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Editorial

Thank you to all the authors and all who helped make Issue 2 of Volume 27 of the *Journal of Energy in Southern Africa* a success! Much consideration will preferentially be given to research designed or set up in the southern African region and to studies associated with energy-related matters in the southern African region.

JOURNAL OF ENERGY IN SOUTHERN AFRICA

Promoting energy efficiency in a South African university

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Abstract

Electricity supply issues have resulted in widespread blackouts and increased utility costs in South Africa. This is placing financial pressure on universities as they have limited means of increasing their income to cover the additional energy costs and, at the same time, are energy-intensive due to peculiar usage patterns and sprawling campuses with many (and often large) buildings. Thus, they must become energy-efficient. This is a case study of one such attempt. Four main findings emerged. Firstly, energy demand side management (DSM) had to be implemented in distinct phases due to unforeseen implementation hurdles. Secondly, there are both barriers and enablers to becoming an energy-efficient campus; that is, DSM requires managerial buy-in, capacitated operational personnel and money. Thirdly, personnel can either support or hinder DSM implementation. So, while hiring dedicated, skilled personnel to harness organisational commitment to DSM is essential, all personnel need training in energy-efficient behaviour and should be held accountable for DSM initiatives within their sphere of influence. An energy champion – at the highest level of the organisation – to influence policy and drive the behavioural and structural changes required, is strongly recommended. Lastly, DSM technologies may be readily available but are not necessarily bought, installed or used correctly due to behavioural and institutional cultural constraints.

Keywords: sustainability, campus operations, barriers, champions

Highlights

- The challenges facing universities when adopting energy-efficiency are identified.
- There are also enablers to achieving energy-efficiency targets.

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1. Introduction

South African universities, like other organisations, households and businesses are faced with increasing pressure to manage electricity demand and costs down by becoming energy efficient [1]. This is to address financial and generation capacity constraints. As Pretorius et al. note, residential energy consumption increased by 50% from 1994 to 2007 [2]. The price of electricity in South Africa has increased by over 200% between 2008 and 2014, so that universities face escalating energy costs, at a time when their operating budgets face multiple demands and opportunities to increase income are few. In addition, South Africa's main energy supply company, Eskom, is unable to keep up with demand and rolling blackouts (known locally as load shedding) often ensue [3]. Such losses of electricity supply are hugely disruptive and costly. Thus, managing energy costs down has become essential. Furthermore, many South Africans look to universities to provide leadership, and as such pressure is on them to be exemplars of energy efficiency. One key aspect thereof is to retrofit their built environment into an energy-efficient one, as buildings are known to consume significant amounts of energy, mostly during the operations phase. Most South African campuses were not, however, designed for energy efficiency. They cover large areas, have many buildings, and were mostly constructed in an era when energy optimisation was unimportant. As energy efficiency is seldom viewed as a core university function, prioritising it is a new concept. There are a number of implementation barriers that need to be overcome. This study, of a large, multi-campus contact residential university in Gauteng, explored what managerial approach is required to 1successfully achieve energy efficiency, that is manage down electricity consumption. It contributes to the literature, as previous energy efficiency studies at universities, focused mainly on national initiatives. Furthermore, little research has been conducted on energy efficiency within public building typologies.

1.1 An international perspective

A number of authors have long maintained that universities have a moral responsibility to engage in sustainable practices, including the creation of energy-efficient campuses [4–8]. Thus, the notion that universities must lead by example is not new [9, 10]. Despite this, few universities have assumed a leadership role in environmental responsibility and sustainability [11–13]. Arguably, this is due to a number of barriers impeding the emergence of sustainable campuses [14–15]. Empirical studies posit numerous explanations for why this is so. These include: (1) university management not seeing sustainability as part of their core business; (2) rhetoric is more common than action; (3) lack of financial resources (made worse by the usually long payback periods); (4) lack of expertise and information; (5) inhibiting organisational structures and organisational culture; and (6) a lack of incentives [16]. Krizek et al. [17] suggest that universities face specific and unique pressures, such as competing yet equally important priorities; organisational diffusion; financial constraints and internal power struggles, as shown in Figure 1.

Sharp suggests that the various university subcultures (teaching, research, administration, operations) create power groupings and internal struggles ensue [18] so that organisational alignment is required to ensure an overarching vision of campus sustainability. Some scholars also point to the lack of leadership within the sector [15,19,20]). Rosenbloom concurs, recommending that sustainability requires a champion at very senior levels to drive it, as implementation requires authority and resources [21]. Therefore, institutions have to accept that sustainability is not simply an accounting exercise, but requires a change in approach and way of thinking.

Pearce and Miller [23] argue that universities often fail to capitalise on the enviro-economic opportunities because campus operations are invisible to campus decision-makers, making them unaware of the issues at hand. In addition, there is a tendency to save money by deferring maintenance, especially in an environment where capital and labour are often costly and scarce in the first place. For example, a survey of approximately 400 USA colleges and universities found billions of US dollars value in deferred maintenance [22]. Rosenbloom [21] found that decentralised decision-making is a major inhibitor. For example, although a (temporary) shift in funds from student services to retrofitting buildings would ultimately offer students a better service, this seldom happens, as budgets are devolved to different people with different responsibilities. Other studies point to organisational complexity as the primary problem [5,18,23–26].

1.2 Sustainable campuses – the South African perspective

South African universities face not only internal barriers to the establishment of sustainable campuses, but also considerable national ones (see Table 1), the most significant being energy generation, transmission and distribution. In particular, Eskom monopolises electricity generation [2,27] and so plays a pivotal role in either hindering or helping an organisation become energy efficient. For example, Eskom is the custodian of national energy data, it sets electricity prices (along with the National

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[1] Universities' primary goals are seen as recruiting students, skilled staff and grant funds [22], [6].

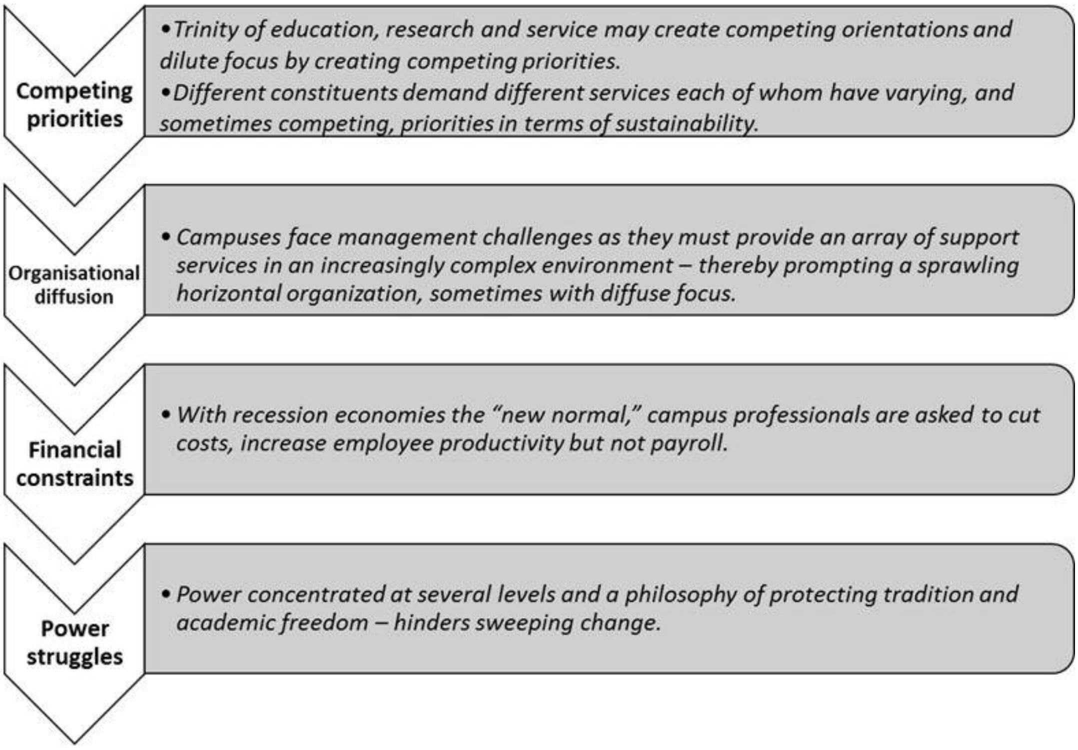

Figure 1: Barriers to achieving sustainable campuses (adapted from Krizek et al. [17]).

Table 1: National barriers to energy efficiency [29, 30].

Barrier	***Description***
Historically low energy pricing	Due to historically low prices of coal and electricity
Lack of knowledge and understanding of energy efficiency	Across all stakeholders
Institutional barriers, and resistance to change	Fears that energy efficiency will disrupt production or work processes
Lack of investment confidence	Scepticism that the returns on the initial investment will materialise

Energy Regulator and the municipalities) and often large users pay less per kilowatt hour than smaller ones. This creates an unfavourable environment for energy efficiency [28]. However, with Eskom facing serious supply problems, rolling blackouts and steep electricity prices increases (at rates far above inflation) are frequent occurrences, so that many consumers are prompted to seek ways to become energy efficient (to contain costs) and reduce their reliance on Eskom (to ensure security of supply).

Another pivotal player is the local municipalities, who buy electricity from Eskom and sell it to consumers, such as universities. Consequently, municipalities are 'middle men' in the electricity supply chain and they sell electricity on at a profit. With their small tax base and limited monetary transfers from national government, most municipalities use electricity sales to sustain themselves and cross-subsidise other municipal services. Accordingly, they have a stake in high tariffs and high electricity consumption. Be this as it may, there are additional, and serious problems at the municipality level in South Africa, with respect to metering and billing. That is, most municipalities do not have the technical and financial skill to bill accurately, and what information they do have is often of such a poor quality that it is unusable [28]. So, electricity or utility bills can be best described as estimates, although some municipalities, such as the City of Johannesburg have been found to be systematically overcharging [31]. As Thovhakale et al. [32] highlight, such accounting problems are a significant barrier to energy efficiency because users are unable to make informed decisions about their energy consumption and there is seldom a direct relationship between reduced consumption and a reduced utility bill. Therefore, building a business case for energy efficiency is difficult, as the return on investment cannot be calculated with certainty. Users are often forced to verify their own consumption by installing additional meters. In fact, Thovhakale et al. [32] advocate the installation of additional meters to verify consumption, together with the nomination of champions within an organisation to drive energy efficiency. Thus, they argue, reducing energy consumption in buildings is a skilled activity. South Africa also has specific technological barriers that need to be overcome, in, for example, lighting, solar water geysers and heat pumps. For South Africans, such technologies represent high investment costs coupled with a lack of trust in unfamiliar technology. People lack training and understanding of how they work. In some cases, there are also operational problems relating to the use of the technologies [33]. Thus, incentives for their adoption are not clear.

South African universities also have internal barriers to overcome. To date there have been few studies on their energy efficiency. Heun & DeVries [34], however, found that a lack of clarity within the organisation meant that those wanting to implement energy efficiency measures do not know who to approach or even how to get the process going. University personnel and students are found to be 'disengaged' with respect to DSM – unaware of how much electricity they consume and how much it costs, and unwilling to change unless there are incentives or enablers to do so. They concluded that dedicated personnel and policies are required if energy efficiency is to be achieved. Other studies found other hurdles such as: a lack of in-house expertise (and hiring such personnel is difficult due to the skills shortage and high salaries they can command) and lack of data (a perennial South African problem) [35, 36, 37]. Additionally, the initial high capital investment requires an understanding of long-term savings benefits, which is a challenge as budgetary pressures are usually short-term [34, 37]. If all the savings generated from DSM interventions are not ring-fenced for additional DSM investments, then momentum is lost, limiting opportunities and long-term benefits. Based on the literature, the barriers to achieving energy efficiency are: (1) lack of in-house experience or of dedicated capacity; (2) lack of data; (3) lack of initial capital investment; (4) lack of incentives; (5) unclear organisational boundaries (6) unwilling personnel; (7) lack of awareness, and poor communication with personnel. There are also proposed solutions in the literature: (1) a dedicated enthusiastic driving team headed by an energy manager located in facilities management; (2) support from management, with a focus beyond mere financial viability; (3) submetering and reliable data management; (4) having a sustainability office; and (5) having a revolving energy efficiency fund [34–37]. Systemic solutions to these barriers involve three key components: behaviour, information (or data), and integration [36]. At the institutional level, Delport [35] recommends the formation of an Energy Co-ordination Committee, an Energy Action Team, and the drafting of an Energy Policy as a precursor for successful energy DSM. This is in line with what Fawkes [38] found in a specific South African industry, along with poor managerial commitment, low levels of commitment by personnel, confusing investment and communication channels, and the lack of an energy policy. Lastly, any public South African organisation, including universities, will find that most energy DSM research has focused on residential, commercial and industry buildings. With little research on public building typology, the learning curve is great and costly.

Unlike some of their international counterparts, however, South African universities also experience other unique pressures, including the need to promote transformation and diversification. Dealing with issues of access, equity and quality relative to the standard functions of a university are significant challenges [39]. Thus, Badat [40] refers to a situation where universities face 'demand overload', compounded by the fact that South African universities are significantly underfunded. South African universities are, then, seldom in a position to implement DSM, even should funds be available, as pressure to channel such funds to other functions is immense. In such a context, it seems that a way forward for them is to focus on the pragmatic benefit of cost reduction, to enable savings on the utility bill to be redirected to the core mission of teaching and research [3]. Although energy-efficient campuses are not common in South Africa, where attempts have been made, the focus has been on technical interventions to reduce consumption (e.g. energy-efficient lighting). But technical interventions have their limits [41–43]. There is a growing body of evidence to suggest that adopting a behavioural approach in conjunction with technical interventions is required if energy efficiency is to be achieved [43–45]. The behavioural approach involves trying to influence people's attitudes using various techniques such as incentives, awareness raising or skills development [46]. Saini [47] argues that 'well-motivated personnel are best able to develop and implement energy efficiency policies'.

2. Research design and methodology

A qualitative research design, with in-depth interviews with key university personnel and a case study approach, was adopted. Case studies are a popular qualitative research methodology [48]. Case studies have been adopted in various studies with a sustainable campus focus [49–54]. The university that formed this case study is one of South Africa's the largest residential universities, with a student population of roughly 50 000 and a personnel complement of approximately 6 000. It was formed through the merger of various smaller higher education institutions and has four campuses comprising 302 buildings or 661 974m^2 of built environment [55]. The utility bill is high. The institution is flagged as a 'high energy user' by the local authority, indicating that in the future it will be forced to implement energy reduction targets or endure financial penalties. Recognising this, the university committed itself in 2012 to achieving a 7% consumption reduction by 2013 [3]. This study explored the process through which the university set about achieving this target and records the lessons it learnt along the way. Interviews with key stakeholders involved in DSM initiatives were conducted between January 2011 and December 2012, using a purposive sampling approach, and each was interviewed twice. Seven individuals (academics, executive managers and a consultant) participated (see Table 2). All ethical considerations were adhered to and consent from university management was obtained. The narrow range and limited number of participants is a shortcoming, and a better distribution between academic and administrative personnel would have been preferred.

Table 2: Description of respondents with references used in text.

Respondent	*Level in organisation*	*Cited as*
Prof A	Research professor	Respondent A
Dr B	Senior lecturer	Respondent B
Dr C	Executive	Respondent C
Mr D	Director	Respondent D
Mr E	Director	Respondent E
Mr F	Director	Respondent F
Mr G	Consultant	Respondent G
Mr H	Campus official	Respondent H

3. Results

The need to manage the 2005 merger between the three 'parent' institutions of university, meant that for a number of years energy efficiency was not a priority. Thus, the first step towards DSM was an electrical safety audit in 2010. Although the audit revealed that the biggest campus had the highest electricity consumption, the serious problem of no extant wiring data for the other campuses meant that all electrical infrastructural investment had to go into extensive (and costly) electrical infrastructural rehabilitation and upgrading (Respondent D).

Then attention turned to electrical metering and the auditing of the municipal electrical accounts. This audit found that accounting personnel had left some utility accounts unpaid for years as, with no access to meter readings, they could not authorise payments as they could not verify their accuracy (Respondent H). Forensic auditing of all the utility accounts revealed that the municipal bills were inaccurate, sometimes resulting in under-billing, but evidence of systematic overcharging by the municipality emerged and it could not be determined if the electricity meters were read on a regular basis (Respondent C). Improving the electricity metering system to verify accounts was, therefore, urgent. But this was seriously hampered when, in 2011, there was a data system crash, and all real-time electricity readings for the main campus were lost. Consequently, the creation of an electricity consumption baseline dataset was delayed (Respondent C). In addition, establishing and validating electrical metering took on a lengthy trial and error approach until it was realised that metering must at the level of individual buildings (Respondents D and H).

