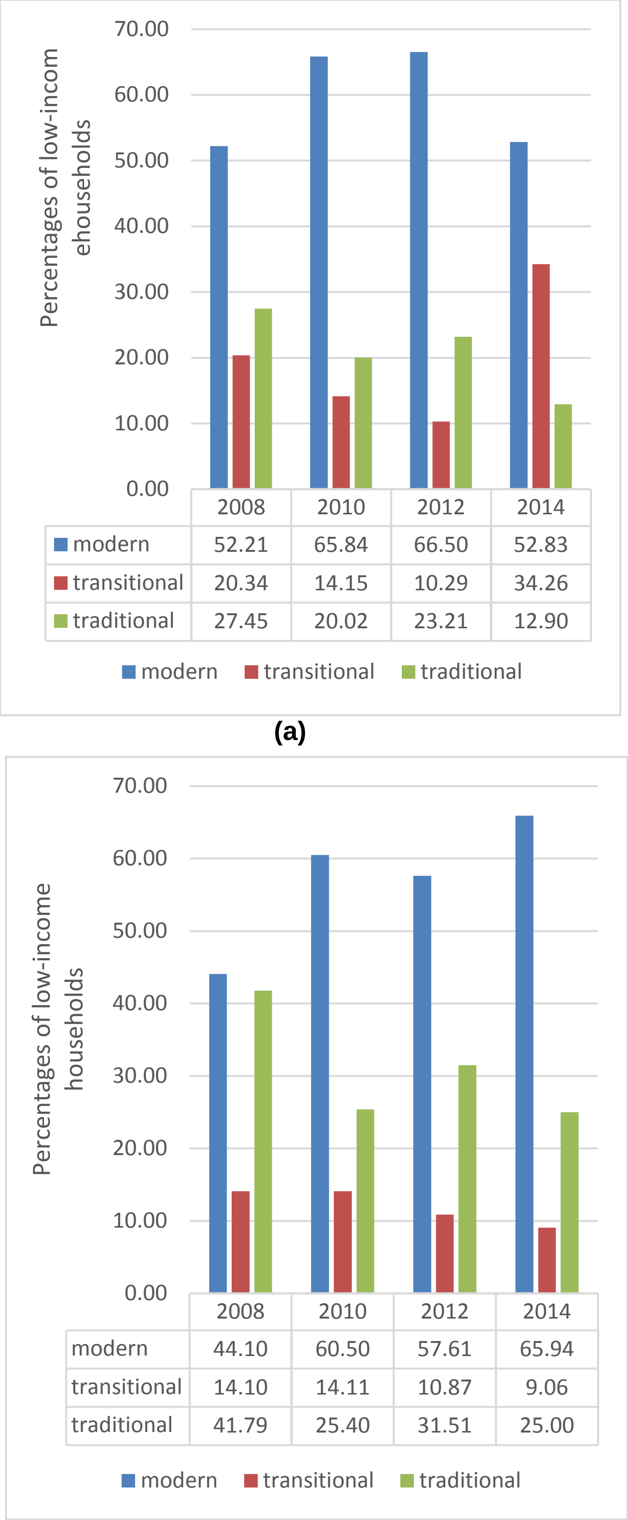
2.3 Procedures and technique of analysis

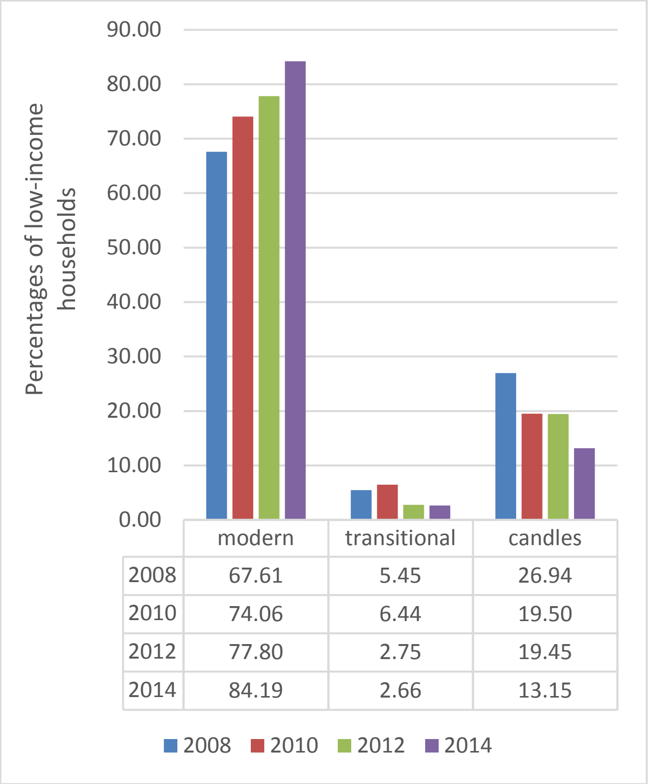
The description of low-income households for the allocation of FBE is households where the gross monthly income of all the members of the household does not exceed two old age pensions (DME, 2003). The dataset for low-income households from the NIDS study contained 10 804 observations. A balanced panel data model was used for the analysis to track the energy transition of the low-income households. A panel is said to be balanced if it had the same time or periods, t = 1 … T, for each cross-sectional observation (Hsiao, 2014). A balanced panel dataset will contain all elements observed in all period allowing an observation of the same household across the years of survey. An average observation of 760 low-income households was used for the analysis.

The independent variables or the endogenous characteristics to be used were first tested for multicollinearity. (See the supplementary information for the description and measurement.[1]) The independent variables include income, age, gender, rurality, household size and dwelling type. The variable 'Year' is also included as part of the independent variables. The variance inflation factor (VIF) and tolerance value were used to detect whether multi-collinearity existed among the variables. A variable whose VIF value is greater than 10 or the tolerance value is lower than 0.1 means that there is a linear combination of other independent variables and thus may merit further investigation (Gujarati and Porter, 2009). The test result shows that the VIF for each independent variable is less than 1.5 and the tolerance value ranges from 0.7 to 0.9. Multi-collinearity, is as such, not a threat for the regression analysis.

3. Results and discussion

The sample households used different types of energy carriers for their cooking, heating and lighting. Modern energy carriers include electricity from the grid, gas, solar energy and electricity from a generator. Transitional energy carriers comprise paraffin and coal, while traditional energy carriers include animal dung and wood. A definition of the different energy choices by South African low-income households for cooking (Panel 1), heating (Panel 2) and lighting (Panel 3) from 2008 to 2014 is given in terms of Figure 3.





(c)

Figure 3: Energy choices for cooking heating and lighting, where (a), (b) and (c) = Panels 1, 2 and 3 of cooking, heating and lighting respectively.