During this time, some DSM interventions were carried out, such as installing energy-efficient lights, banning the purchase of new air-conditioners, removing hot water boilers and buying stand-by generators to cope with the blackouts. It was found that the main campus-wide air-conditioning system was extremely energy-intensive, partly because the plant was old and inefficient. The student residences were also found to be major energy users (Respondent G). It was also a period when a Steering Committee on Energy Efficiency, Water and Resource Efficiency was formed and made a sub-committee of the University Council. But still 'a lot had to be done' (Respondent C), especially as 'over weekends [power consumption] should drop yet [it hasn't]' but where, how and why this was occurring remained unknown and unaddressed (Respondent D).

Another realisation was that dedicated personnel – energy efficiency champions to drive energy efficiency – are needed (Respondents F and D). The use of 'consultants and temps' meant DSM initiatives were undertaken on an ad hoc basis. There was no overall plan, policy or strategy. Thus, a 'utilities director' with high levels of DSM technical expertise (knowledge and experience) and competence is needed to institutionalise DSM (Respondent D). Such a utilities director would ensure that institutional energy efficiency targets are met, and that a more structured or coordinated approach to energy efficiency is taken. Considering the size of the problem and the lack of internal capacity, this Utilities Director also needs strong leadership and managerial skills, and the ability to think on their feet and be a consummate problem solver (Respondent D).

Be that as it may, both the creation of the utilities director post and filling it was fraught with delays, partly due to financial constraints and human resources policies. Although the position required a highly skilled, senior, qualified and experienced engineer, the university remuneration bands could not accommodate the salary such a person commanded. Although one was eventually hired, once the university overrode its remuneration bands, he soon left due to uncompetitive performance incentives and retention polices (Respondents D and E). Despite this, significant advances were made under his leadership. The university was able to recoup monies overpaid to the municipality (about R23 million) and energy efficiency targets were included in the performance contracts of specific personnel members for the first time (Respondent D).

Lack of training and development of personnel in relation to DSM was another finding. It was realised that all personnel, 'even the finance guys', need to know about energy efficiency (Respondent F). This includes management, which must grasp the business case for DSM, that is, that 'the capital costs will be recovered through lower operating costs' (Respondent F). There also needs to be collaboration with academics, which was not occurring and so the skills and knowledge of academics went unutilised: 'we should be tapping into that intellectual space … we may have done stuff which, if we consulted with them, we could have done differently or solved the problem' (Respondent D). Lastly, it was realised that a formal energy policy was required to get buy-in from all stakeholders and ensure enforcement of energy efficiency decisions, systems and initiatives. Policy proved to be pivotal as it 'binds every person' and 'without an energy efficient policy, you do not have a fall-back position' (Respondent B). With no clear-cut policy on energy efficiency there was 'no enforcement, no rules, and no regulation' (Respondent G). That is, the policy can be used to defend DSM initiatives if they are challenged.

The promulgation of an energy policy was a turning point in DSM initiatives, as it institutionalised energy efficiency, preventing new employees derailing it with a new focus (Respondent B). Thus, policy has a lasting effect. Unfortunately it took years to get the policy drafted and ratified as it was delayed by conflicting priorities and bureaucratic procedures (Respondents D and F). University structures and governance processes are so cumbersome and complex, with numerous administrative steps and approval levels required, so 'you need to be very patient' (Respondent B). It took time to get everyone to sign off the documents, but the tender processes are also very long, as is the evaluation period and appointing the contractor. There could be up to 12 months of delays, or even more (Respondents D and F).

Rising electricity costs proved to be a major driver of DSM (Respondent C). Above-inflation increases and threatened financial penalties compelled university management to include energy-saving targets in the institutional scorecard (Respondent D). Once this occurred, the business case to use a return on investment argument to justify DSM enabled the approval of energy-efficiency projects. But as there was 'only so much money', DSM arguments needed to be financially very strong to compete against other priorities, as all were funded from one limited reserve fund (Respondent C). One respondent said that 'five years ago [management] wouldn't be very positive [but as] these initiatives [have] such a huge effect on the bottom line…it makes business sense [now]' (Respondent C). Despite this, money was limited and the projects were run on tight budget (Respondent D). Once management set targets, operational personnel had to meet them, with targets embedded in the performance contracts of personnel at Director level. As these targets were not filtered down to more junior personnel, however, their effectiveness was limited (Respondent F). For example, procurement personnel did not have DSM targets. Procurement itself was highly inefficient (Respondent G described procurement as the 'backwards and forwards throwing of documentation'). Procurement challenges demoralised operational personnel. Thus, there is a need to 'streamline procurement and [fix) glaring problems' (Respondents G and F).

The organisational structure of the Operations Division resulted in 'nobody [being] responsible for DSM' at individual campus level, as DSM projects were driven centrally despite implementation being required at campus level (Respondents B, D and G). Consequently there was a lack of focus and coherency (Respondents D & F). It also caused tensions between campus and central decision-making (Respondent D). For instance, campus personnel, who controlled capital budgets, were told to reduce spending, which they did – by purchasing cheaper, energy-inefficient incandescent lights (Respondent F).

Whilst there was recognition that 'projects should be planned [and] executed', the university seldom followed planned processes as regular crises/emergencies derailed a strategic approach (Respondent D). Power struggles between personnel and between divisions were another problem. For example, academics and operations personnel competed for money: 'You [want] money for greening [but] a professor needs something urgently for his research laboratory' (Respondents C, F and H). What is more, although there were a number of academics involved in the field of energy efficiency, only a few actively participated in the operational interventions of the university.

The institutional culture did not value energy efficiency or change. Long-serving personnel were the most resistant to change, perhaps due to extensive merger-related change resulted in 'change fatigue' (Respondent F). Personnel were apathetic and/or negative towards energy efficiency: 'The tap isn't closed … air-conditioners left on'. Some refused to co-operate. For example, each division or department had its own kitchen but personnel each had 'their own kettle, own heater, even their own microwave in their office' (Respondents C and G). This was also true for students in residences, all of whom had a plethora of personal appliances in their rooms (Respondent B). Negligence was another issue, such as failing to switch off computers or lights: 'If it doesn't affect a person in his personal capacity, there is a tendency of 'don't care that much' (Respondent C). It was felt that personnel and students did not treat university funds and property with care (Respondents A and C).

Some of this could be attributed to users being unaware of the need to conserve energy or how much electricity cost the university (Respondents B, D and F). Technology could, therefore, assist in reducing wastage: 'Technology will solve 60% of the … issues where people fail to put off their computers, lights' (Respondents A and H). Respondents felt that if users were provided with feedback and information, using the university website, personnel circulars, and posters in lifts and real time displays (e.g. dashboards) things would improve (Respondent C). One respondent suggested that management should inform personnel better, communicate the energy target and reiterate that it must be met (Respondent F).

4. Discussion

The four main findings emerging from the data will now be discussed. For this university, implementation of DSM occurred in two distinct phases: an 'uncoordinated phase' and a 'coordinated phase'. The former was characterised by the dominance of merger-related issues, with DSM not being prioritised. Thus, the merger was a disruptive, time- and resource-intensive process. There was no energy policy, which also inhibited the achievement of energy efficiency targets. The coordinated phase commenced with the appointment of a professional engineer as utilities director. This phase had an energy policy that empowered operations personnel and linked energy efficiency interventions to institutional goals and governance systems. Thus, an energy policy promotes buy-in to DSM, embeds energy efficiency into institutional practice, makes DSM targets enforceable, and ensures procurement of energy-efficient products (embedding DSM targets into purchasing decisions so that the lowest bid is not automatically accepted if it means DSM targets cannot be met). Furthermore, such a policy ensures that new managers cannot arbitrarily change targets, systems and procedures.

Analysis of the utility accounts proved to be invaluable. Firstly, scrutinising the bills made personnel aware of the true cost of energy inefficiency and awakened personnel to possibilities for saving money, as other researchers have found [57, 58]. Secondly, the university realised that independent meters must be used to verify account readings. In this regard, the sub-metering of individual buildings is essential. Unfortunately the overall university budget hindered the adoption of DSM systems and technologies, as capital was seldom available for retrofitting. In particular, limited operational budgets caused all energy-efficiency projects to be driven by short-term financing concerns. This is problematic as most DSM return on investment takes place over the medium to long term. The human resources budget was also a barrier to the hiring (and retention) of the energy champion in the form of the utilities director. Thus, finances can act as a driver and a barrier at the same time, as others have found [21,59,60].

Personnel are key role-players in DSM and, as such, operational and technical personnel must be empowered with the right levels of expertise, decision-making ability and accountability. Energy-efficiency targets must be embedded in the performance contracts of all operations personnel. They also require specific DSM training and development. In addition, as finance personnel pay the utility bills and manage procurement, they also need DSM training and targets. Initially, the lack of an energy-efficiency champion with specific DSM expertise hindered the implementation of DSM. For example, although the energy policy took a long while to be adopted, partly due to competing priorities that are natural in a large, complex institution, it was mainly because there was no one to drive or chaperone it through the system. In South Africa professional engineers with DSM experience are, however, much in demand and in short supply, so hiring such a person challenged the university human resources policy due to performance bonuses and retention-incentive constraints. This situation was aggravated by the need to adhere to national (and regional) employment equity targets. Without dedicated personnel, however, DSM progress is slow, ad hoc and subject to whimsical changes.

The study also revealed that the academics were an untapped source of expertise, so that opportunities for academics and operational personnel to collaborate on DSM initiatives went unrealised. For example, academics could supervise postgraduate students using the campus as their study site, or assist with the analysis of campus energy consumption data. Academics could also embed energy efficiency and sustainability issues into the university curriculum, at the very least promoting user awareness of the need to save energy. That said, operational personnel must still be able to achieve energy efficiency targets independently. In this regard, an energy efficiency task team has a crucial role to play in integrating DSM measures across all university activities. In particular, a senior university manager, preferably the utilities director, must chair the team. The task team must meet regularly and everyone involved in DSM initiatives should report to it.

For this university, organisational culture hindered the uptake of DSM projects, as the organisational culture inhibited quick decision-making, slowing reaction times in an environment that is unpredictable and fluid. Delays in the adoption of an energy policy, for example, were partly due to the cumbersome, procedural and bureaucratic nature of the organisation. For example, numerous stakeholders had to be engaged and re-engaged. This artificially prolonged the processes and caused frustrating delays. This is in line with the findings of Tudor et al. [56], who identify an 'ingrained' organisational culture often negating individual actions. In addition, organisational culture did not promote cooperation across divisions. Thus, although personnel from different divisions were responsible for different aspects of the energy efficient campus initiative, they did not work as a team. Decision-making devolved to the level of the division, but the overall lack of collective ownership meant that operational logjams resulted. Line managers found themselves having to make both reactive decisions and manage crises simultaneously. The structural separation of divisions contributed to inter-departmental power struggles, tensions and conflicts. For example, there were often tensions between institutional-level decision-making, where energy efficiency projects had to be approved, and the campuses which were responsible for day-to-day implementation. Finance personnel had a significant role to play (with respect to analysing utility accounts, procuring DSM technologies and managing capital expenditure), but this was seldom recognised by the various parties. Improved communication, information-sharing, training and development are required to effect a cultural change. Another inhibitor was the mismatch between the skills and attitudes of people in the job and those required for the job. In line with many studies, all respondents were unanimous that the management of the behaviour of users (personnel and students) was a key factor to reduce energy consumption [43, 61, 62]. Users drive up energy consumption for reasons related to perceived comfort levels, convenience and neglect. Thus, managing behaviour is the next step for this university to achieve energy efficiency. It is recommended that marketing campaigns are used to communicate energy efficiency messages to users.

5. Conclusions

Overly bureaucratic systems and internal power struggles were barriers to DSM in this study, showing that organisational structure and culture impact on DSM initiatives. In addition, other priorities, such as dealing with the merging of three different institutions, can delay the implementation of DSM. Untrained and unaccountable personnel hinder DSM initiatives; DSM is enabled when employees are skilled and tasked with achieving energy efficiency. The existence of a high-level champion contributes significantly to the success of DSM activities. Finally, academics should be viewed as a key resource that can be harnessed to enhance DSM achievements. In conclusion, successful DSM requires top-level managerial buy-in, capacitated operations personnel capacity, and dedicated funds.

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Scoping exercise to determine load profile archetype reference shapes for solar co-generation models in isolated off-grid rural African villages

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Abstract

For many off-grid rural communities, renewable energy resources may be the only viable option for household and village energy supply and electrification. This is especially true for many rural regions in southern Africa, where the population spread is characterised by small villages. These rural villages rely heavily on firewood, charcoal, biochar, biogas and biomass to meet thermal energy needs (hot water and cooking), while candles, kerosene and paraffin are mostly used for lighting. Alternative energy systems such as hybrid concentrated solar micro-CHP (combined heat and power) technology systems have been proposed as viable energy solutions. This paper reports on a scoping exercise to determine realistic hourly reference profile shapes for thermal and power energy consumption in isolated rural African villages. The results offer realistic energy consumption load profiles for a typical rural African village in time-series format. These reference load profiles enable experimental comparison between computer-modelled solar micro-CHP systems and control automation solutions in isolated rural village micro-grid simulations.

Keywords: smart village; community microgrids; discrete time simulation; off-grid demand response; disaggregated load profile; sustainable energy

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1. Introduction

Limited grid infrastructure to certain sparsely populated parts of Africa still deprives many rural Africans of access to the basic energy requirements. Figures from the International Energy Agency (IEA) show that around 59% of the total African population do not have access to electricity (IEA, 2014). To improve living standards in remote parts of Africa, research towards rural electrification and the provision of clean green energy to isolated domestic rural settlements are essential (Dagbjartsson et al., 2007).

A framework for rural renewable energy provision has shown that energisation options, based on hybrid renewable energy systems and resources, may be the only viable option for rural village energy supply and electrification (Kruger, 2007). This is true for many off-grid rural communities in Africa, where the nature of the population spread has resulted in small isolated villages. Such rural settlements call for smart energy management in standalone decentralised off-grid renewable energy systems (Mulaudzi and Qase, 2008), and zero-net-energy based 100% renewable energy systems in community-shared solar power solution configurations (Lund, 2015).

Standalone concentrating solar micro combined heat and power (micro-CHP) technology has been identified as a potential solution to meet energy demands in isolated off-grid rural areas (Barbieri et al., 2012; Prinsloo & Dobson, 2015). In order to simplify the development of control automation solutions for micro-CHP systems, dynamic modelling approaches have been followed to simulate these systems (Cho et al., 2007). These parametric model representations are then used in control approaches (i.e. Model Predictive Control), to mathematically optimise the micro-CHP system operation and energy balance through energy storage and intelligent dispatch algorithms in a multi-family homestead or family micro-grid environment (Lund, 2015; Cho et al., 2008).

Realistic hourly energy consumption profiles for heat and electricity are required to validate and compare mathematical and computer simulation models for storage and control automation solutions in cyber-physical micro-CHP model representations (i.e. TRNSYS, Homer, EnergyPlus, EnergyPlan, ReEds, REopt) (Ho, 2008). Currently, it is difficult to find time-series datasets that represent load profiles for thermal and electrical power consumption in a rural African village context. Thermodynamic modelling and optimisation can be improved when realistic reference profile shapes (archetypes) are available. These profiles can be used as a benchmark in the evaluation and comparison of computer simulation and system control models for new locally relevant village-scale autonomous solar Stirling micro-CHP systems, such as the community solar system currently under development at Stellenbosch University (Prinsloo & Dobson, 2015).

Big Data (large datasets, in this case containing information on user energy consumption) and energy informatics research offer smart-meter (a device that can record and communicate user electricity consumption) datasets to study hourly domestic household energy usage patterns. The recorded datasets are used to develop residential load profiles (OpenEI, 2015). These load profiles have proven to be immensely valuable in optimising intelligent power systems, particularly when developing optimisation strategies in deep learning and demand response algorithms (Cho et al., 2008). In modern co-generation and micro-grid optimisation research, micro-grid and Smartgrid user demand data can be processed to determine standardised hourly load profile shapes as archetypes for various types of energy users (Shilts & Fischer, 2014). These datasets are further valuable in load forecasting, daily demand response analysis, storage scheduling optimisation and resource coordination strategies in smart micro-grid ecosystems (Deloitte, 2011; OpenEI, 2015). Smart-meter datasets are almost exclusively available for electricity usage in grid-connected urban applications, making it difficult to statistically determine realistic thermal or electrical load profile patterns for prospective new installations in rural Africa.

This paper presents a load profiling and scoping exercise based on available literature on thermal and electrical power consumption patterns in small rural African villages (Cross & Gaunt, 2003; Heunis & Dekenah, 2014; Meyer, 2000; Muya, 1996; OpenEI, 2015; Tinarwo, 2009; Sprei, 2002). The results of the study offer basic geometric archetypal energy reference shapes for hourly heat and electric load profiles. These load profiles will be incorporated in simulation software, and used in conjunction with computer models representing combined heat and power as well as distribution automation for remote rural electric power systems. These demand profiles will allow researchers to evaluate the performance of the modelled generation system in remote rural and islanded community microgrid configurations for deregulated micro-markets, based on statistical tariff price data, generation capacity, energy storage capacity, weather data, and user load profiles.

2. The traditional rural African village energy context

The South African government has committed itself to provide basic free electricity to its citizens, based on a favourable low-income social residential energy tariff structure (DME, 2003). In certain parts of Africa and southern Africa, however, the land topography and mountainous terrain have, over the years, caused people to spread out and to live on the habitable parts of the hilltops and ridges. In this context, families often live in these isolated homestead clusters and typically stay in round/square indigenous huts with thatched grass-top roofs. This pattern of development makes it important to research the determinants of electricity demand for potential newly electrified low-income rural African village households.

Many of these traditional rural African villages rely on a combination of biomass and fossil-fuel sources to meet their day-to-day energy requirements (i.e. candles, biomass, firewood, paraffin) (Mulaudzi & Qase, 2008; Lloyd, 2014). Surveys have also found that fuelwood is often the main source of energy for cooking and heating, while paraffin and candles are mainly used for lighting (Masekoameng, 2005; Reddy, 2008). Specific data for the African country of Malawi is shown in Table 1. The data shows an overwhelmingly high percentage of fuelwood consumption relative to the other sources of energy (Makungwa et al., 2013). This is especially true in the case of the rural population, where most of the rural communities are traditionally dependent on subsistence farming. Table 1 shows that fuelwood accounts for 89% of energy consumed by households in Malawi; in fact, solid biomass such as fuelwood is the primary source of energy used in cooking in many self-sufficient African homes.

The map of Africa in Figure 1 shows the population percentage in African countries that use solid fuels (fuelwood, charcoal, coal, crop waste, and dung) as the primary cooking fuel, especially in rural areas (WHO, 2010). This is further supported by the IEA's *Africa Energy Outlook* report (IEA, 2014), which offers a breakdown of the cooking fuel type per African region in Figure 2. The statistical bars for *rural Africa* on the right-hand side of the figure confirm that a large portion of rural Africa relies mostly on fuelwood and other forms of solid biomass for cooking. It also emphasises the fact that African governments have not yet been able to energise rural areas, to the extent that electricity is recognised as a basic right or basic service as force for development (DME, 2003). Figure 2 shows that rural people in sub-Saharan Africa, with South Africa being the exception, rely heavily on fuelwood for their day to day energy needs.

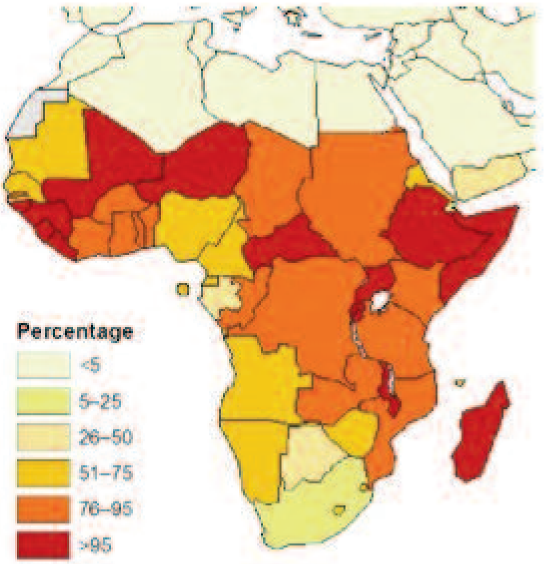


Figure 1: Percentage of households in Africa using solid fuels such as fuelwood as the primary cooking fuel (WHO, 2010).

The situation in the rural areas of South Africa is little different. A survey conducted in three rural villages in the area around Giyani, Limpopo Province, for example, showed fuelwood to be the main source of energy for heating and cooking, while candles and paraffin provided indoor and outdoor lighting (Masekoameng, 2005). Another study looked at domestic energy use in recently electrified low-income households in a fairly remote area in the Eastern Cape Province (Africa et al., 2008) and reported that, despite electrification, a large portion of the rural community still used (non-forest type) fuels to meet much of their energy requirements, particularly cooking, boiling water and space heating. It is typical for communities in rural areas that gain access to electricity to keep using more tradi-

Table 1: Energy share and variations in African household cooking fuel type for rural and non-rural areas in Malawi, figures in terra-joules per year (TJ/y) (IEA, 2014).

Fuel type	*Rural*	*Urban*	*National*	*%*
Fuelwood	105 320	10 560	115 880	89.1
Charcoal	2 360	6 340	8 700	6.7
Crop residue	2 980	11	2 991	2.3
Electricity	0	1 798	1 798	1.4
Paraffin	240	430	670	0.5
Coal	0	5	5	0.0
LPG gas	0	2	2	0.0
Total	110 970	19 076	130 046	100

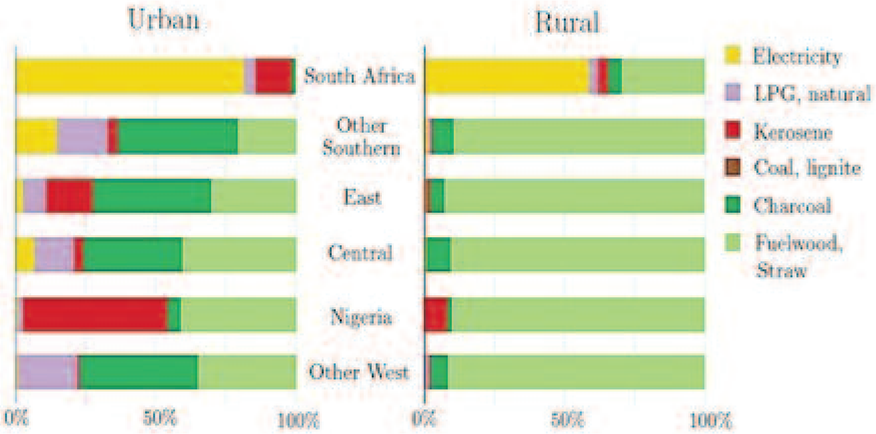


Figure 2: Energy share and variations in household cooking fuel type for rural and non-rural areas in African regions (IEA, 2014).

tional fuels (such as wood) for such thermal related activities. Another investigation in the Eastern Cape Province, into the use of household fuelwood in small electrified towns in the Makana District, found that more than two-thirds of rural households still used fuelwood (despite wood carrying burdens and transportation discomforts). The consistent opinion in this region had favoured fuelwood, as it was said that wood provided good heat and was available to be collected cheaply, while it helped saved electricity costs (Shackleton et al., 2007). The study further provides interesting figures on the territorial use of energy, the annual demand and direct-use value of fuelwood; the volume/weight of wood collected; amounts used for cooking and boiling hot water per household; the collection trip duration; drought impact and shortages; collection frequencies and perceptions around the ease of collection (Shackleton et al., 2007).

Fuelwood deficits are becoming an increasing problem in rural parts of Africa, adding to the wood collection burden on rural households. In many parts of Africa, households are highly vulnerable to the rapidly degrading forest resources (Palmer & MacGregor, 2008). The reason is that fuelwood is collected primarily from natural wood-land and shrub-land, which are non-forest-type sustainable sources (Aron et al., 1991). A study in Ethiopia shows that rural households in forest-degraded areas increase their labour input for collection in response to a shortage in fuelwood (Damte et al., 2012). A Namibian study on fuelwood scarcity also confirmed more labour going into wood collection rather than reduced energy consumption (Palmer & MacGregor, 2008). These studies found limited evidence for energy substitution away from fuelwood to other energy sources, despite the declining availability of forest and non-forest stocks. It shows that sheer determination and the Ubuntu culture helped Africans learn to cope with fuelwood scarcity. Interesting in Table 2 is the gender-disaggregated household responses to changes in firewood availability and time allocated to collect energy resources for rural Ethiopia (Scheurlen, 2015).

From a solar co-generation energy supply and village demand profiling point of view, the data from these studies is valuable in a bottom-up load profiling exercise, especially in an environment where fuelwood and other traditional fuels. The information from studies cited is also useful in anticipating the potential energy demand and shape of the daily load profile for any potential co-generation system solution that may be installed as prosumer-based systems (cooperative, self-generation or self-supply). The profiles are also required in grid-edge utility or municipal power supply systems for isolated rural villages in Africa. A survey conducted by Lloyd and Cowan (2004) in an informal settlement in South Africa further provides important information on average daily and monthly household electricity consumption. A summary of this survey, presented in Table 3, shows that the average monthly energy consumption level for rural households cooking without electricity is 150 kWh, while for those cooking with electricity is 210 kWh (Lloyd & Cowan, 2004). An average monthly ener-

Table 2: Average numbers of hours per week spent to fetch fuelwood in African rural areas (United Nations Development Programme, 2011).

Subjects	*Guinea*	*Madagascar*	*Malawi*	*Sierra Leone*
Women	5.7	4.7	9.1	7.3
Men	2.3	4.1	1.1	4.5
Girls	4.1	5.1	4.3	7.7
Boys	4.0	4.7	1.4	7.1

Table 3: Monthly use of electricity and paraffin at homesteads in Khayelitsha (Lloyd & Cowan, 2004).

Homestead type		***Paraffin***	***Electricity***
	Sampled	***Median***	***Median***
Households cooking with electricity	124	6 litres	210 kWh
Households not cooking with electricity	102	18 litres	150 kWh

gy consumption level of 150 kWh per rural household equates to approximately 0.484 kWh per day. This information can help to define a realistic reference archetype energy profile for a rural African homestead once the load shape has been defined.

Another finding from Lloyd and Cowan's study (2004) is that many houses with access to electricity also use paraffin for cooking, corroborating the findings of other studies showing that a significant percentage of newly electrified households continue to also use alternative fuels (iShack, 2013). Approximately 68% of Khayelitsha households with a regular metered supply of electricity use electric stoves as the main cooking appliance and the rest typically use paraffin stoves. Among non-electrified households, it was found that 92% used paraffin stoves as the main cooking appliance and the rest mainly used LPG.

3. Rural African village hourly load profiles

Since renewable energy can act as socio-economic catalyst, this section focuses on electricity supply to isolated rural villages from a smart village perspective. It describes the load profile or hourly schedule of energy use (electrical and thermal) anticipated for rural households in Africa from an energy management system perspective. This load profile analysis uses both quantitative and qualitative information on energy use patterns by non-electrified and electrified rural households. Sample load profiles are typically presented as hourly or sub-hourly time graphs that show the variation in energy consumption over the duration of a full day.

In general, a two-dimensional load profile represents the relative timing in the demand versus the amount of energy used for each time increment. Of particular interest is the time factor of the load profiles, while less emphasis is placed on variation in magnitude between the different studies. The information presented in this section will assist with the emulation of realistic rural electrical and thermal load profiles to be used in solar combined heat and power microgrid simulations.

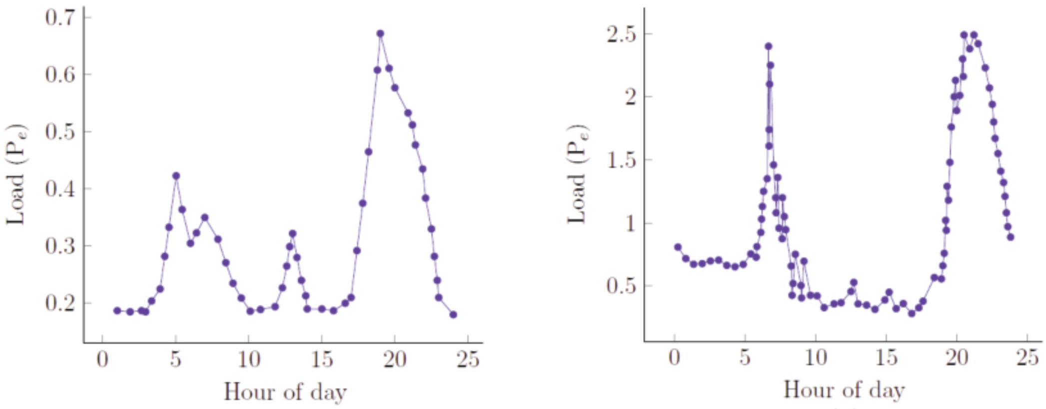
In this part of the profile scoping exercise, the interest is more on the timing of the energy usage pattern for the energy consumption curve than on the comparative energy load amplitude levels. With this in mind, it becomes interesting to compare the basic geometric shapes and general trends in the load profiles for rural and agriculture-based homesteads in Africa.

3.1 Rural electrical energy usage profile shapes

It is difficult to locate hourly-based time-series datasets on electrical power consumption in isolated rural African homes since existing smart-meter instrumentation datasets are almost exclusively available for electricity usage in grid-connected urban applications. This is one reason why the present scoping exercise was initiated, to locate whatever data is available on energy consumption for remote rural areas and to be able to match these patterns to hybrid renewable energy based microproduction of electricity. It further allows researchers to see how this data can contribute towards compiling a reference archetypal remote rural load profile that represent the behavioural patterns and social practices around the energy usage culture in Africa.

In this respect, consider two hourly-based electrical load profiles for single rural village households measured in two different African countries. Figure 3 shows the averaged single household load profiles for rural villages in Zimbabwe and Uganda (Tinarwo, 2009; Sprei, 2002). The load profiles in both these studies were obtained from physical measurements taken in rural African settlements. The measured load profiles for the two sets of rural households (Figure 3) are both broadly characterised by an energy peak in the morning followed by a slightly larger energy peak in the late afternoon and evening. The geometric shape of these load profiles are typical for domestic energy systems, where occupants mainly use electricity when at home during the morning and evening (Shilts & Fischer, 2014). A study concerning microgrid design for rural African villages made use of load profiles that are remarkably similar to those in Figure 3 (Bokanga & Kahn, 2014).

In the data logger-based measurements, taken at a small farming community in Zimbabwe in Figure 3 (a), a smaller third load peak of electricity usage is visible around noon. This mid-day peak which appears briefly before fading away and can probably be attributed to farmworkers returning home during their lunch hour. This behaviour is typical for a farming village where people work in close proximity to their homes. For the energy consumption



(a)

(b)

Figure 3: Average household load profiles, in kW, measured at rural villages at (a) Zimbabwe and (b) Uganda (Tinarwo, 2009; Sprei, 2002).

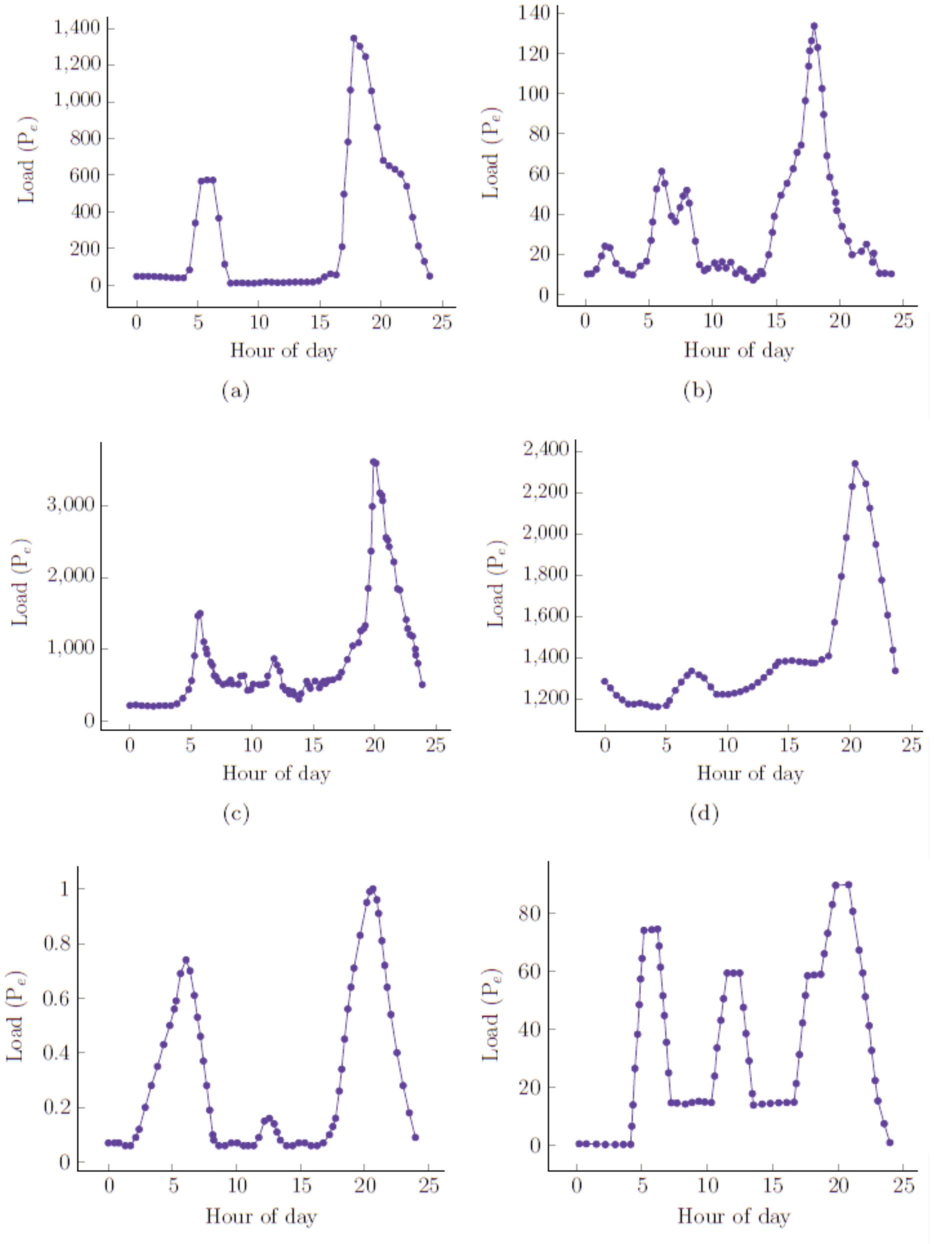
pattern in Figure 3(b), measurements were taken directly on the distribution transformer of a rural village microgrid power system in a semi-agricultural setting (Sprei, 2002). These measurements were taken with a load metering system with a finer time resolution, explaining the sharper peaks in the load profile representation.