The use of modern energy for cooking was predominant across the waves. Wave 3, year 2012, had the highest percentage (67%) of low-income households using modern energy carriers. There was, however, a sharp increase in the use of transitional energy carriers, from 10% in 2012 to 34% in 2014. This could mean that substitution of modern energy for transitional energy occurs because of an increase in the price of modern energy carriers, forcing a change in energy choice. Traditional energy carriers in 2014 were used in a small percentage of households (13%) as the main energy source for cooking.

Modern energy carriers for space heating were the most common across the waves, with 2014 recording the highest proportion (66%) for low-income households. In the same year, households used fewer of the transitional energy carriers for space heating, in 9% of cases, compared with other waves. These trends illustrate energy substitution strategies in which modern energy carriers become increasingly used for space heating. More households (42%) used traditional energy carriers for space heating in 2008 than in other years but the use of modern energy carriers for space heating in the same year was relatively low (44%). The use of transitional energy carriers for space heating appeared to be phased out.

The use of traditional energy carriers for lighting doesn't feature, and as such, no case of the households across the waves was observed. The use of modern energy carriers for lighting was predominant across the four waves and increasingly so: by 2014 the largest percentage (84%) ever of households was using this source. The use of candles for lighting seems to be phased out as the number of households using candles for lighting declines. Transitional energy carriers for lighting were no longer often used by households.

3.1 Marginal effects for energy choice for cooking

The marginal effects after ordered logistic regression with respect to cooking are shown in Table 1. These provide the amount of change in Y that will be produced by a unit change in X_k holding other independent variables constant at their reference points. The reference point for dwelling type is modern dwelling, gender – female, geographical location – urban and household size – small (1–4 persons). Income and age are set at their means, which are respectively – ZAR 825.88 (per month) and 50.82 years. For the 'year' variable, Stata (a statistical software that enables users to analyse, manage, and produce graphical visualisations of data) sets a mean for 2010, 2012 and 2014.

All of the following independent variables are expected to have negative signs for traditional and transitional energy carriers holding other independent variables constant at the reference points. This will be the case for all situations considered. For gender, rurality, household size, and dwelling type, it is expected that the marginal effect will be that low-income households with a female household respondent, in an urban settlement, having a small household size and living in a modern dwelling will make less use of traditional and transitional energy carriers for cooking and heating. For lighting, it is expected that the marginal effect will be that low-income households with a female household respondent, in an urban settlement, having a small household size and living in a modern dwelling are expected to use few candles plus transitional energy carriers. The expected signs are presumed to be negative, knowing that health and safety risks are associated with traditional or transitional energy carriers and candles compared with modern energy carriers (Kowsari and Zerriffi, 2011; Swart and Bredenkamp, 2012).

Age is an ambiguous variable as it is unknown *a priori* if it positively or negatively influenced household energy choice for cooking and heating. For household income, the *a priori* expectation with respect to the sign is also ambiguous, depending on which energy transition model holds (energy ladder or energy stacking).

For the 'year' variables, it is expected that low-income households in 2010, 2012, and 2014 will use less traditional or transitional energy carriers than they did in the base year 2008 for their cooking and heating. For lighting, it is expected that low-income households in 2010, 2012, and 2014 will use fewer candles.

Furthermore, the *a priori* expectations of each independent variable for a modern energy carrier is different from those for traditional and transitional energy carriers. Thus, for gender, rurality, household size, and dwelling type, a positive sign is expected. Therefore, the marginal effect is expected to be that low-income households with a female household respondent, in an urban settlement, having a small household size, and in a modern dwelling are more likely to use modern energy carriers for their cooking, heating, and lighting. Positive signs are expected for modern energy carrier usage because it impacts on human well-being by reducing the health and safety risks associated with traditional or transitional energy carriers (Kowsari and Zerriffi, 2011; Swart and Bredenkamp, 2012). The use of modern energy carriers could decrease time budget constraints on household members particularly women and children, increase labour productivity, and improve gender inequality and literacy (Howells *et al*, 2003; Swart and Bredenkamp, 2012).

Household income and age may be either positive or negative, as with the *a priori* expectations for traditional and transitional energy carriers.

Finally, for the 'year' variable, low-income households in 2010, 2012, and 2014 are hypothesised to have positive signs for modern energy carriers. The marginal effect is expected to be that low-income households are more likely to use modern energy carriers for cooking, heating, and lighting in 2010, 2012, and 2014 than was the case in the base year 2008.

In the interpretation of the results, household income is an important variable, as it determines the energy consumption for low-income households. Therefore, if low-income households move up the energy ladder as their income increase, the 'energy ladder' model is confirmed. This is assessed if income is statistically significant in relation to a household's decision concerning the energy choices for cooking, heating and lighting, holding other variables constant. From a policy point of view, if income were the major determinant of a complete transition to modern energy sources, the implication is that energy transition will take place automatically as household income increases, thus reducing energy poverty. Beyond providing access, specific energy policy may not be needed.

The 'energy stacking' model, on the other hand, hypothesises that households continue to use a mixture of energy sources, even if their income increases. Therefore, if income is not statistically significant in relation to the household's decision concerning energy choices for cooking, heating, and lighting, this may provide support for the 'energy stacking' model. In this case, one cannot assume that an increase in household income will automatically result in a transition to cleaner and more efficient modern carriers, in which case more specific energy policies may be needed. The marginal effects with respect to cooking energy service are presented in Table 1.

Real income is statistically significant for both traditional and modern energy carriers at the 10% level of significance. This result has partly confirmed an 'energy ladder' behaviour with respect to cooking. The implication is that as real income rises, there is transition up the energy ladder for the choice of energy source for cooking. Therefore, households initially using a traditional energy source for cooking

Table 1: Marginal effects for energy choice for cooking.

	Marginal effects for traditional energy carrier	*Marginal effects for transitional energy carrier*	*Marginal effects for modern energy carrier*
Real income	-5.44e-05*	-2.97e-05	8.42e-05*
Dwelling type (modern)	-0.1807***	-0.0735***	0.2542***
Age	8.09e-05	4.42e-04	-0.0012
Gender (female)	-0.0107	-0.0057	0.0164
Rurality (urban)	-0.2043***	-0.1055***	0.3099***
Household size (small)	-0.1086**	-0.0440**	0.1526***
Year (2010)	-0.0685**	-0.0413**	0.1101**
Year (2012)	-0.0959***	-0.0599***	0.1559***
Year (2014)	-0.0947***	-0.0598***	0.1546***

*T-statistics in parentheses: * significant at 10%; ** significant at 5%; *** significant at 1%*

will switch automatically to a transitional or a modern energy carrier as their income rises.

Dwelling type (modern), rurality (urban) and household size (small) have negative signs and are statistically significant at 1, 1 and 5 percent level of significance respectively for traditional and transitional energy carriers. For dwelling type, for example, low-income households living in modern dwellings are 10% less likely to use traditional energy carriers and 8% less likely to use transitional energy carriers for cooking than their counterparts living in non-modern dwellings. For a modern energy carrier, the sign for modern dwelling type is positive; therefore, low-income households living in modern dwellings are 19% more likely to use a modern energy carrier than low-income households living in traditional or informal dwellings for their cooking. Thus, the expectation that a modern dwelling enhances the probability of choosing a modern energy carrier for cooking was substantiated, even when income was held constant.

For rurality, urban low-income households are 15% less likely to use traditional energy carriers and 11% less likely to use transitional energy carriers for cooking than rural low-income households. For the modern energy carrier, the sign for urban is positive. In consequence, urban low-income households are 27% more likely to adopt a modern energy carrier for cooking compared with rural low-income households.

For household size, small low-income households are 5% less likely to use a traditional energy carrier for cooking than their larger counterparts. Small low-income households are 5% less likely to use a transitional energy carrier for cooking than larger low-income households. For modern energy carriers, the sign for small household size is positive. It implies that small low-income households are 10% more likely to use modern energy carriers for cooking than their larger counterparts, even holding income and location constant.

The 'year' variables, 2010, 2012 and 2014 have negative signs for traditional and transitional energy carriers. The implication is that in 2010, 2012 and 2014, low-income households were respectively 3%, 4% and 4% less likely to use traditional energy carriers for cooking than in 2008. Low-income households were 3% less likely to use transitional energy carriers for cooking in 2010, 4% less likely in 2012 and 2014 than in 2008. For the modern energy carrier, however the signs for 2010, 2012 and 2014 were positive. This implies that low-income households were 6% more likely to use modern energy carriers for cooking in 2010 than in 2008 and 8% more likely in 2012 and 2014 than in 2008. South Africa, therefore recorded progress in terms of improving the use of modern energy sources.

The study further analysed the predicted probabilities of the low-income households for the choice of energy for cooking to see their probability of preference and to determine if the result of the logistic regression makes sense. The predicted probabilities for energy choice for cooking are presented in Table 2.

Table 2: Predicted probabilities for energy choice for cooking

	95% confidence interval
Pr (y=1= less preferred | x: 0.1826	[0.1531, 0.2120]
Pr (y=2=moderately preferred | x: 0.1803	[0.1504, 0.2102]
Pr (y=3=most preferred | x: 0.6371	[0.5987, 0.6755]

The interpretation of the result was that there was a 64% probability of the choice of modern energy carriers being most preferred for cooking by low-income households, holding other variables constant at their reference points. There was also 18% probability that low-income households would choose transitional energy carriers, which was a moderately preferred energy choice for their cooking, holding other variables in the model constant at their reference points. There was, lastly, 18% probability that the low-income households would choose the option of traditional energy carriers for cooking, which was a less preferred option, holding other variables in the model constant at their reference points. This conforms to expectations.

3.2 Marginal effects for energy choice for heating

Table 3 presents the marginal effects after ordered logistic regression with respect to heating energy service.

Real income was not a statistically significant determinant of household energy choice for heating, therefore even if household income rose, the switch to modern energy sources would not be automatic, as explained by the energy ladder theory. Other variables such as being in a modern dwelling type, located in an urban area and having a smaller household size all increased the probability of using a modern energy source for heating, and were statistically significant at the 1, 1 and 5 percent level of significance respectively.

For dwelling type, low-income households living in modern dwellings were 18% less likely to use a traditional energy carrier, 8% less likely to use transitional energy carrier for heating, and 27% more

Table 3: Marginal effects for energy choice for heating.

	Marginal effects for traditional energy carrier	*Marginal effects for transitional energy carrier*	*Marginal effects for modern energy carrier*
Real income	-2.98e-05	-2.33e-05	5.32e-05
Dwelling type (modern)	-0.1846***	-0.0876***	0.2723***
Age	0.0007	0.0005	-0.0013
Gender (female)	0.0086	0.0069	-0.0156
Rurality (urban)	-0.2047***	-0.0916***	0.2964***
Household size (small)	-0.0711**	-0.0462**	0.1173**
Year (2010)	-0.0794***	-0.0664***	0.1458***
Year (2012)	-0.0621***	-0.0517***	0.1138***
Year (2014)	-0.0635***	-0.0531***	0.1167***

*T-statistics in parentheses: * significant at 10%; ** significant at 5%; *** significant at 1%*

likely to use a modern energy carrier for space heating.

Similarly, urban low-income households were 21% less likely to use traditional energy carriers for heating, 9% less likely to use transitional energy carriers and 30% more likely to use modern energy carriers.

Low-income small households were 7% less likely to use traditional energy carriers, 5% less likely to use transitional energy carriers and 18% more likely to use modern energy carriers for heating. Therefore, with household size, as found with the energy choice for cooking, small household size implied less energy demand and therefore the low-income households would prefer to use a modern energy carrier for space heating.

The inference for the ‘year’ variables is that low-income households were 8% less likely to use traditional energy carriers in 2010 than in 2008 and 6% less likely in 2012 and 2014 than in 2008. For modern energy carriers, low-income households were 15% more likely to use them for heating in 2010, 11% more likely in 2012 and 12% more likely in 2014 than 2008.

As found with the choice of energy for cooking, the variables, age and gender of the household head were not statistically significant, indicating they were not relevant in influencing the choice of energy carriers (traditional, transitional or modern) for heating by low-income households, holding all other variables in the model constant.

The predicted probabilities for the energy choice for heating by low-income households are given in Table 4. In Table 4, the outcome showed a 54% probability that a modern energy carrier would be chosen for heating among low-income households - considerably less than for cooking. There was a 19% probability that a transitional energy carrier would be chosen and 28% probability for the option of a traditional energy carrier for space heating, holding other variables constant at their means.

Table 4: Predicted probabilities for energy choice for heating.

	95% confidence interval
Pr (y=1= less preferred | x: 0.2755	[0.2380, 0.3129]
Pr (y=2=moderately preferred | x: 0.1886	[0.1549, 0.2223]
Pr (y=3=most preferred |x: 0.5359	[0.4934, 0.5784]

3.3 The result of marginal effects for energy choice for lighting

Table 5 presents the marginal effects for lighting energy service to be compared with those in Tables 1 and 3.