What is important to note in this load profile shape in Figure 3(b) is the relatively smaller energy consumption peak in the load profile around noon. In this case, the smaller mid-day peak in the load profile may be indicative of the behaviour for the semi-farming community where not all workers return home for lunchtime and use electricity. Apart from the mid-day peak in the load profiles, there seems to be a strong correlation in the measured energy usage patterns for the two independent rural load profile datasets from the two countries (two prominent peaks, morning and evening). The similarities suggest that the load profile shapes for different parts of Africa may be fairly uniform, showing a strong correlation with people being at home to use electricity. The morning peaks can be associated with people switching on lights, using kettles and making breakfast. The large peak in the evening results from people returning home and again switching on lights, cooking dinner, heating water for cleaning/bathing and use televisions.

Extending the scope beyond the African context, to literature on the international front, it is clear that the same load trends and profile shapes prevail in the rural load areas of non-African countries (Ketjoy, 2005; Nayar, 2014; Fall et al., 2007; Susanto, 2012). This is illustrated in Figure 4 where measured energy load profiles are presented for Ban Pang, Praratchatan, Thailand; a rural settlement in Western Australia; a small village in Alaminos, Philippines; the San Juanico, Mexico; rural households in Lao People's Democratic Republic and a load profile for a single family home in Puerto Plata, Dominican Republic (Ketjoy, 2005; Nayar, 2014; Fall et al., 2007). The spread of rural load profiles, in Figure 4, illustrates that the same daily energy pattern, measured for rural Africa, appears to hold true in rural households and small rural villages in other rural parts of the world. All include an energy peak in the morning, another around noon, and a large peak in the evening. A potential smaller (single) energy consumption peak around noon may represent customer presence and energy usage during lunchtime break.

Literature also describes a spread of rural energy load profiles that have been used in rural electrification computer simulation and modelling schemes (Yumoto, 2011; Casillas & Kammen, 2012; Ohijeagbon & Ajayi, 2014; Kenneth & Tarilanyo, 2013). Most of these models represent a slightly coarser scale of measurement (depicting hourly load profile time-steps), but the same load shape appears in most of these other load profile models for rural Africa. Figure 5 shows the average hourly representative load profile shapes for models in rural areas of Uganda (HOMER defined model), Botswana, Nigeria, and the Niger Delta (Yumoto, 2011; Casillas & Kammen, 2012; Ohijeagbon & Ajayi, 2014; Kenneth & Tarilanyo, 2013). These correlate with the trends observed in the measured load profiles for rural settlements in Zimbabwe and Uganda (Figure 3).

In a computer simulation study, Varma et al. (2015) proposed various rural community load profile models, based on household type in the State of Uttarakhand in India as part of a hybrid solar system evaluation experiment (Figure 6). The Uttarakhand region needs special consideration in terms of electrification as the population density in this region is quite low and more than half of the population lives in rural areas (Verma et al., 2015). As in Africa, many of the remote villages and communities in Uttarakhand do not always have access to affordable and clean energy as a result of the terrain and the general lack of infrastructure. The load profiles in Figure 6 show strong resemblances to the rural African load profiles in Figure 3. These profiles



(a) (b) (c) (d) (e) (f)

Figure 4: Energy load profiles for rural households and villages in various countries: (a) Ban Pang, Praratchatan, Thailand (Ketjoy, 2005); (b) Rural Western Australia (Nayar, 2014); (c) Alaminos, Rural Philippines (Fall et al., 2007); (d) San Juanico, Rural Mexico (Fall et al., 2007); (e) Rural Lao household, PDR (Susanto, 2012); and (f) Puerto Plata, Dominican Republic (Fall et al., 2007).

were chosen to represent actual rural household configurations in India and were used in experiments relating to energy access analysis and techno-financial evaluations. It shows similarities with the research of this paper where archetype load profiles for a typical rural villages are being formulated.

Research has also been conducted on a load profile prediction model for residential consumers in South Africa (Heunis & Dekenah, 2014). This prediction model formed part of the development of an electrical distribution pre-electrification software tool (Figure 7). This powerline software planning tool and software architecture was developed in collaboration with the electricity utility Eskom in South Africa, to serve as a standalone design parameter decision support system aimed at building, compiling and formulating energy load profiles prior to new grid electrification projects.

During the first phase of the development of this load prediction model and tool, measurements were taken from pre-paid meter systems and smart meters in newly electrified houses, in order to define new electrification energy datasets. These pay-as-you-go datasets were then used to find the average and standard deviation values in the domestic electricity consumption patterns for a typical new home or household, as shown in Figure 7(a). This infor-

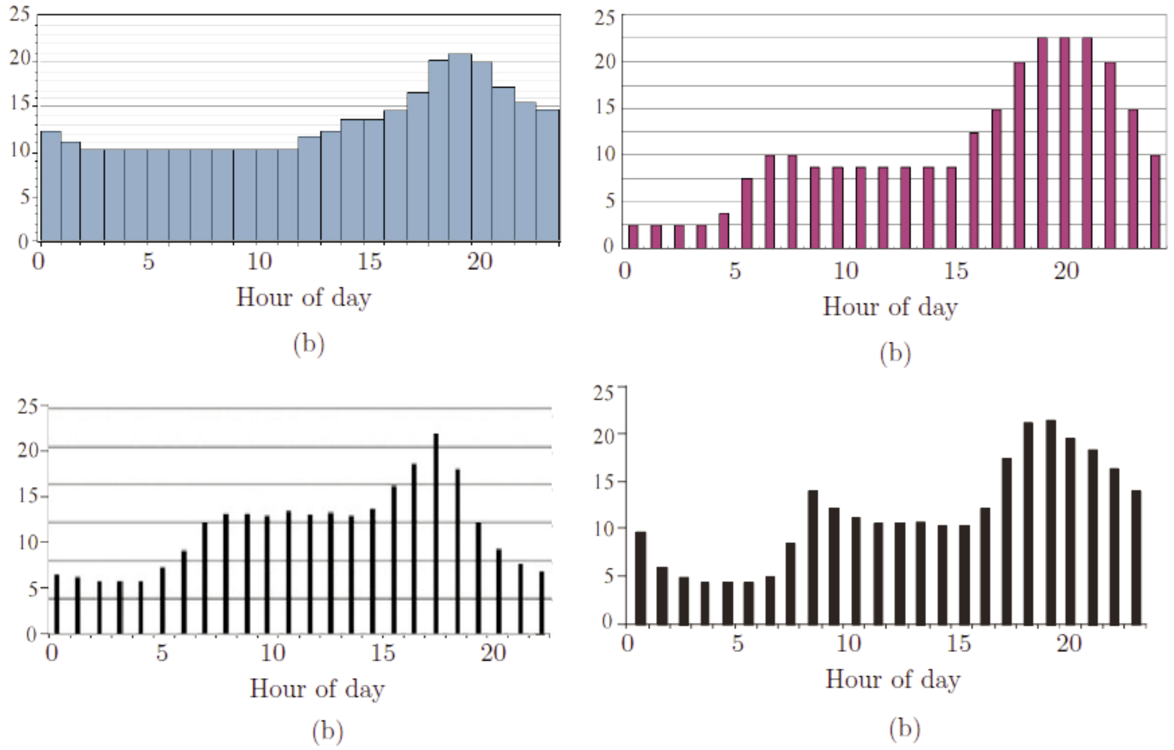


Figure 5: Computer models for selected daily rural energy load profiles for various African countries (a) Homer model, rural Africa (Casillas & Kammen, 2012); (b) Botswana (Yumoto, 2011); (c) Sokoto, North-west Nigeria (Ohijeagbon & Ajayi, 2014); and (d) Akassa, Niger Delta (Kenneth & Tarilanyo, 2013).

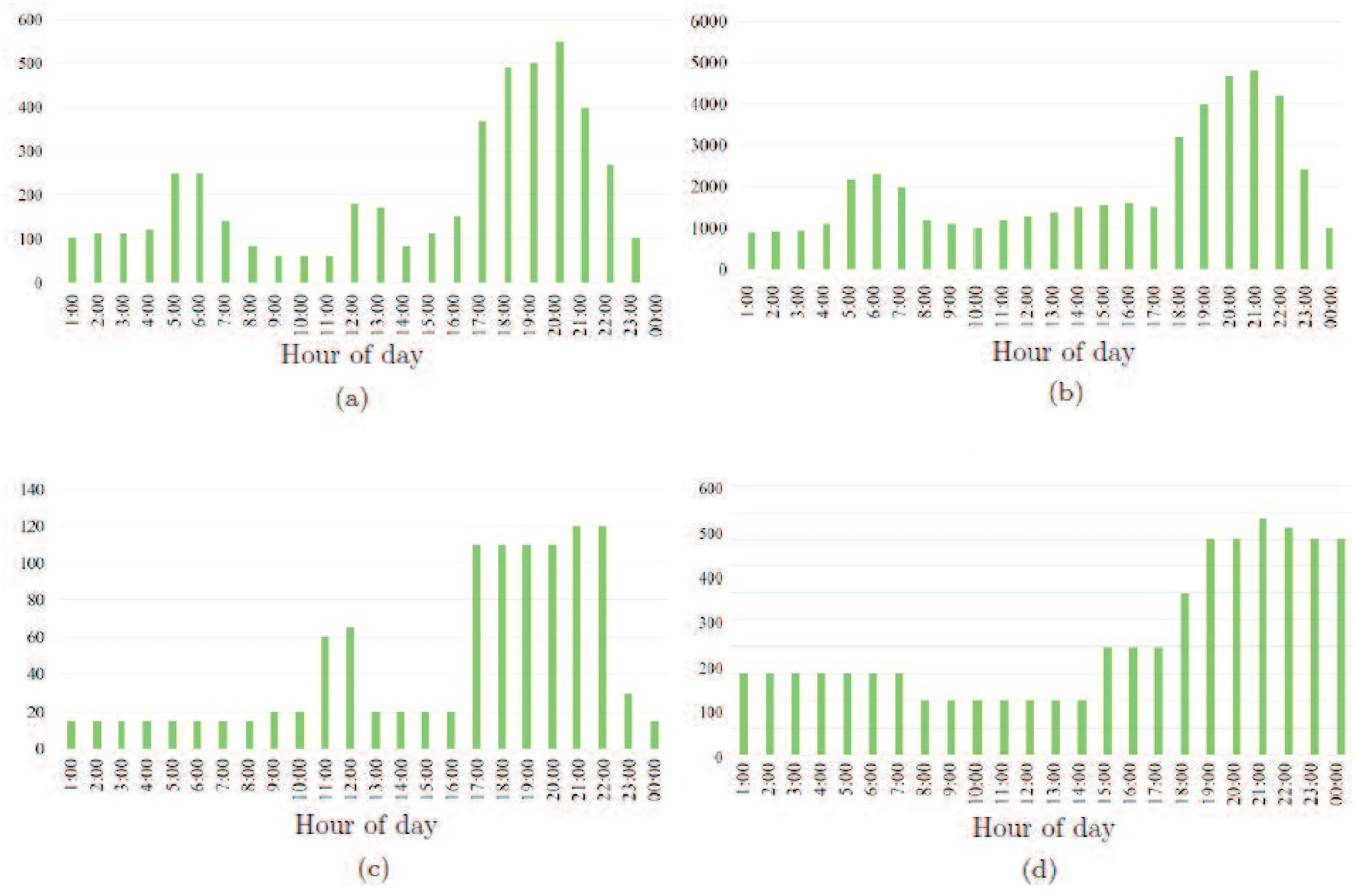


Figure 6: Daily average connected load for rural village scenarios in India. (a) Small village 5–6 small households; (b) Medium households, range of appliances; (c) Small standalone household; and (d) Small standalone off-grid rural household (Verma et al., 2015).

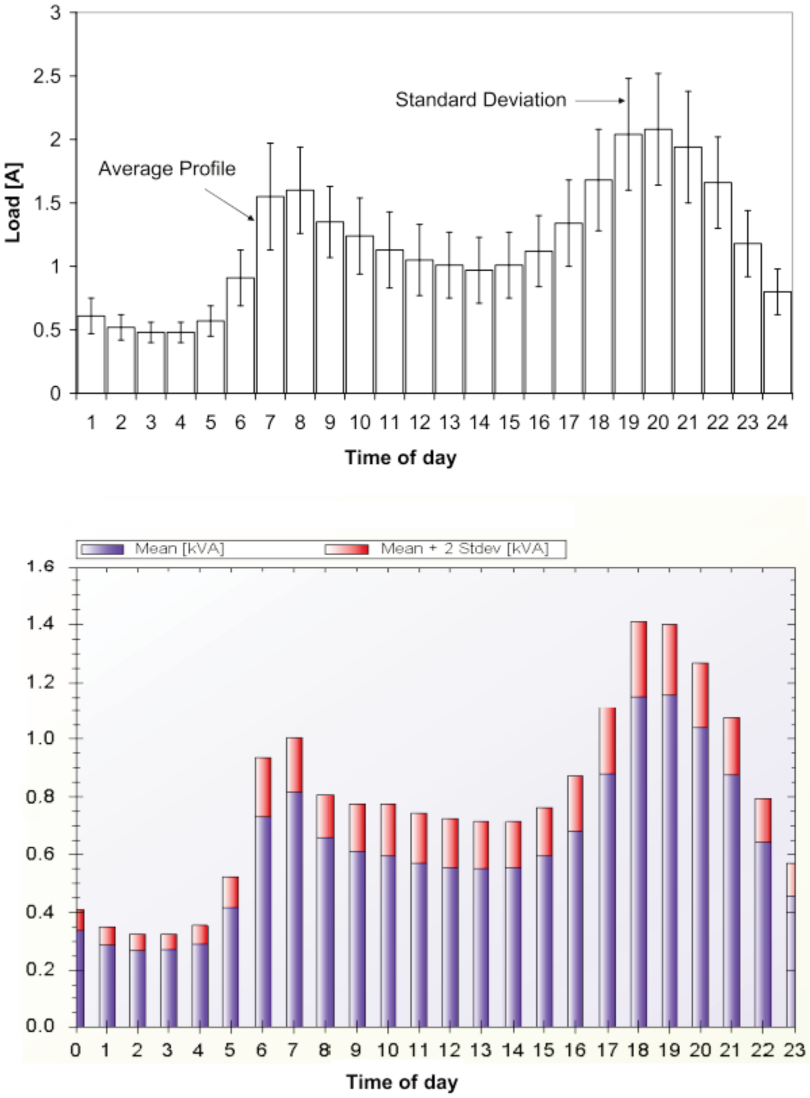


Figure 7: Load prediction with a grid distribution pre-electrification tool. (a) Average and standard deviation profiles; (b) Predicted energy profile and deviation (Heunis & Dekenah, 2014).

mation was subsequently used in a prediction model and grid-planning strategy to compute probable domestic load curves for a group of new households, as shown in Figure 7(b). This prediction model and tool was developed to help anticipate consumption levels in newly planned electrical grids as well as in planning distribution retrofits for grid power network infrastructure extensions to new village zones and small towns.

By nature of the demand side load modelling technique, the load characteristics and electricity consumption patterns in Figure 7 represent profiles for newly planned homes in grid-connected township areas, where newly built homes are often fitted with electrical water heaters. These, and the addition of other appliances that would not typically be present in off-grid households, may explain the mid-day variations in the daily energy consumption profiles when comparing urban housing load profiles to the load profile shapes for rural village homes as shown earlier in Figure 3.

3.2 Rural thermal energy profile shapes

The consumption load profiles for thermal energy, like electrical energy, are also presented on a two-dimensional chart that shows the instantaneous thermal or electrical load in kilowatts over 24 hours. This again offers a convenient way to visualise geometrical profiles for thermal energy usage patterns and to observe dynamic timing variations in the thermal load requirements, while making it easy to study the temporal load variations and changes. Since the current research focus is on water-cooled micro-CHP systems, the interest in thermal energy in this paper is largely biased toward rural hot water usage. In an electrified rural environment, hot water usage makes up, on average, 30–50% of total energy usage (Harris et al., 2008).