Energy choice for lighting was also not statistically affected by income. While heating is very energy intensive (and thus expensive), lighting is very energy efficient and thus affordable for almost all low-income households. Figure 3 shows that a clear majority of low-income households (84% in 2014) used a modern energy source for lighting. Dwelling type (modern) and rurality (urban) were, however, statistically significant determinants of energy choice at the 1% level of significance and had negative signs for traditional and transitional energy carriers.

Low-income households living in modern dwellings were 17% less likely to use candles, 3% less likely to use transitional energy carriers and 21% more likely to use modern energy carriers for lighting than those living in non-modern dwellings.

Similarly, urban low-income households were 6% less likely to use candles for lighting, 1% less

Table 5: Marginal effects for energy choice for lighting.

	Marginal effects for candles	*Marginal effects for transitional energy carrier*	*Marginal effects for modern energy carrier*
Income	-2.67e-05	-6.69e-06	3.34e-05
Dwelling type (modern)	-0.1792***	-0.0327***	0.2120***
Age	0.0001	2.76e-05	-0.0001
Gender (female)	-0.0311	-0.0074	0.0385
Rurality (urban)	-0.0576***	-0.0131***	0.0708***
Household size (small)	-0.0176	-0.0042	0.0219
Year (2010)	-0.0155	-0.0039	0.0195
Year (2012)	-0.0303	-0.0077	0.0380
Year (2014)	-0.0498***	-0.0129**	0.0627***

*T-statistics in parentheses: * significant at 10%; ** significant at 5%; *** significant at 1%*

likely to use transitional energy carriers and 7% more likely to use modern energy carriers than rural low-income households, holding other variables in the model constant. This marginal effect implied that there was much less difference in the probability of using modern energy carriers for lighting between urban/rural than there was for cooking and heating.

Table 5 shows that 2014 was statistically significant at the 1% level of significance for candles and the 5% level of significance for transitional energy carriers and had negative signs. Thus, in 2014, low-income households were 5% less likely to use candles compared with 2008 and 1% less likely to use transitional energy carriers compared with 2008. For the modern energy carrier, the marginal effect suggests that the low-income households are 6% more likely to use modern energy carrier for lighting than in 2008, holding other variables in the model constant at their means. Unexpectedly, 2010 and 2012 were not statistically significant for the three energy choice options as they were for cooking and heating. This may be caused by electricity supply crises faced by the country with emergencies in supply declared in 2008/2009.

Finally, in addition to the 'year' variables, age and gender of the household head and the size of the household were statistically insignificant, indicating they were not relevant in influencing the choice of energy carriers for lighting by low-income households.

The predicted probabilities for energy choice for lighting by low-income households is thus shown in Table 6. Notably, in making the energy choice for lighting, 'less preferred' is associated with candles, 'moderately preferred' with transitional energy carriers and 'most preferred' with modern energy carriers. The result from Table 6 implied that there was a 77% probability that a modern energy carrier would be chosen for lighting and less than 1% probability that the low-income households were likely to opt for transitional energy carriers. Lastly, there was 19% probability that low-income households would choose candles for lighting. For cooking, the predicted probability was 60%; it was 54% for heating and 77% for lighting. These percentages reflect the energy intensity needed for each service considering electricity as the source of energy.

Table 6: Predicted probabilities for energy choice for lighting.

	95% confidence interval
Pr (y=1= less preferred | x: 0.1871	[0.0316, 0.0629]
Pr (y=2=moderately preferred | x: 0.047	[0.1572, 0.2168]
Pr (y=3=most preferred | x: 0.7657	[0.7329, 0.7986]

4. Conclusions

The quantitative insight on energy ladder behaviour for cooking is one key finding in this study; low-income households that originally used traditional or transitional energy carriers would shift up to transitional or modern energy carriers for cooking as their income increases. The importance of low-income households adopting energy ladder behaviour is the reduction in the use of traditional or transitional energy carriers; this in turn has positive external results for society, including less deforestation and reduced greenhouse gas emissions into the atmosphere (Baiyegunhi and Hassan 2014).

The implication of the finding regarding energy stacking is that even in South Africa, where most people have access to electricity; some households still demonstrate energy poverty. The use of energy efficient appliances for heating could assist in the switch to modern energy carriers. Policies to reduce energy poverty need a multi-pronged approach, not only a focus on electricity access. Rural low-income households have greater access to wood than urban ones, and could be using fuelwood as energy security or for some cultural preferences (especially when it comes to cooking).

The type of dwelling and geographical location could aid the adoption of modern energy carriers by low-income households. Suitable measures to combat energy poverty should therefore be urban-rural specific. This information is important for providing support for the design and implementation of effective energy policies for the residential sector.

Note

1. A supplementary file containing the variable description and measurement, literature on energy transition patterns and determinants of energy choice by low-income households in developing countries is available at: https://journals.assaf.org.za/jesa/article/view/4389.

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Journal of Energy in Southern Africa

Volume 29 Number 3

The viability of biomethane as a future transport fuel for Zambian towns: A case study of Lusaka

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Abstract

The objective of the study was to determine the viability of biomethane as a transport fuel for Zambian urban towns. The study revealed good potential for biomethane production and use as a transport fuel in Zambian towns, using Lusaka as a case example. There is 3.67 million m^3 *biomethane potential from municipal solid waste alone in Lusaka. About 3 000 tonnes of organic fertiliser would replace an equivalent amount of chemical fertiliser. The replaced chemical fertiliser would lead to about 5.816* $GgCO_2eqy^{-1}$ *as avoided emissions. The study showed a positive net present value at the prevailing market interest rates of 28–40%; the project would become unviable at interest rates higher than that. It was estimated that the project would recover its initial investment in a maximum of two years. The research findings have closed data and information gaps in Zambia and have potential to contribute to academic research, policymaking, investments, financing and interested parties.*

Keywords: *biogas, municipal solid waste, environmental, social and economic benefits*

Journal of Energy in Southern Africa 29(3): 86–95
DOI: http://dx.doi.org/10.17159/2413-3051/2017/v29i3a4893
Published by the Energy Research Centre, University of Cape Town ISSN: 2413-3051
http://journals.assaf.org.za/jesa
Sponsored by the Department of Science and Technology

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1. Introduction

Biogas is the main product of the anaerobic digestion (AD) of organic waste and wet biomass. The organic fraction of municipal solid waste (MSW)' slaughterhouse waste, agricultural and forest residues, livestock manure, dedicated energy crops, and sewage waste are all potential feedstock types that can be used to produce biogas [1, 2]. During the AD process, a major portion of the carbon compounds are converted to methane (CH_4), carbon dioxide (CO_2) and water [3, 4]. Biogas normally contains 50–70% CH_4, 35-50% CO_2 [5] and trace gases like hydrogen sulphide (H_2S), depending on the feedstock type [6].