As with the electrical energy profiling exercise, it was found that very little data was available on hot water usage in rural African village settlements. Electronic datasets on hot water draw-off patterns for off-grid isolated rural areas are virtually non-

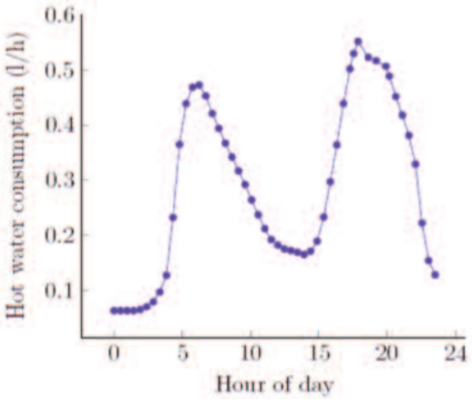
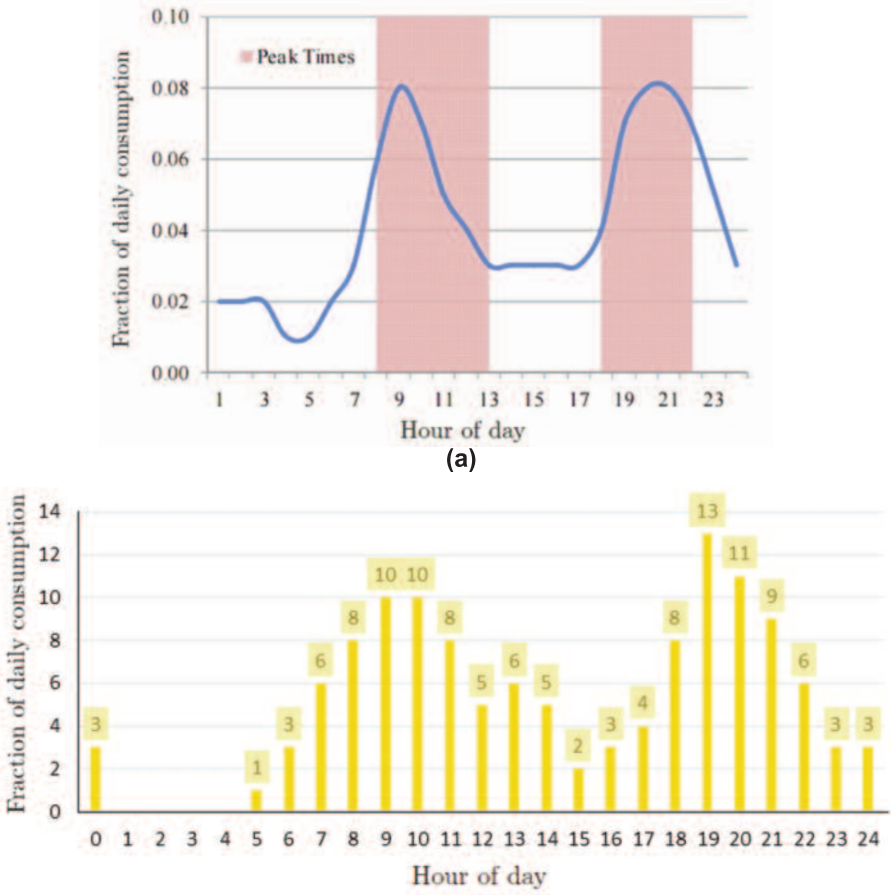


Figure 8: Per capita hourly hot-water consumption for a traditional rural South African household (Meyer, 2000; Muya, 1996).

existent. This means that one has to rely on information obtained in a scoping exercise to obtain pattern templates to use in computer modelling and simulation experiments. Research has been conducted on hot water consumption in rural households in Southern Africa since the early 1990s. Two studies, in particular, present a unique view on the energy context in Southern Africa and provide valuable information on hot water usage patterns based on elaborative surveys (Meyer, 2000; Muya, 1996). The results obtained once-again show the double-peak demand shape, as illustrated in Figure 8.

As with the electrical energy profile patterns described earlier in this paper, the hot-water draw-off pattern in Figure 8 shows strong correlation with human activities and household behavioural patterns (place profile-based). The bulk of hot water consumption is also concentrated in the morning and the evening. In a traditional agricultural homestead, most family members would wash and clean in the afternoon and evening, making the peak load for hot water consumption profile pattern to be mostly be shifted towards the afternoon.

It is also important to note the relatively sudden onset in the usage pattern around 04h00 to 05h00, showing that these households are early risers (typical of rural areas). In general, it is logical that the hot water consumption onset peak will start around the time when people rise. The rest of the daily hot water draw-off pattern would depend on the daily routine of that particular homestead, and be influenced by user occupancy. The average per capita hot water consumption (litres per person per day) for low-density homesteads is also influenced by seasonal effects such as average temperature changes (Meyer & Tshimankinda, 1997). The example presented in Figure 9(a) shows a South African hot water consumption profile (with the



(a)

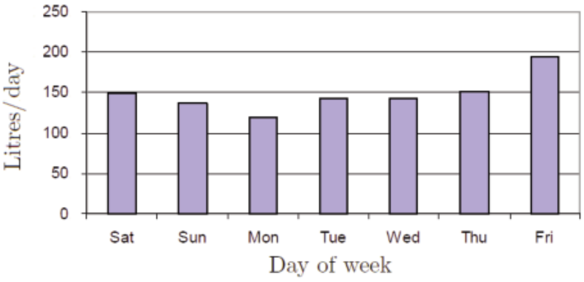
(b)

Figure 9: Hot water consumption profile for (a) a South African household, and (b) an Indian household (Meyer & Tshimankinda, 1997; Sameti et al., 2014).

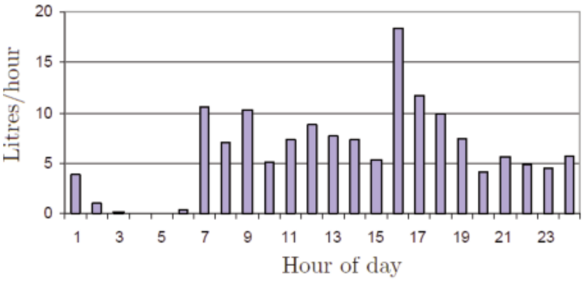
peak band marked in the maroon bars), and Figure 9(b) shows a so-called Rand profile for the fraction of daily hot water energy consumption. This Rand profile is an archetypal profile pattern profile shape used to represent daily hot water consumption (120 litres at a temperature of 50 °C) for a family of four (Sameti et al., 2014). These profiles agree with the findings of Meyer shown in Figure 9.

The REEE 5/99 report on the *Simulation and monitoring of solar powered electric water heating systems in Namibia* used pre-installed digital data logging and flow rate recording equipment to report on hot water usage patterns in rural Namibia (EMCON, 2000). The report shows graphs of hot water consumption patterns measured at sites in Namibia, with plots of hot water draw-off patterns in terms of month-days, week-days and daily-hours measured in a variety of households. Figure 10 shows the hot water drawing pattern for an independently located low-income household of seven people (EMCON, 2000). The data was recorded with a digital data logger to show two important results. Figure 10(a) shows the household's typical hot water consumption for each day of the week, and Figure 10(b) shows the average hourly hot water consumption profile for the household in hour time steps.

This section concludes with a reference to the thermal energy requirements related to cooking in a rural African village. The micro-CHP system will be able to supplement some of the heat required for cooking, which is why this thermal energy profile is considered to be important. In this regard, Figure 11 shows a digitised version of a daily cooking profile, indicating the electricity used for a recently electrified rural homestead in southern Africa (Cross and Gaunt, 2003).



(a)



(b)

Figure 10: Recorded hot water draw-off patterns for a low-income homestead in Namibia, showing the average hot water draw-off pattern per week (a) and draw-off per day (b) (EMCON, 2000).

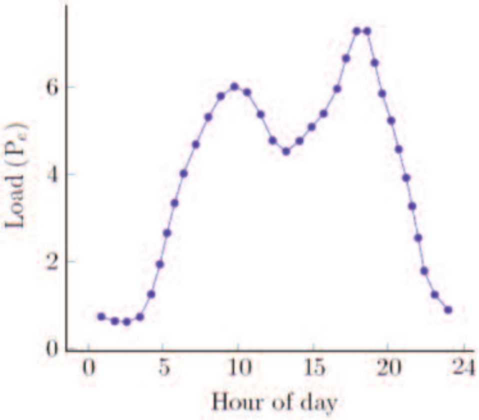


Figure 11: Daily cooking activity profile for rural house in South Africa (Cross & Gaunt, 2003).

Although this paper will not discuss this profile in detail, it is valuable to note that the cooking profile is similar to the hot water usage profile. Once again, occupant behaviour may be related to the profile peaks and will vary between households. From the information presented in this part of the scoping exercise, one can more confidently define appropriate load requirements for rural African communities. The above exercise thus forms the basis for formulating a reference daily energy profile, in anticipation of a potential transition for the village towards a modern solar co-generation supply system.

4. Consolidation of the load profiling results

Load profiling and energy consumption analysis is central in energy usage planning and micro-CHP modelling analysis for isolated and remote rural areas. Realistic load profiles are required, and serve as a guideline for the supply system design, as well as the dynamic distribution viability on the demand side. This scoping exercise focused on the thermal (mainly hot water) and electrical load profiles. The results should be presented in a data format suitable for reading or import by thermodynamic and electrical multi-carrier microgrid technology platforms and smartgrid software simulation platforms. These computer modelling simulation tools typically use the terms 'Rows-per-day' or 'Single-column data' to describe the format used to save data. In the Rows-per-day format, daily load profile data is saved as 24-hour packets (i.e. date, time, kWh) in a single row with the following day in the next row, etc. In the single column format, all the data can be saved in a single column. In these formats, every line record in the dataset may contain several energy parameter fields, separated by a comma, semicolon, tab or blank characters.

The focus of this study is on finding load profile shapes for hot water and electricity consumption that are typical for rural African households. This means that less emphasis is placed on the actual quantity of energy used (kW or litres of hot water), but rather on the amount used per time step relative to other times of the day. The aim is to provide a scientific base for evaluating and comparing technology options and control automation options based on realistic load profile patterns for African villages. At the same time, an understanding is required of the operational requirements in an off-grid village with no previous access to electricity. This will assist in emulating a profile that is realistically comparable to experiences and trends observed in the load patterns from recently electrified rural homes. This, in turn, can be used in computer models and simulation experiments aimed at rural African customised system design. The previous section described the context and circumstances around rural African village energy consumption. Following an energy load profile scoping exercise, the background from available literature allows one to experiment with realistic thermal power consumption patterns in such locations (Tinarwo, 2008; Sprei, 2002; Meyer, 2000; Muya, 1996). The remainder of the discussion offers basic archetypal energy reference shapes for rural heat and power load profiles aimed at micro-CHP research for rural Africa.

4.1 Rural African village electricity use profile pattern: Scoping

From the scoping exercise, a load profile that defines a realistic reference consumption pattern for a rural African homestead needs to be selected. The key aspect in defining the archetype is the one that relates to the time of energy consumption over a 24 hour time interval.

In this paper, Section 2 presented information on the patterns of rural African electricity usage, with data and plots offering various options from which to select a potential candidate load profile reference pattern for use as electrical load pattern for remote isolated rural village homesteads in Africa. The shape of the electrical load profile for rural Western Australia (Figure 4(b)) may seem particularly familiar, as it has informally become a standard or benchmark reference in many studies that require a rural energy load profile and is often used as an exemplary load profile in computer modelling studies (Ibrahim & Ilinca, 2012; Nayar, 2014). It is similar to the profiles measured by Tinarwo (2008) in Figure 3(a) and Sprei (2002) in Figure 3(b), which are other attractive candidates, both correlating well with the experimental energy load profile models developed as representative models of energy consumption in rural African (Casillas & Kammen, 2012; Yumoto, 2011; Ohijeagbon & Ajayi, 2014; Kenneth and Tarilanyo, 2013). Of all the load profile shapes observed in this scoping exercise, the model in Figure 3(b) was found to be particularly valuable. This profile represents the rural African village context in a realistic way. The shape also correlates fairly well with rural profiles in other developing countries (Figure 4), as well as with African village load profile models generally used in computer simulation models (Figure 5). Since the Sprei (2002) dataset was measured with a high time-resolution, the load data should be smoothed to be comparable to hour-based resolution load profiles typically used in computer simulation models. For this reason, an interpolation algorithm was used on the measured dataset of Sprei to provide smoother average hourly energy usage samples. The resulting archetypal reference load profile is presented in Figure 12.

By using inverse algorithmic curve fitting techniques, one can further approximate this reference rural power load profile in terms of a mathematical expression. The formula given in Equation 1 offers one such approximation for the load P_e profile depicted in Figure 12, representing the electrical power consumption (kW) for a typical rural village demand load as a function of time.

$$P_e = {}_e[\sin(0.3409 - \sin(0.68039t) - 0.16801t)] \quad (1)$$

An important aspect in defining a reference archetype energy profile for a rural African homestead or village is to define the amplitude scale for the hourly load curve. This scale may represent the average daily level of the energy consumption, or the hourly power kW requirement for the household or rural village. From a rural African reference load profile perspective, one can correlate this requirement with government regulations, with IEA local load estimates, or alternatively to conduct a load synthesis analysis to determine the integrated scaled village load profile amplitudes (IEA, 2014, Prieto-Araujo et al., 2015).

From Table 3, it was noted that the monthly energy consumption level for a rural household not cooking with electricity is around 150 kWh, while the energy consumption for electricity cooking households averaged around 210 kWh per household (Lloyd & Cowan, 2004). An average monthly energy consumption level of 150 kWh per month per rural household equates to approximately 0.484 kWh per household per day. This estimated average daily electricity load would thus spread out over the 24-hour time period in accordance with the proposed archetypal hourly rural load profile shape in Figure 12. This would give the correct amplitude scaling of the curve.

When the village size changes, load scaling must further be used. In this way one can vary load profile magnitude as a function of village size (number of clustered homesteads grouped in a small rural village, connected to the same local microgrid distribution line). This means that the same geometric shape for the reference archetype energy profile in Figure 12 would be used to represent any village size by scaling the amplitude based on the number of houses. Figure 13 offers the final proposed and digitised hourly load time-series graph for a rural village settlement suitable for microgrid control intelligence analysis and experimentation. This digitised generic hourly scaled computer modelling dataset version of the proposed hourly rural village energy consumption profile is presented in an hourly format suitable for use in energy systems analysis and computer simulation platforms (i.e. TRNSYS, Homer, EnergyPlus, EnergyPlan, ReEds, REopt), as well as transactive financial and economic analysis packages (i.e. SAM, CREST, Community Solar Scenario).

4.2 Rural African hot water profile pattern: Scoping

In terms of hot water consumption in a rural African energisation context, micro-CHP computer simulation evaluation experiments further require information about hot water usage in a rural African village. A valuable option is to learn from solar hot water draw-off patterns measured at flat-plate and evacuated tube solar hot water systems at remote locations. In general, domestic hot water patterns are driven by water use for household activities such as house cleaning, washing dishes, washing laundry, bathing and cooking. At the same time, this domestic hot water typically needs to be heated in a hot water heater and stored at around 55 ˚C, and then applied at a blended outlet temperature of

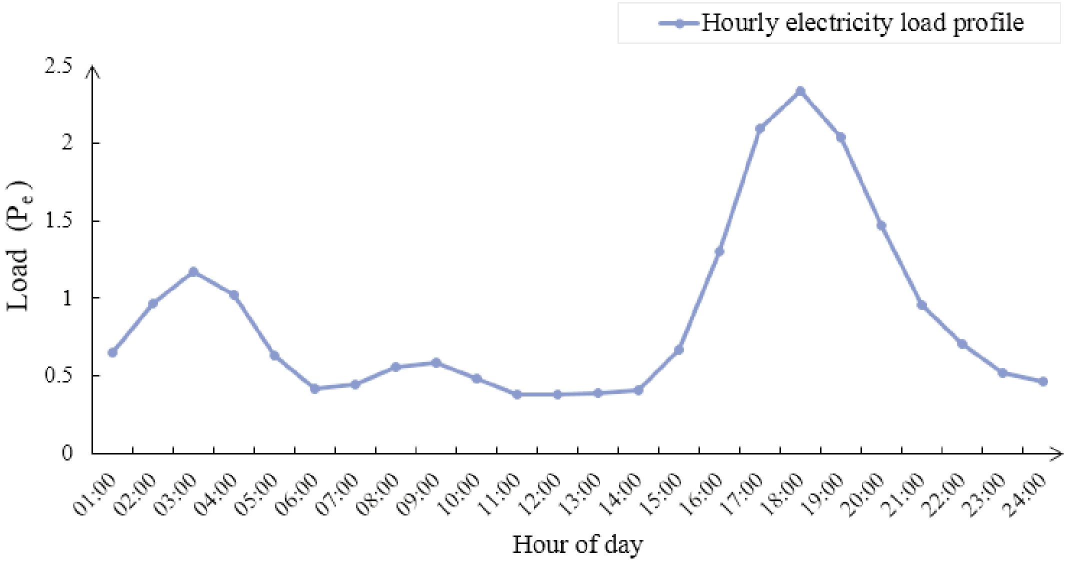


Figure 12: Potential rural electrical energy load profile reference shape for micro-CHP computer modelling and simulation experimentation.

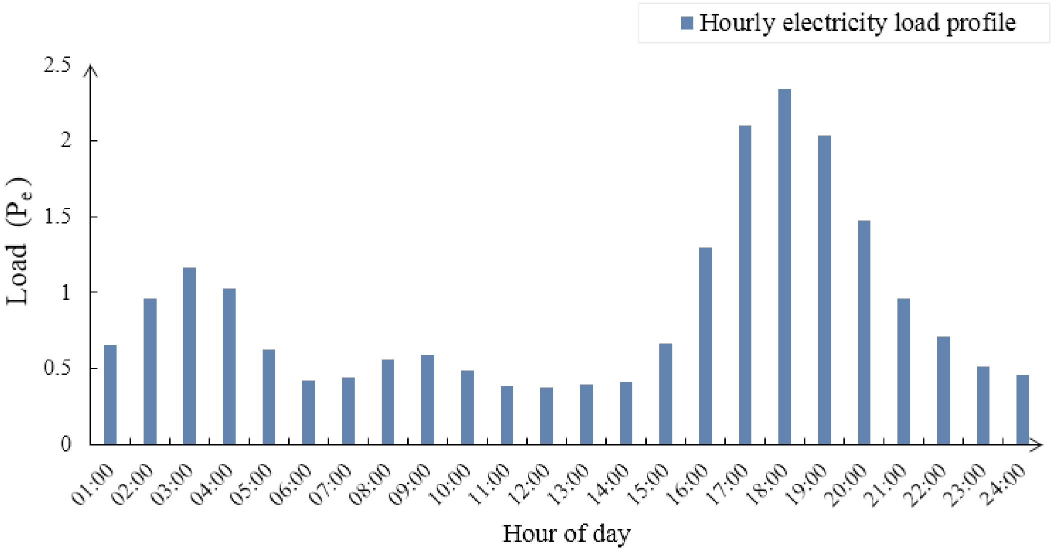


Figure 13: Reference hourly electrical energy load profile for rural African village suitable for micro-CHP computer modelling and simulation experimentation.

around 40–45 °C (Agama, 2002).

In the case of the first Namibian low-income household (Figure 10), seven people occupied the dwelling. The average measured daily hot water consumption per day was 14.4 ± 4.8 l/person, while a second low-income household with two inhabitants showed an average daily consumption of 23.7 ± 5.8 l/person (EMCON, 2000). The daily hot water consumption of rural African villages without access to municipal water is typically lower than the numbers found in this study (Meyer, 2000). While the exact amount of hot water used in each case may be different, the usage pattern in both of these studies follow the same trend.

Figure 8 shows the chosen geometric shape for hot water draw-off patterns which is based on extensive research by Muya (1996) and Meyer (2000) and should serve as the guideline in profile-based central domestic hot water distribution. Figure 14 represents the digitised computer modelling version of the proposed hourly hot water draw-off profile in a format suitable for use in computer software simulation and thermodynamic analysis platforms. This hourly time series hot water draw-off profile dataset can also be used to help validate and compare mathematical and computer simulation models for storage and control automation solutions in micro-CHP models.

The above load profiling and energy/hot water consumption analysis is central in the energy usage planning and micro-CHP modelling analysis for isolated and remote rural areas. The above section offers realistic load profiles in format suitable for computer simulation platforms. These profiles can now be used as archetype rural consumption reference shapes in solar microgrids and solar micro-CHP system simulation experiments. It will in future also be helpful in comparing embedded off-grid distribution management system control schemes and stand-alone distributed energy resource management system approaches in micro-CHP microgrid simulation experiments.

5. Conclusions

A community solar micro-CHP system generates energy from variable renewable energy sources. In such shared community energy systems, special consideration should be given to a control automation and energy management solution. Such a solution should be capable of energy conservation as well as energy supply and demand-balancing in scalable community microgrid configurations. To develop and evaluate suitable computer-guided control automation and storage solutions for digital micro-CHP system models in isolated rural microgrid applications, reference energy consumption profiles for the use (or potential use) of thermal and electrical energy usage is required. Even with the availability of Big Data and Smart metering, it is still proving to be difficult to find thermal and electrical energy profile shapes for a rural African village. A scoping exercise was subsequently performed to investigate how literature data can be used as means to define universal load profile shapes for a remote and isolated rural African context (Cross & Gaunt, 2003; Heunis & Dekenah, 2014; Meyer, 2000; Muya, 1996; OpenEI, 2015; Tinarwo, 2009; Sprei, 2002).

The results from the scoping exercise showed that the thermal and electrical profiles for domestic rural energy had certain characteristic features. The most important is the two peaks that have been extensively discussed. The scoping exercise showed that the peaks in the electrical and thermal loads coincided with the patterns of user activity, being present in the early morning and in the evening, with the latter always being more prominent. In

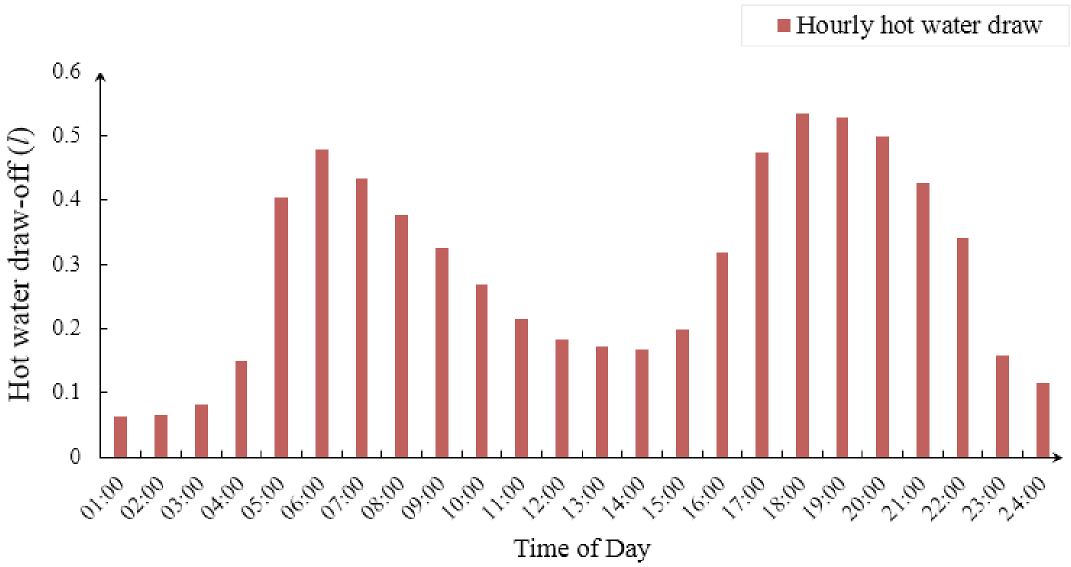


Figure 14: Proposed characteristic rural domestic hot water profile archetype reference shape for micro-CHP computer modelling and simulation experimentation

some cases, a peak around noon could be seen and was mostly associated with agricultural communities.

From the scoping exercise, hot water usage by rural households is better understood. There is much more consistency in the data, which is different from electricity usage in rural households where patterns fluctuate greatly between studies. This means that even though the time of electricity consumption is known, it is difficult to know how much generation the system needs to be designed for. The scoping profile can also serve as baseline load in the development of a software tool to formulate and predict load profiles in multi-carrier microgrids for off-grid rural areas.

The outcome of the scoping exercise offers digitised computer model ready hourly electricity and hourly hot water draw-off profiles in a format suitable for use in dynamic microgrid analysis and computer software for energy simulation platforms (i.e. TrnSys, Homer Energy, EnergyPLAN, EnergyPlus, ReEds, RetScreen, Leap, and OSeMOSYS). These hourly time series electricity usage and hot water draw-off profile datasets can now be used to help validate and compare mathematical and computer simulation models for storage and control automation solutions in micro-CHP models. It will also be useful in techno-economic analyses for integrated or isolated district community energy systems. Disaggregated load profiles (radio, TV, cellphone charger, lights, security system) derived from the above load profiles will further help to develop demand response, demand management, responsive load curtailment and dynamic load control systems, to account for renewable supply variability in distributed energy resources within sustainable rural development systems.

Acknowledgments

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Varying percentages of full uniform shading of a PV module in a controlled environment yields linear power reduction

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Abstract

Partial shading of a PV module has received much attention over the past few years, as it results in uneven cell power generation, compromising a PV system performance. Full uniform shading of a PV module has not received as much attention. This article correlates the percentage of full uniform shading of a given PV module within a controlled environment to its output power. The percentage of full uniform shading provided by shade nets was firstly determined. These shade nets are then used to cover a specific PV module (experimental system), while an identical PV module remains totally unshaded (control system). Increasing percentages of full uniform shading negatively affected the direct beam component in a linear way. Decreasing the light intensity falling on the PV model exhibited a linear increase in the percentage of output power reduction of the PV module. This is observed in that a shade net providing 36% of full uniform shading resulted in a 56% output power reduction, while a 63% full uniform shading net yielded 82% power reduction. These results hold a strong promise to improve current simulation modules that focus on determining the output power of a given PV array under specific environmental conditions or for specialised geographical locations.

Keywords: *partial shading, PV simulation, shade net*

Highlights

1. Six different shade nets were quantified using the shading experiment.
2. A 36% shade net resulted in a 56% output power reduction.
3. A 63% shade net yielded 82% power reduction.

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1. Introduction

'Almost every way we make electricity today, except for the emerging renewables and nuclear, puts out carbon dioxide. And so, what we're going to have to do at a global scale is create a new system. And so, we need energy miracles' [1]. Energy miracles, as referred to by Bill Gates, require on-going research into developing and understanding new energy systems, including renewable energy systems in the form of photovoltaic (PV) systems [2]. The PV systems still require much research and development in order to improve efficiency and reduce manufacturing costs. In fact literature states that an ever-increasing need to improve the efficiency of energy production still exists today [3], especially in view of the ever increasing global demand, as shown in Figure 1. This demand has a potential to not only necessitate the production of more energy (an increase of 60% by 2030), but also the increase of carbon dioxide by an even greater percentage (an increase of 62% by 2030).

The efficiency of PV cells varies depending on the technology, light spectrum, atmospheric conditions, temperature, design and material used, and can be up to 46% efficient [5]. The conventional solar PV panels have a conversion efficiency of only 5–17% [6]. Interrupting direct beam radiation lowers the output voltage of a PV module significantly, influencing the amount of output power available for driving an alternative energy system, which may lead to system downtime or even component failure over a period of time [7]. This interruption is usually due to cloud movement or shading of the PV module by natural or man-made causes. Partial shading of a PV module has received much attention over the past few years, as it results in uneven cell power generation that my compromise total power production [8]. Numerous simulation models were proposed to study the effect of partial shading, including the model by Tian et al. [9]. A Google Scholar Search of the terms 'partial shading' and 'photovoltaic' revealed some 3510 hits in December 2014, while the words 'uniform shading' and 'photovoltaic' revealed only 95 hits in that same month.

It must therefore be noted that research relating to the exact effect that varying percentages of full uniform shading exert on the output power of a PV module is lacking. For example, Giaffreda et al. [10] contrasted full uniform shading to partial shading of a PV cell and proved that its cell temperatures increased when shaded. No percentages of varying shade were, however, reported, nor the effect on the output power. Results given by Christy regarding shading suggested that the reduction in current was not proportional to the amount of shading on the PV panel [11]. Again, no varying percentages of full uniform shading were reported. Gummeson et al. [12] reported that a fully-shaded 11.4 cm^2 PV module produced 29 times less power than the same PV module under bright indoor lighting conditions. Again, no percentages of full shade were mentioned, although a significant power reduction was given. Johnson [13] used Blue Hawk 4 mm thick, heavy-duty plastic sheeting to cover the top of PV modules to provide varying levels of insolation, which included unshaded, partially shaded and fully shaded modules. Power reduction was found to be around 33% for full uniform shading. Again,

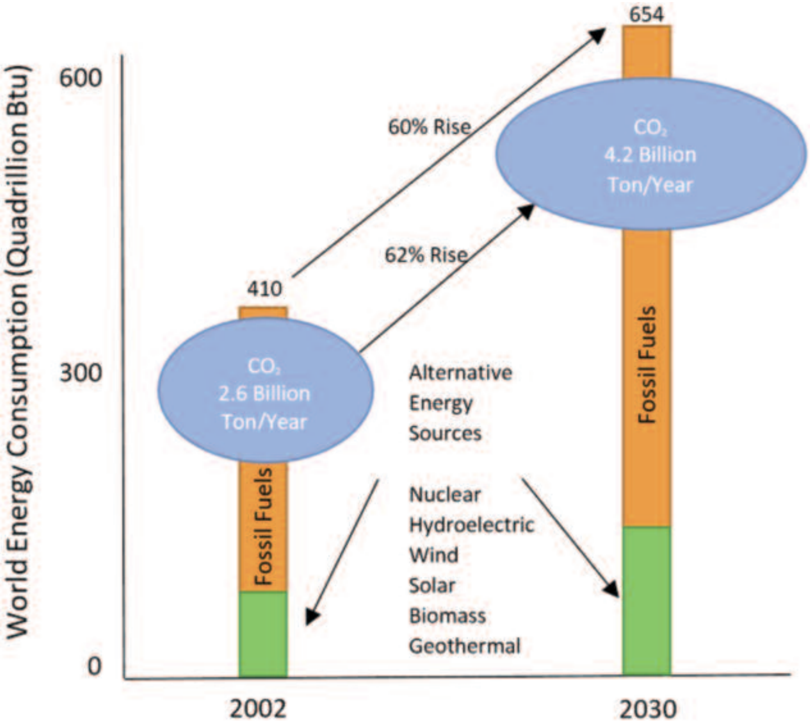


Figure 1: Global energy demand [4].

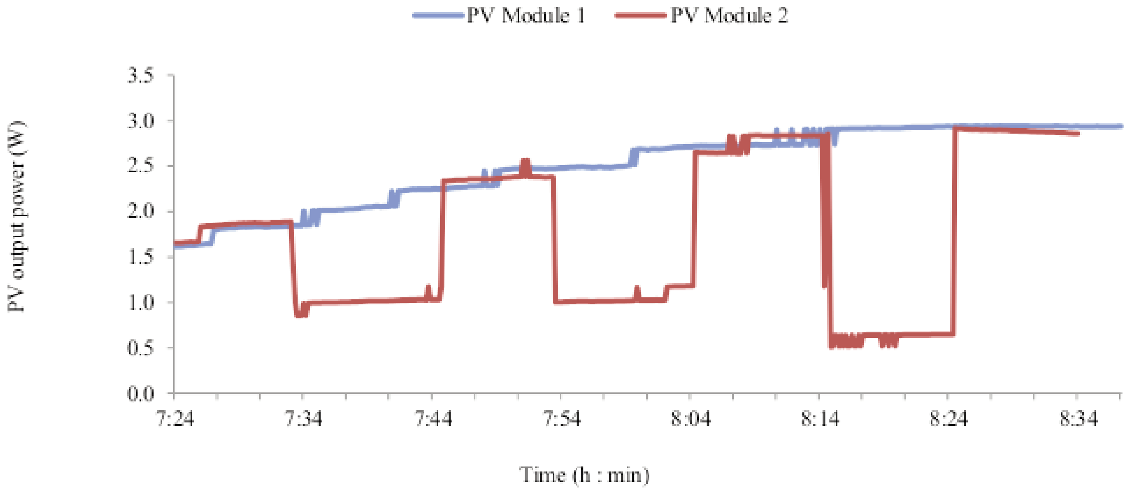


Figure 2: Output power of two modules used by Swart and Hertzog where one module was uniformly covered with three different shade nets of differing shade percentages [14].

no varying percentages of shading were used.

In 2014, Swart and Hertzog [13] contributed towards quantifying the percentage of uniform shading of a PV module, correlating it to the PV module's output power. This study was, however, based on using only three shade nets to uniformly cover a specific PV module around 8 a.m., when maximum solar radiation is not present (see Figure 2). Furthermore, this study featured only two samples of data that were recorded using a PICOLOG data recorder. It can, therefore, be asked whether increasing the number of samples would not indicate a linear relationship between incoming light intensity and output power reduction of the PV module, as opposed to a non-linear relationship expressed by Swart and Hertzog [13].