The co-product of anaerobic digestion is organic fertiliser, which is preferable to chemical fertiliser in terms of environmental impacts [7] and can lead to higher yields [8]. Traditionally, biogas has been used by households as a source of energy for cooking [9] and combined heat power plants to produce electric power and heat [10]. Countries like Germany, Sweden, Switzerland, Italy, Hong Kong and Ireland demonstrated that biogas could be upgraded to biomethane and used more efficiently by injecting it into the compressed natural gas grid or used as a transport fuel for both heavy and light duty vehicles [11, 12].

The main objective of this study was to assess the viability of biomethane production and use as a transportation fuel. The study first assessed the biogas potential from municipal solid waste in Lusaka, discussed the upgrading processes of biogas in general, and estimated how much biomethane could be available for light-duty vehicles weighing 0.75–3.00 tonnes. The focus was on these vehicles because they have small engines and mostly use petrol, which can easily be switched to biomethane [13]. The study then looked at the potential environmental, health and sanitation, and social and economic benefits of adopting biomethane as a future transport fuel in Zambia.

2. Methodology

The information and data used in this study was obtained from the Central Statistics Office reports, official reports from government ministries, non-governmental and community-based organisations, the Food and Agriculture Organisation statistics database, and publications on similar studies in other countries where such projects have been and are being implemented.

2.1 Biogas potential

Biogas potential was determined according to Sanches-Pereira et al. [14]) and Shane et al. [15]. Jingura and Matengaifa [16] stated the biogas potential as the product of quantity of feedstock and the biogas potential per ton of feedstock less 6% losses. The biogas potential can be estimated according to Equation 1. The population from different wards of Lusaka province was obtained from the Census of Population and Housing report [17]. The generated solid waste per capita used in the estimation was obtained from the Zambia Environmental Outlook report for which the Environmental Council of Zambia, now the Environmental Management Agency (ZEMA), carried out studies and determined this figure. The MSW collection efficiency was also obtained from studies by ZEMA and Senkwe et al. [18]. The organic matter content and the biogas potential were taken from similar studies done in sub-Saharan African countries like Zimbabwe and Uganda. A 6% biogas loss was also incorporated into the formula [19] to account for characteristic leakages in production of the biogas.

$$BP_{MSW} = \sum N_i \times Q_{pc} \times C_{eff} \times OM_f \times B_p \tag{1}$$

where BP_{MSW} is the biogas potential from municipal solid waste (m^3d^{-1}); N_i is the ith ward total human population; Q_{pc} is the quantity of municipal solid waste generated per capita ($kgp^{-1}d^{-1}$); C_{eff} is the municipal solid waste collection efficiency or rate of municipal solid waste collection (%); OM_f is the organic matter fraction in the municipal solid waste (%); and B_p is the biogas potential of the organic fraction of the municipal solid waste (m^3kg^{-1}).

2.2 Organic fertiliser production potential

The organic fertiliser was estimated using the estimated biogas and/or biomethane potential, the standard ratio of methane in the biogas, standard density of methane and the organic fertiliser that could be produced per unit volume of biogas generated. These parameters were obtained from similar studies on organic fertiliser production, according to Equation 2 [20-22].

$$Q_f = \frac{M_{CH_4}}{\rho_{CH_4} \times R_{CH_4} \times V_B \times D_P} \tag{2}$$

where Q_f is the production rate of fertiliser (kgd^{-1}); M_{CH_4} is the mass of methane generated within a year (kgy^{-1}); ρ_{CH_4} is the density of methane (kgm^{-3}); R_{CH_4} is the ratio of methane in the biogas; V_B is the biogas generated from a unit mass of organic fertiliser (m^3kg^{-1} of fertiliser); and D_p is the number of days per year of production.

2.3 Avoided greenhouse gas emissions

Avoided greenhouse gas (GHG) emissions that were considered were CO_2 from chemical fertiliser production, nitrous oxide (N_2O) emissions from chemical fertiliser (replaced urea and D-compound) applications to managed soils, and non-CO_2 GHG emissions such as combustion of MSW in disposal sites and emissions from fuel combustion. Managed soils are soils that undergo enhancement in terms of their performance and fertility through practices such as tiling, ploughing, and the addition of agricultural lime and fertiliser.

2.3.1 Avoided greenhouse gas emissions from fertiliser production

To estimate the amount of GHG emissions from fertiliser production, the amount of GHG emission per kg of nitrogen fertiliser produced is multiplied by the percentage of nitrogen in the fertiliser and the quantity of fertiliser produced (kgy^{-1}), according to Equation 3 [23, 24]. The amount of fertiliser was obtained from the quantified organic fertiliser, which could be replaced by the chemical fertiliser. The nitrogen content was obtained from a standard nitrogen phosphorus and potassium fertiliser used in Zambia, and emission factors are standard factors obtained in chemical fertiliser production.

$$GHG_{FP} = 365\sum_{i=1}^{n} Q_f \times P_{N,i} \times EF_i \times 10^{-6} \quad (3)$$

where GHG_{FP} = GHG emissions from fertiliser production ($GgCO_2eqy^{-1}$); Q_f = quantitate of fertiliser type *i* (kgd^{-1}); percentage of nitrogen in fertiliser type *i* (%); and EF_i is the GHG emissions per kilogram of fertiliser type *i* ($kgCO_2eqkg^{-1}$ N-fertiliser). The values of GHG emissions per kg of nitrogen fertiliser produced are given in Table 1. The fertiliser in row one was used in the calculation because of the large number of citations in the literature, which could indicate wide applications in research.

Table 1: Greenhouse gas emissions from fertiliser production.

Fertiliser type	*N*	*P*	*K*	*Source*
GHG emissions (kg CO_2-eqkg^{-1} fertiliser	3.30	1.10	0.73	IFA, 2009; TGO, 2015; Lal, 2004b
	3.30	1.57	0.50	(TGO, 2015
	3.63	1.55	0.97	Kool et al, 2012

2.3.2 Avoided greenhouse gas emissions from fertiliser application to managed soils

The GHG emissions from both chemical and organic fertiliser application to managed soils were estimated according to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, Volume 4 and Chapter 11 [25], Elsgaard [26] and Figueiredo et al. [28]. Equations 4 and 5 were used to calculate direct and indirect nitrous oxide (N_2O) emissions, respectively, from the nitrogen, phosphorus and potassium (D-compound), urea and organic fertiliser application to managed soils. The quantity of chemical fertiliser used in the estimation was based on the equivalent fertiliser that would be replaced by organic fertilisers.