This article correlates the effect exerted by six different percentages of full uniform shading on the output power of a PV module in a controlled environment. Ten different samples were recorded with an Arduino device connected via LABVIEW over a four-month period at noon, when radiation is at its maximum value. Reasons for using the Arduino device along with the LABVIEW software are given. The percentage of full uniform shading equates to the percentage of light intensity of the direct beam component that has a direct effect on power production. Included is the literature pertaining to the importance of direct beam radiation, with varying percentages of full uniform shading being equated to diffuse radiation. Next the methodology and the two practical setups are described. Results are presented in sketches, tables and photographs, followed by conclusions.

2. Direct and diffused beam radiation

The PV modules receive direct (beam), diffused and reflected ground radiation during varying atmospheric conditions [15]. Direct radiation is the part which travels unimpeded through space and the atmosphere to the surface of the earth, while diffused radiation is the part scattered by atmospheric constituents such as molecules, aerosols and clouds [16]. Figure 3 illustrates the annual sum of global horizontal radiation for South Africa and Figure 4 shows the difference between reflected, direct and diffused radiation. The annual aggregate for Bloemfontein, South Africa, borders around 2050 kWh/m^2. The highest recorded values are around Upington, while the coastal regions around Durban have the lowest values. It is essential that as much as possible of this global horizontal irradiation reaches the surface of a PV module by means of direct radiation.

Wenham et al. [19] reported that, on a cloudy day, all the incoming radiation is assumed to be diffused, with intensity approximately equal to 20% of the direct beam component. Cloudy conditions, as well as air pollution, therefore inhibit direct radiation, giving rise to diffuse radiation, which is not conducive to optimum PV performance [18]. Diffuse radiation on a PV module could take many forms, including shading from:

- a tree in summer (all leaves present),
- a tree in winter (no leaves present),
- condensation trails,
- thin clouds, and
- thick clouds.

These forms of diffused radiation do not all exhibit the same percentage of shading. For example, evergreen trees provide a higher percentage of shading than deciduous trees [20]. Furthermore, research has shown that appropriate positioning of large trees near buildings could save approximately 4.7% in cooling demand and 3.3% of electricity [21]. These varying types and sizes of trees all exhibit different percentages of shading that could impact differently on the output power of a PV module installed within its reach.

Condensation trails (also called contrails or vapor trails) are aircraft-generated cirrus clouds that often form in the absence of other cirrus clouds in

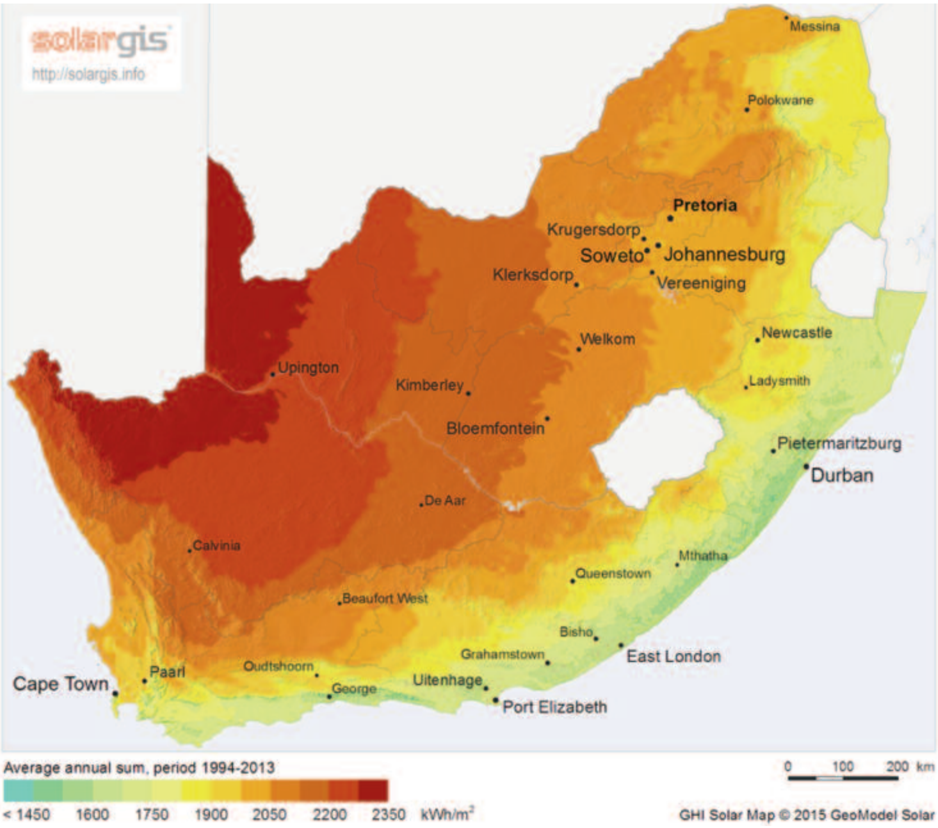


Figure 3: Daily average solar radiation for South Africa [17].

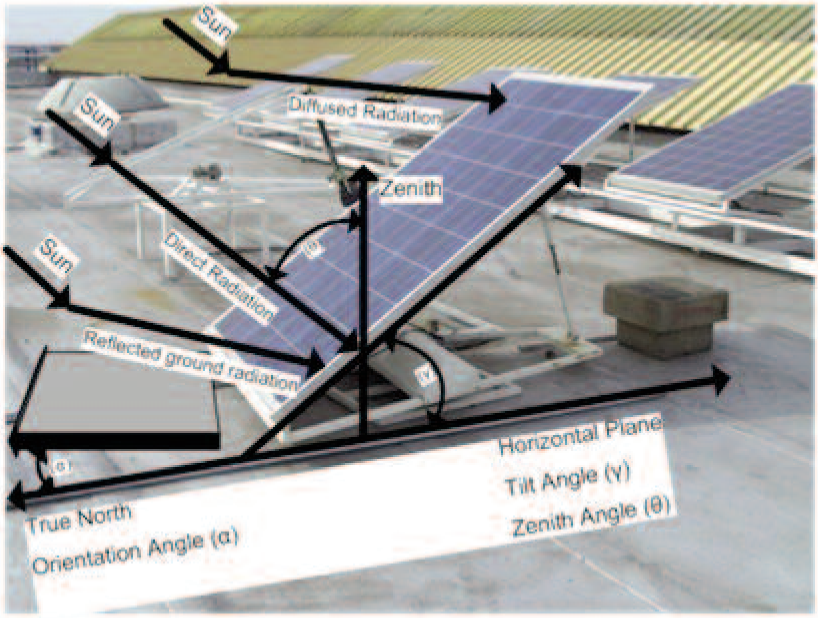


Figure 4: Different radiation beams [18].

ice-supersaturated conditions at temperatures less than -39 °C [22]. Since such conditions are relatively common in the upper troposphere, contrails can develop into relatively long-lived cirrus cloud [23]. They can add to naturally occurring cloud cover and may be important for the earth's radiative balance [24]. Persistent contrails are an important climate impact of aviation that could potentially be reduced by re-routing aircraft. This, however, generally increases both the flight length and its corresponding CO emissions [25]. Contrails are visible for several minutes, or even longer when the relative humidity is slightly below saturation, in particular at low temperatures [26]. A national flight operator in South Africa has a number of scheduled flights between Johannesburg and Port Elizabeth, with the flight path often being directly over Bloemfontein [27]. This results in a number of contrails that are visible on the ground, especially during the colder winter months. However, these contrails may be considered to be cirrus-clouds that are usually optically thin in the sub millimeter [28], as shown in Figure 5.

Figure 5: Contrails are considered to be cirrus clouds which may be equated to thin clouds [29].

Figure 5 shows that thin clouds are relatively transparent to sunlight [30], thereby providing a lower percentage of shading on the earth's surface when compared to thick clouds. These thin clouds are hard to identify on satellite images because they either reflect too little solar radiation or block too little terrestrial emission [31], while thick clouds are easier to detect [32]. Thick clouds are easy to distinguish because they are obviously brighter, and usually gathered together, forming a large block [33], resulting in a larger percentage of shading on the earth's surface. PV modules, being exposed to both thin and thick clouds, are subjected to varying percentages of shading [34].

These varying percentages of shading have the potential to negatively influence PV-based systems, such as PV/hydro hybrid renewable energy systems or innovative solar vehicles. In turn, these hybrid generators could be used as a standby power source for remote sites [35] where an important requirement would be the availability of direct beam radiation. In terms of solar vehicles, the size of the PV system is usually determined according to the power and voltage requirements of the electrical motor [36]. Direct beam radiation, as opposed to diffuse beam radiation, makes up the majority of total solar radiation and is required for the optimal operation of these types of energy generator systems and vehicles [37]. Quantifying the percentage of full uniform shading of a given PV module to its output power may assist in optimising the design and development of these types of hybrid generators and solar vehicles for varying percentages of direct beam radiation.

3. The PV technology

A typical PV cell generates around 0.6 V, depending on the type of semiconductor used and the manufacturing technology employed [38]. To increase the voltage and current requires several cells to be connected in series and/or parallel to form a PV module. The working principle of a PV cell is based on the 'photovoltaic effect' in that when sunlight falls on a cell that consists of a normal p-n junction, photons are absorbed, resulting in electron-hole pairs being generated [39]. Essentially, circuits that contain semiconductor devices are non-linear, most obviously for devices such as diodes and silicon-controlled rectifiers where the IV characteristics change abruptly [40]. The characteristics of PV cells are therefore non-linear, depending to a large degree on environmental parameters like temperature, solar irradiation, shading, humidity and pressure [41]. It may, therefore, be hypothesised that the relationship between the incoming light intensity and the output power of a PV module is non-linear. One aim of this research is to either support or reject this hypothesis.

4. Research methodology

The first objective of this study is to quantify the percentage of the direct beam radiation that passes through the six different shade nets that will be used in the full uniform shading of the PV modules. This was done using two methods. In the first method, a constant light source, light sensor and two black cylinders (see Section 5 for setup) were used. Multiple tests done on the same day results in a higher reliability coefficient than does a test–retest on separate days [42]. A number of tests were, therefore, done on the same day, using both an analogue light intensity meter (PHYWE) and a digital light intensity meter (ISO-TECH). This was done to verify the percentages of light reduction that were stated by the manufacturers of the shade nets. A second method involved placing the shade nets directly over the sensor (placed at the same tilt angle as are the PV modules) of the light intensity meter, using the sun as the light source.

The second study objective is to correlate the different percentages of full uniform shading to the output power of a PV module (termed PV Module 2). Each shade net was used to cover PV Module 2 for one minute (experimental system), with one-minute intervals where no shading was used. This enabled PV Module 2 to return to normal operation in line with PV module 1, which remained completely unshaded (control system) for the duration of the tests. Multiple samples were acquired on different days of the months (May–August 2014) around 11:30 am, as maximum solar radiation occurred around noon. The reasons for using this time period was the low rainfall during these months at the research site.

The multiple samples within a natural setting ensured reliability and validity of the results. The reliability of a study begins to decrease when it becomes more difficult to replicate the results [43], and would therefore be increased if the same results were obtained over a period of time.

5. Practical setup 1: Determining shading percentages

A constant light source, light sensor and cylinders were used in order to establish an environment with minimum influence from external light. Two black cylinders (each 525 cm long and 27 cm in diameter) were staked upon each other (see Figure 6). The top cylinder was sealed from external light and a 12 V, 3 W (230 lm) light-emitting diode (LED) lamp was securely mounted in the centre of the top cylinder as a light source. In the control system, the LED lamp was switched on and the light intensity measured using an analogue PHYWE light intensity meter (light sensor mounted at the bottom of the bottom cylinder) and a digital ISO-TECH light intensity meter. Six different percentages of shade net were placed between the top and bottom cylinders (525 cm from the light source and light sensor) in the first method. In this instance, light from the light source would have to travel through the shade net to reach the light sensor. This light intensity was measured to enable the exact calculations of the shading percentages. These shade nets were then used in the practical setup of the PV system. In the second method, the sensors of the light meters were placed at the same tilt angle of the PV modules. The shade nets were then placed directly over the sensors, just as the shade nets would be placed directly over the surface of the PV modules. Three different samples were obtained from which the averages values were used.

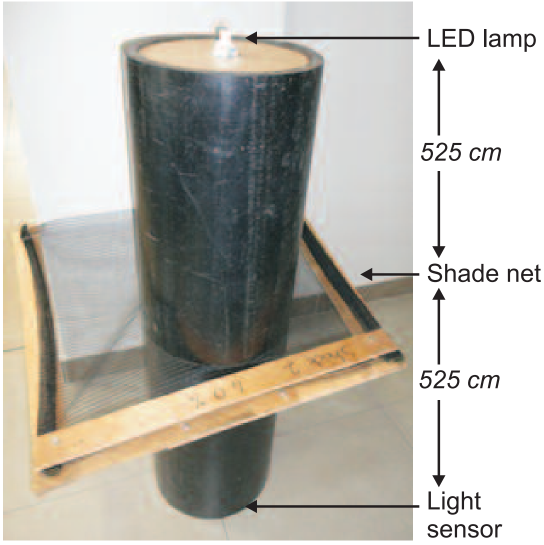


Figure 6: Practical setup for verifying the shade net specifications.

6. Practical setup 2: Identical PV systems

No batteries were included in the practical setup of the two identical PV systems because of uncertain variations that might exist between batteries from the same manufacturer and with the same model number. In fact, battery-to-battery variations in electromotive force at a given state of charge could be in the order of 50 mV due to variations in the manufacturing process, ageing and charge-discharge cycling of a single 2.25 V cell [44]. A 60 LED lamp (12 V, 3 W) was, therefore, chosen as the load resistance that was connected directly to the PV module via a 22 Ω resistor. The purpose of the series resistor was to raise the threshold operating voltage and ensure that the voltage across the LED never exceeded 12 V, as the stated output voltage of the PV module used was 16.5 V at standard test conditions. The threshold operating voltage is the point at which the LED starts emitting light, despite being very faint. A data logging interface was included between the PV module and the LED lamp, which served to condition the voltage and current from the PV module to enable logging via an ARDUINO board to a PC. This circuit was based on Swart [45] and Asowata [46, 47].

The ARDUINO board is an electronic platform designed to simplify the process of studying digital electronics, and comprises a microcontroller, a programming language and an integrated development environment [48]. The ARDUINO was established to teach interaction design, a design discipline that puts prototyping at the centre of its methodology [49]. The hardware is relatively cheap and the development software can be downloaded for free from the internet. There are also a growing number of freely-available software examples that make the implementation of ideas on these boards easier to achieve. Academics from different fields make extensive use of these ARDUINO boards [50-52]. These boards are used in conjunction with the National Instruments LabVIEW software, a graphical programming language that has its roots in automation control and data acquisition [53]. The LabVIEW has several key features that make it a good choice in an automation environment and includes simple network communication, turnkey implementation of common communication protocols, powerful toolsets for process control and data fitting, fast and easy user interface construction, and an efficient code execution environment [54]. The practical setup is shown in Figure 7. Six different shade nets (with exact measured and calculated shading percentages) were placed over PV Module 2 (becoming the experimental system – Point A in Figure 7), while PV Module 1 remained completely unshaded (becoming the reference or control system – Point B in Figure 7). An aluminum frame, with a protractor placed 90° due North, was constructed to securely mount the two identical 10 W PV modules (Point D in Figure 7). This protractor was used to verify the direct alignment of the sun to the PV modules at 12:00. The modules were mounted at the same tilt angle of 39°, equating to the latitude value of 29° plus 10° for the Central University of Technology, Bloemfontein. Values of latitude plus 10° for PV module tilt angles in South Africa were suggested by Chinnery [55] and substantiated by Asowata [56]. The practical setup was done inside an air-conditioned room where the temperature was kept constant at 24 . This was in order to prevent excess temperature degradation that has a significant effect on the output voltage of a PV module [57]. Due to the low output power of these PV modules as well as the short period of time (one minute) in which the shading nets were applied, no significant temperature differences between the two modules were observed. The current through the LED lamp (Point C in Figure 7 indicating that Module 1 is completely unshaded) as well as the voltage across it was logged for both the control and the experimental system.

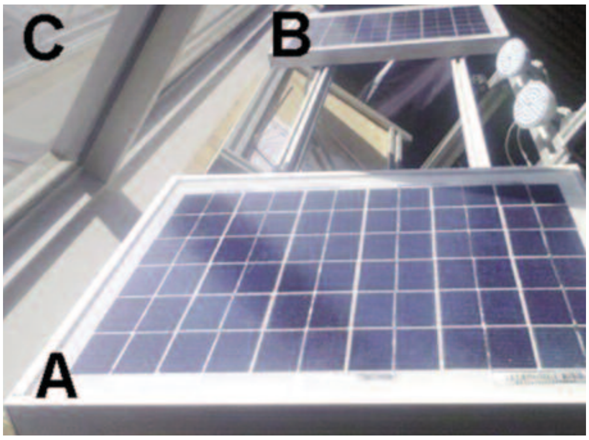


Figure 8: Photograph of the practical setup inside an air conditioned room with a north-facing window. Points A = the experimental system, B = control system, C = north-facing glass window.