$$N_2O_{DE} = N \times \frac{44}{28} \times EF_1 \times 10^{-6} \quad (4)$$

$$N_2O_{IE} = N\left[(F_{Vola} \times EF_4) + (F_{leach} \times F_5)\right] \times \frac{44}{28} \times 10^{-6} \quad (5)$$

where N_2O_{DE} = direct N_2O emissions from synthetic nitrogen additions to the managed soils (Gg N_2O yr^{-1}); N = consumption in nutrients of N-fertilisers (kg N input yr^{-1}); EF_1 = emission factor for N_2O emissions from N inputs (kg N_2O–N/kg N input); N_2O_{IE} = indirect N_2O emissions produced from atmospheric deposition of N, volatilised from managed soils (Gg N_2O–N yr^{-1}); F_{vola} = fraction of applied synthetic N-fertiliser materials that volatilises as NH_3 and NO_x (kg N volatilized/ kg of N applied); *EF4* = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N–N_2O/kg NH_3-N + NO_x-N volatilised; F_{leach} = fraction of applied synthetic N-fertiliser material that leaches as NH_3 and NO_X (kg N leached/kg of N additions); and EF_5 = emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N/kg N).

2.3.3 Avoided greenhouse gas emissions from burning of municipal solid waste in dump sites

The methane and nitrogen oxide emissions were estimated according to the IPCC, volume 2 on energy, chapter 2: stationary combustion, under tier one as stated in Equation 6. The open air burning of the MSW considered under stationary combustion because of the immobile burning. The MSW was left to burn where it was dumped. The combusted fuel was obtained from the amount of MSW that ended up in disposal sites and the emissions factors were default emissions factors as stated in IPCC 2006 [28]. Carbon dioxide emissions accounted for the majority of the GHG emissions from open burning of MSW. However, since its source is biogenic, it was ignored in the calculations.

$$E_{GHG,F} = FCF \times EF_{GHG,F} \quad (6)$$

where $E_{GHG,F}$ = emissions of a given GHG by type of fuel F(kg GHG); FC_F = amount of fuel combusted (TJ); and $EF_{GHG,F}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ).

2.3.4 Avoided emissions from fossil fuel consumption

The GHG emissions from fossil fuel were estimated using the average combusted fuel for each fuel types. The historical statistics on fuel consumption in Lusaka were obtained from the energy statistics report by the Central Statistics Office. Equation (7) was adopted from the IPCC [17] to estimate these GHG emissions.

$$E_{GHG} = \sum_{i=1}^{n} [F_i \times EF_i] \qquad (7)$$

where E_{GHG} = GHG emissions (kg); F_i = fuel type i sold (TJ); and EF_i = emission factor for fuel type i ($kgTJ^{-1}$).

The magnitude of avoided GHG emissions from the use of biomethane in Lusaka equals the GHG emissions from petrol consumption minus the GHG emissions from an equivalent energy from biomethane that would be produced from municipal solid waste.

2.4 Economic viability

The net present value (NPV) and the payback period (PBP) [29, 30] are the two methods that were used to estimate the economic viability of the biomethane use as a future transport fuel in Lusaka. The basis for using NPV was that if the project NPV is greater than zero the project is considered to be profitable over that time period and the opposite applies for NPV less than zero [31]. The PBP considers the length of time in which the investment is recovered. Equations 8–11 were used to estimate the NPVs and the PBP.

$$NPV_n = (PV_1 + PV_2 + ... + PV_n) - IIC \qquad (8)$$

$$PV_n = FV_n * PVF_{n,i} \qquad (9)$$

$$PVF_{n,i} = \frac{1}{(1+i)^n} \qquad (10)$$

$$PBP = \frac{IIC}{CI} \qquad (11)$$

where NPV_n = NPV of a project over n years; $PV_1 \ldots PV_n$ = project cash flows from each project year one to n; IIC = initial investment cost; FV_n = the known future value of the project cash flow in year n; PVF_{ni} = a present value factor for the year (n) and the project discount rate (i); PBP is the payback period in years and CI is the cash inflow.

3. Results and discussion

3.1 Biogas potential from municipal solid waste for Lusaka

The waste generation per capita of 0.5 kgd^{-1}, MSW collection efficiency of 40% and organic matter fraction of 40% [32, 33] were used in the estimation. Biogas potential of 128 m^3t^{-1} with 6% losses was used [16] for MSW. The total estimated biogas potential was 16 777 m^3d^{-1}, bringing the total to 6 123 605 m^3y^{-1}. Taking the biogas to constitute 60% methane [21], there would be about 3.67 million m^3y^{-1} of biomethane potential in Lusaka. Table 2 presents the estimated biogas potential.

3.2 Organic fertiliser production

Using Equation 2, the co-product of biogas (bioslurry) that would be produced was estimated to be just above 3 kilotons per annum. With proper packaging and branding, the organic fertiliser could result in an income to the developer and offset some crucial costs. The price of chemical fertiliser was used as a proxy for the estimation of earning from organic fertiliser sales. A 50 kg bag of chemical fertiliser (NPK and/or urea) costs between USD 38.00 and USD 46.00 [34], yielding 0.76–0.92 USD/kg of D-compound or urea. The net income from organic fertiliser sales would be equal to the product between the quantity of the organic fertiliser produced and the unit cost less processing, storage, marketing and miscellaneous costs, which were estimated at 50% based on similar studies [35]. The net earnings from organic fertiliser sales would range from USD 1.2–1.4 million/year.

3.3 Avoided greenhouse gas emissions from chemical fertiliser production

Using Equation 3, the GHG emissions resulting from chemical fertiliser production were estimated to be approximately 2.836 $GgCO_2$ eqy^{-1}. The emission factor (EF_i) was taken as be equal to 3.30 kg CO_2eq kg^{-1} for N-fertilisers [23, 36]. The use of organic fertiliser would, consequently, not produce chemical fertilisers of an equivalent amount. Table 3 gives the calculated GHG emissions avoided from the production of urea and D-compound fertilisers.

3.4 Avoided greenhouse gas emissions from chemical fertiliser application to managed soils

Taking D-compound, urea and organic fertiliser to contain 10, 46 and 10% nitrogen respectively, a net 2.980 $GgCO_2eq$ y^{-1} was estimated (Table 4). Urea contributed the largest percentage to the net GHG emissions from chemical fertiliser application to managed soils because it has the highest nitrogen percentage [37-39].

Table 1: Daily biogas potential for Lusaka.

Constituency	*Population*	*Municipal solid waste generated (kgd^{-1})*	*Biogas potential (m^3d^{-1})*
Chawama	184 227	14 738	1 773
Kabwata	171 224	13 698	1 648
Kanyama	366 170	29 294	3 525
Lusaka Central	125 030	10 002	1 203
Mandevu	353 807	28 305	3 406
Matero	278 693	22 295	2 683
Munali	263 828	21 106	2 540
Total	1 742 979	139 438	16 777

Table 3: Greenhouse gas emissions from fertiliser production.

Fertiliser production	*Quantity*	*CO_2eq (Ggy^{-1})*
Urea	1 534 388	2.329
D-compound	1 534 388	0.506
Total		2.836

Table 4: Greenhouse gas emissions from fertiliser application to managed soils.

	Quantity (kgy^{-1})	*Direct N_2O (kgy^{-1})*	*Indirect N_2O (kgy^{-1})*	*CO_2eq (Ggy^{-1})*
Chemical fertiliser (D-Compound)	1 534 388	2 411	259	0.83
Chemical fertiliser (Urea)	1 534 388	11 091	1 192	3.81
Organic fertiliser	3 068 776	(4 822)	(518)	(1.66)
Total		8680	933	2.980

Note: Values in parentheses are negative.

3.5 Avoided greenhouse gas emissions from petrol consumption

Equation 8 was used to compute the GHG emissions from biomethane and equivalent amount of fossil fuel (petrol) that would be replaced by the biomethane. Default emission factors for tier 1 from the IPCC were used in the calculation. When calculating the total energy from each of the two energy sources, 39.82 and 34.20 MJm^{-3} were used as calorific values for biomethane and petrol respectively [40]. The avoided GHG emissions resulting from the use of biomethane as a transport fuel were estimated as the difference between the GHG emissions from the consumption of fossil fuel and the GHG emissions from the biomethane of an equivalent energy. Equation (8) was also used to estimate the amount of GHG emissions from petrol consumption in Lusaka and GHG emissions from an equivalent energy of biomethane that could replace the petrol. The biomethane energy amounted to 146 TJy^{-1}. Table 5 shows that the total GHG emissions from this biomethane were estimated to be 0.418 $GgCO_2eqy^{-1}$. This biomethane would replace an equivalent of 146 TJy^{-1} of energy from petrol. A total 11.000 $GgCO_2eqy^{-1}$ of GHG emissions would be recorded from the use of petrol (Table 6). Using biomethane would obviate 10.582 $GgCO_2eqy^{-1}$ of GHG emissions. This contribution from the use of biomethane as a transport fuel would be about 5% of the total GHG emissions from petrol consumption in Lusaka. This means that 95% GHG emissions from fossil petrol would be avoided if 146 TJy^{-1} biomethane from MSW is produced and used in Lusaka.

3.6 Avoided greenhouse gas emissions from burning municipal solid waste in dump sites

Waste is normally dumped in legal and illegal sites and later burnt [18, 41-42]. With MSW being used to produce biogas and biomethane, these emissions are reduced to at least half.

Table 5: Greenhouse gas emissions from biomethane consumption as a transport fuel.

	Energy	*Emission factors*		*Emissions*		*CO_2-eq*
	(TJy^{-1})	*CH_4 ($kgTJ^{-1}$)*	*N_2O ($kgTJ^{-1}$)*	*CH_4 (kgy^{-1})*	*N_2O (kgy^{-1})*	*(Ggy^{-1})*
Biomethane	146	92	3	13 432	438	0.418

CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide

Table 6: Greenhouse gas emissions from petrol consumption as a transport fuel.

	Energy	*Emission factors*			*Emissions*			*CO_2-eq*
	(TJy^{-1})	*CO_2 ($kgTJ^{-1}$)*	*CH_4 ($KgTJ^{-1}$)*	*N_2O ($KgTJ^{-1}$)*	*CO_2 (kgy^{-1})*	*CH_4 (kgy^{-1})*	*N_2O (kgy^{-1})*	*(Ggy^{-1})*
Petrol	146	69 300	25	8.0	10 117 800	3 650	1 168	11

CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide

Table 7: GHG emissions from the burning of municipal solid waste in dump sites.

	Energy (TJy-1)	*EF (kg CH4/TJ)*	*EF (kg N2O/TJ)*	*CH_4 (kgy-1)*	*N_2O (kgy-1)*	*CO_2-eq (Ggy-1)*
MSW	146	300	4	43800	584	1101

MSW = municipal solid waste, EF = emission factor, CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide

3.7 Economic benefits

Initial investment costs consist of installation of anaerobic digesters, a biogas upgrading unit and a biogas storage unit. Other costs included in the initial investment include the cost of conducting an environmental impact assessment for the proposed project and planning, and authorisation costs. Annual recurring costs include operational and maintenance, insurance, depreciation, and tax. Project life was estimated at 25 years [43–44]. The cost of anaerobic digesters, biogas upgrading units and storage, with their installation costs, were obtained from publications of similar studies where this technology is fully developed in Poland, Germany, Italy, China and Kenya [3, 45, 46–48]. According to the Environmental Management Act [49], an Environmental Project Brief costing about USD 1 000 (review fee) should be submitted to ZEMA.

The economic viability was determined by estimating the NPV and the simple payback period (PBP) of the proposed project using Equations 9 and 12. Over the years, interest rates in Zambia increased from about 17% to 28% and even higher [50–51]. Table 8 presents the important parameters with their sources used in the economic viability determination. The NPV calculations indicated that the proposed project was viable with NPV values ranging from USD 1 360 000 at 28% to USD 37 000 at 41% interest rates. At 42% interest rate, the proposed project became unfeasible as shown in Figure 1. The simple PBP estimations indicated that the proposed project would recover the initial investment cost within two years. The initial investment cost comprised the capital costs, operating expenses and corporate tax. This amounted in year one to USD 6 083 000 and the annual cash inflow amounted to USD 4 467 000. This implied that in year one there would still be USD 1 616 000 unrecovered. This balance would only be fully recovered in year two. In short, dividing the initial investment cost with the annual cash inflow gives the PBP of 1.4 years, which was therefore taken to be two years.

4. Enabling platform

Biomethane can be produced from a broad range of feedstocks suitable for anaerobic digestion, such as livestock manure, municipal solid waste, food processing wastewater, dairy processing, vegetable canning, potato processing, breweries and sugar production. Shane et al. [32] reported that feedstock for bioenergy and biogas is available in abundance in Zambia, with a surplus of 151 million kilograms of crop residues, 6.5 million cubic metres of forest residue, 304 kilotons of MSW and 4.8 kilotons of livestock manure per year. The water and sewerage companies across the country have the potential to provide wastewater as a feedstock for biogas production. Crop and forest residues can also be used for biomethane production if there is proper seeding and with wastewater having microorganisms.

Table 8: Cash flow for using biomethane as a transport fuel: Lusaka real case example.

Parameter	*Unit*	*Unit cost*	*Reference*	*Quantity*	*USD 1000*
Anaerobic digesters	USDm^{-3}	109	[108]	16 777 m^3	1 829
Biogas upgrading unit	kUSDMW^{-1}	250	[32, 45]	3 886 MW	972
Biogas storage	kUSDMW^{-1}	14.39	[44, 52]	3 886 MW	56
Environmental impact assessment	USD/unit	2.60	[53-54]	433 units	1
Planning and authorisation	%	5	]38]		204
Initial capital costs					**2 858**
Commercial insurance	%	5	[55]		143
Depreciation	%	5.5	[46]		157
Operational and maintenance	USD$_{ct}$kwh^{-1}	4	[47]	34 038 000 kWh	1 362
Total operating expenses					1 662
Earnings					
From organic fertiliser sales					1 381
Biomethane sales	USDCTm^3	84.00	[48]		3 086
Total earnings					4 467
Corporate tax	35%		[56]		1 563
Profit/(loss)					(1 616)

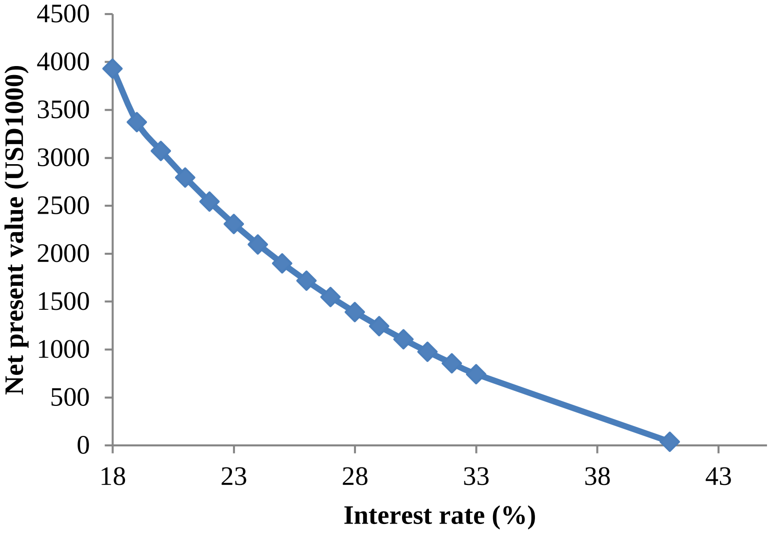

Figure 1: Net present value versus interest rates.

4.1 Biogas upgrading technology availability

For biogas to be used in a motor vehicle as a fuel, it requires processing to upgrade it to compressed biomethane gas. Once it has been compressed it can be transported to the end user or its delivery arranged. Upgrading involves removing carbon dioxide, particles, water vapour, hydrogen sulphide, siloxane, and trace gases such as ammonia, chlorine or fluorine compounds, depending on the feedstock from which biogas has been produced [57].

Figure 2 shows the biomethane upgrading technology using wet scrubbing. This technology has been used in Denmark, Sweden, Norway, USA, Italy, Brazil, Hong Kong, Germany and many other European, American and Asian countries. It is a physical process which takes advantage of the fact that carbon dioxide (CO_2) and hydrogen sulphide (H_2S) are more soluble in water compared to CH_4. The pressurised biogas if fed from the bottom and water from the top of the scrubber. The water exits

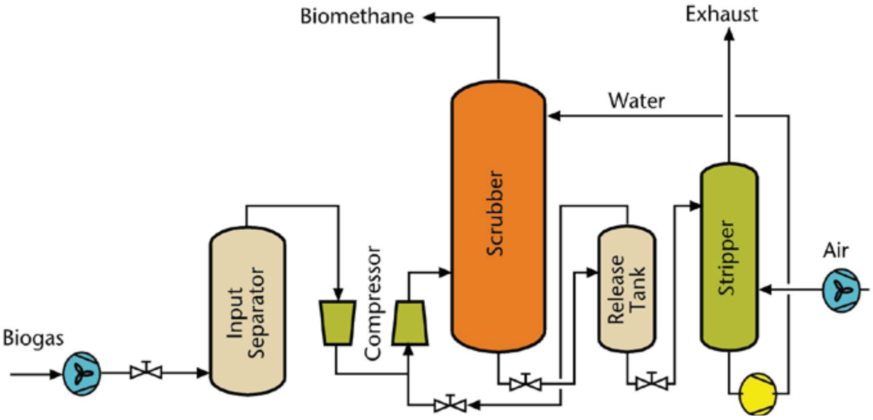

Figure 2: Biomethane upgrading technology - wet scrubbing [58].

with the CO_2 and H_2S dissolved into it at the bottom while the biomethane exits at the top of scrubber [59].

In Zambia, neither light nor heavy duty motor vehicles are ready to use biomethane with the current engine systems. The fuel system of the motor vehicle must be modified so that it can run on gasoline and biomethane, depending on which one is available. Equipment designed for converting petrol engines to use natural gas or petrol is readily available from a number of manufacturers in many countries in Europe and Asia. Technology is readily available on the market to upgrade biogas to biomethane, which could be compressed and used as a fuel for transport in both heavy and light duty vehicles in Zambia. With appropriate policy and implementation, petrol engine light duty vehicles could be targeted first. This would involve adding a biomethane conversion system to each vehicle in addition to the existing conventional one. The reason for targeting light duty petrol engines is that they have a lower fuel consumption and require less sophisticated engine modification requirements than heavy duty ones. They also commonly use petrol or biomethane, as opposed to heavy duty vehicles which mostly use diesel.

5. Conclusions

The study showed a potential to produce 3 670 000 m^3 of biomethane from municipal solid waste with 146 TJy^{-1} of energy. This would result in 10.582 $GgCO_2eqy^{-1}$ of avoided greenhouse gas (GHG) emissions from motor vehicles in Lusaka. The avoided GHG emissions accounted for 95% of emissions from petrol consumption in Lusaka if biomethane replaces fossil petrol. The biogas production process would produce 3 000 tonnes of organic fertiliser as a co-product. The replaced chemical fertiliser would lead to about 5.816 $GgCO_2eqy^{-1}$ as non-CO_2 GHG emissions from its production and application. The net present (NPV) of the proposed Lusaka compressed biogas project as a future transport fuel had a positive NPV at the prevailing market interest rates of between 28–41%, but would became unviable if interest rates increased to about 42%. A simple payback period estimation indicated that the project would recover its initial investment in a maximum of two years. The related data and information gaps that existed in Zambia were also identified, with a potential to contribute to research policymaking, investments, financing and allied parties.

Acknowledgement

Copperbelt University sponsored the presentation of this study in the 8th African Transportation Technology Transfer Conference, 10-13th May 2017, Avan Hotel, Livingstone, Zambia.

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