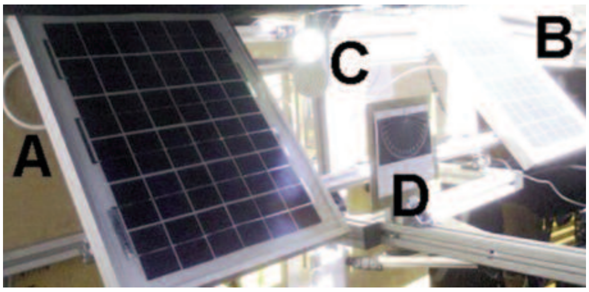


Figure 7: Practical setup of the two identical PV systems. Points A = the experimental system, B = control system, C = LED lamp, D = two identical 10 W PV modules.

These voltage and current values (for both the experimental and control system) were then used to calculate the output power of the PV module, with the percentage of power reduction being calculated using Equation 1. The aluminum frame was placed against a north-facing large glass window (Point C in Figure 8). Point A represents Module 2 (experimental system) and Point B represents Module 1 (control system) in Figure 8.

$$\%\ \text{Power reduction} = \left(\frac{1\text{-}(P(\text{shaded})}{(P(\text{unshaded})}\right)100 \qquad (1)$$

7. Results and discussion

The results of the shading experiment are shown in Figure 9. Using both the noon SUN and two different LEDs (3 W and 4 W) revealed similar results using the different shade nets that were sandwiched between two black pipes, according to Figure 6. The 22% shade net (Net 1) allowed 80% of light to pass, while a 42% shade net (Net 3) allowed 60% of light to pass. A 92% shade net (Net 6) only allowed 10% of light to pass. This, consequently, yielded a negative linear relationship ($R^2 = 0.9807$) between shade net percentage increase and light intensity decrease. The results for the 3 W LED, 4 W LED and the SUN-2Pipes were recorded using the first method described in Section 5 in relation to Figure 6. The second method, using only the sun and shade nets placed directly over the tilted sensor of the light meters (thereby replicating the setup of the shade nets and PV modules), provided the results given for the SUN experimental setup shown in Figure 9.

Figure 10 shows the power reduction for a PV module (PV Module 2 represented by the yellow line), which was exposed to six shade nets with different shading percentages. This sketch is obtained from the LabVIEW interface that was developed for this investigation. The sampling interval was set at one second and the different shade nets were used in one-minute intervals in order to give the system an opportunity to stabilise after each given event. The PV Module 1 (red line) exhibited a continuous output power and served as a control experiment. Figure 10 shows evidence of power reduction for each increase in shade net percentage. This trend was reversed as smaller percentages of uniform shade net were, subsequently, used from 11:09 to 11:22. Large overshoots occurred when the shade net was placed over the PV module and when it was removed, as the boundary around the shade net is composed of solid wood.

Figure 11 illustrates a correlation of output power with the percentage of full uniform shading of a given PV module within a controlled environment. These results were averaged from four samples taken on four days within the same week of August 2014. The percentage of full uniform shading equated to the percentage of light intensity of the direct beam component, which was not proportional to the output power of the PV module (e.g. 22% shading allows 78% of light to pass which results in a 48% reduction in output power). A neg-

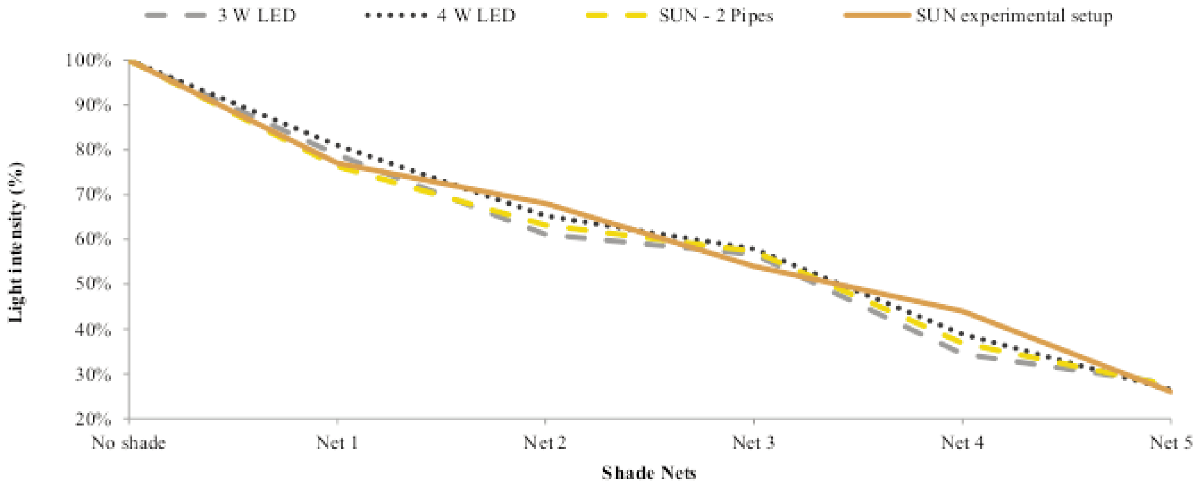
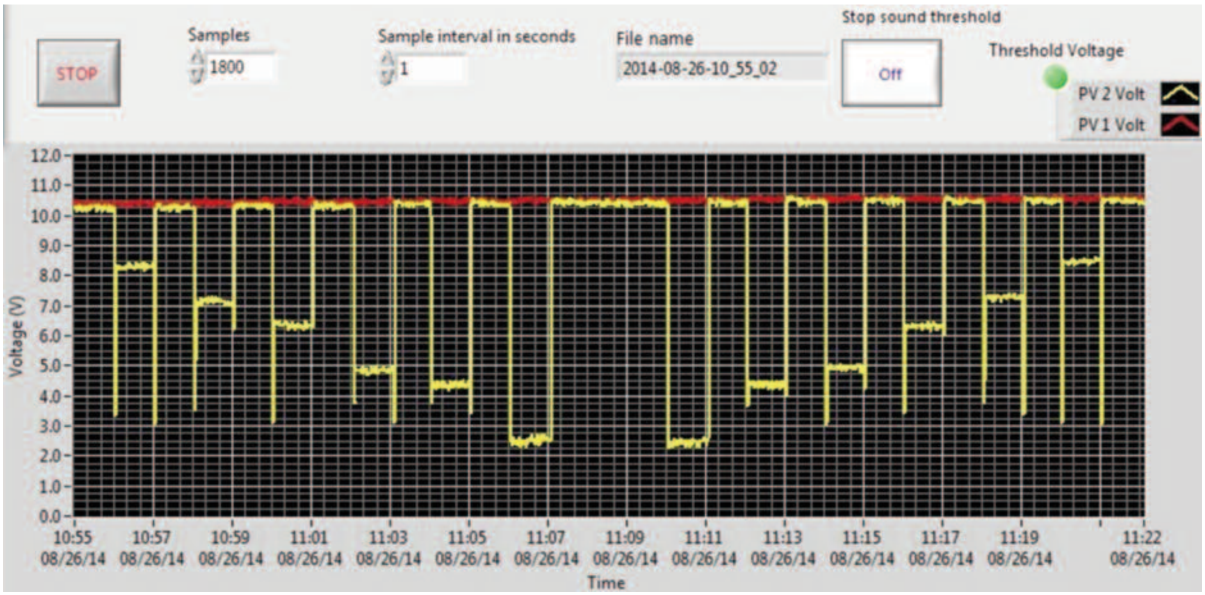


Figure 9: Full uniform shading results using LEDs, and the SUN, measured with an analogue PHYWE and digital ISO-TECH light meter.



Samples 1800

Sample interval in seconds 1

File name 2014-08-26-10_55_02

Stop sound threshold Off

Figure 10: Output voltage of experimental and control systems.

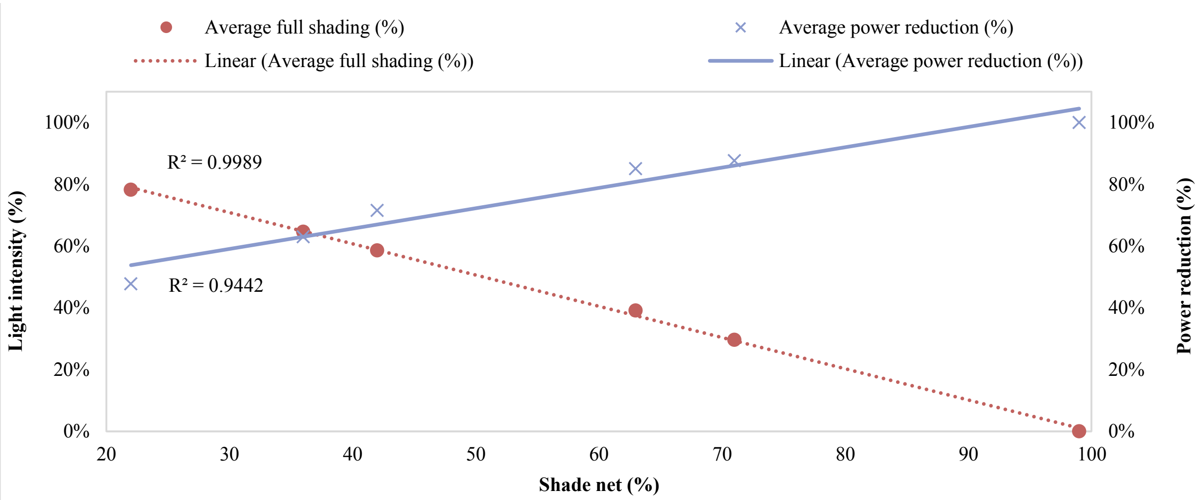


Figure 11: Correlation between the percentages for power reduction and full uniform shading.

ative linear relationship occurred ($R^2 = 0.9989$) between the average full shading percentage and the percentage of light intensity, as shown in Figure 11. A positive linear relationship ($R^2 = 0.9442$), however, occurred between the percentage of light intensity and the reduction in output power of a PV module. This indicates that there was a linear relationship between the percentages of full uniform shading and the output power reduction of a PV module under controlled environmental conditions.

8. Conclusions

The purpose of this investigation was to quantify the percentages of full uniform shading of a given PV module within a relatively pollution-free environment, correlating it to the output power of the module. Several load alternatives were investigated and a 60 LED lamp with a 22 ohm series resistor were chosen, based on previous research done by Swart and Hertzog [2]. Six different shade nets were quantified using the shading experiment encompassing two different methods (outlined in Section 4). Two identical PV systems were used, where PV Module 1 was the control system and PV Module 2 was the experimental system. Results show a negative linear relationship between the average percentage of full shading and the percentage of light intensity, which was allowed to pass through the shade nets. Results further show a positive linear relationship between the average percentage of full shading and the reduction in output power of a PV module. This was caused by a 36% shade net that provided a 63% output power reduction, while a 63% shade net provided 85% power reduction. The hypothesis stating that a non-linear relationship existed between the incoming light intensity and the output power of a PV module, is therefore rejected. These results may be used in future investigations to classify the amount of power reduction given by thick and thin clouds, including contrails left by commercial airplanes. These values may also assist in improving current simulation modules that focus on determining the output power of a given PV array under specific environmental conditions or for specialised geographical locations.

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JOURNAL OF ENERGY IN SOUTHERN AFRICA

Determination of oxidation characteristics and decomposition kinetics of some Nigerian biomass

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Abstract

The oxidation characteristics and devolatilisation kinetics studies of palm kernel shell (Elaeis guineensis), African bush mango wood and shell (Irvingia wombolu), and African border tree wood (Newbouldia laevis), were carried out by the thermogravimetric method. A thermogravimetric analyser TA Q500 instrument was used at a heating rate of 30 °C.min^{-1} under oxidative conditions. It was observed that all the samples followed a two-stage structural decomposition between 200 °C and 500 °C. The greatest mass loss rate occurred within the oxidation stage (200–375 °C) in all the samples. The ignition temperature of the samples ranged from 275–293 °C while their burnout temperatures ranged from 475–500 °C. During the oxidation stage, African bush mango shell was the most reactive sample, while palm kernel shell was the least. During the char combustion stage (375–500 °C), the reactivity of palm kernel shell was the highest. The average activation energy of the samples for the entire decomposition period are 140, 270, 131 and 231 kJ.mol^{-1} respectively. The biomass samples considered are thus suitable for combustion purposes for bioenergy production with minimal external energy input.

Keywords: thermogravimetric analysis; combustion index; activation energy; biomass; bioenergy reaction order

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1. Introduction

The prevailing issues of fossil fuels as primary energy sources have continued to provoke interest in exploiting suitable biomass resources for combustion processes in the energy industry. Climate change persistence, environmental pollution and degradation, uneven widespread of fossil deposit, and price fluctuations are among the problems which integrating biomass into the primary energy production has aimed to abate. With biofuel recognised as an alternative fuel source that is net carbon dioxide-neutral, policies to integrate it into national energy mixes have been promoted by some governments. For instance, Nigeria's biofuel policy stipulated a blend of up to 10% ethanol with gasoline, even though the biofuel would be imported for the initial three years until capacity and capability (infrastructure) are built for local production (Anyaoku, 2007). The policy envisages the country achieve a 100% biofuel production by 2020. Brazil's biofuel programme has a long history (Soccol et al., 2005), with the fuel contributing to local fuel consumption and export. Germany is the largest producer of biodiesel, with Argentina, Brazil, France, Italy, Malaysia and the USA as other leading producers and consumers of biodiesel (Ubrabio & Getulio, 2010). South Africa's national biofuel strategic policy targeted a 2% biofuel integration into the liquid fuel mix by 2015 (DME, 2007).

As the policies are implemented globally at different scales, biomass demand for energy production is going to increase in the near future. In order to forestall the challenge of inadequate supply of suitable plant varieties, a good number of possible biomass species need to be screened for their potential for bioenergy production. As a contribution to this, some biomass species in Nigeria such as palm kernel shell (Elaeis guineensis), African bush mango wood and shell (Irvingia gabonensis/wombolu), and African border tree wood (Newbouldia laevis), were selected for determination of their combustion properties. Palm kernel shell (PKS) is a common residue from oil palm produce which is rich in carbon and is commercially produced in Nigeria and neighbouring West African countries. About 5–7% of a typical fresh palm fruit bunch is composed of PKS, suggesting its relative abundance (Okoroigwe & Saffron, 2012). Similarly, African bush mango (locally called Ogbono) wood and its shell are common residues in the growing and processing of the seed kernel and pulp (for the sweet species), which are commonly consumed as food in West and Central Africa. They are among some highly valuable and extensively utilised tropical African trees (Ainge & Brown, 2001). After extraction of the seed, the shell is generally dumped at waste collection sites. The tree is classified as a non-timber tree even though it attains a height of up to 30 m and a girth of about 1.0 m when fully developed (Extension bulletin, 1999). According to Ayuk et al. (1999), about 169 kg per grower of Irvingia spp seed is recorded in three divisions in Cameroon. Usually, the shell of Irvirngia spp is about five times the mass of the kernel (seed), which would amount to about 845 kg of shell produced per grower in the divisions. The African border tree (called Ogirisi in South-Eastern Nigeria) is non-edible, but medicinal values of its leaves and bark have been reported (Okpala, 2015; Bafor & Sanni, 2009; Ejele et al., 2012), and it is commonly used as a land boundary marker. It is a fast-growing, soft-wood and drought-resistant tree.

Thermogravimetric (TG) analysis is the most commonly applied thermoanalytical technique in solid-phase thermal degradation studies (Ninan, 1989) for the purposes of understanding and establishing their thermal degradation kinetics. Usually, the mass of the material heated at a specific heating rate is monitored with respect to time and temperature. Some researchers have used the technique to study the thermal decomposition of biomass under oxidative and inert conditions. For instance, Wilson et al. (2011) studied the thermal degradation characteristics of bagasse, palm stem, cashew nut shells, coffee husks, and sisal bole under oxidative conditions, and found that cashew nut shells were the most reactive of the samples, based on their mass loss rate and lower burnout temperature. Similarly, Munir et al. (2009) used the TG method to establish the combustion kinetics of cotton stalk, sugar cane bagasse and shea meal, while El may et al. (2012) characterised date palm residue using TG analysis under oxidative conditions.

Understanding the decomposition kinetics and combustion behaviour of the selected biomass would aid in the design of chemical processes leading to biofuel production from them. This is in agreement with similar understanding derived from studies of the kinetics of thermal decomposition of other fuels such as coal char (Roberts et al., 2015; Niu et al., 2016), plastics (Apaydin-Varol et al., 2014), municipal solid waste (Conesa & Rey, 2015) and biodiesel (Lin et al., 2013). Hence, the objective of this investigation is to determine the combustion and decomposition characteristics of the four tropical biomass species using the TG method. The plants are classified as agricultural residues, non-tree timber and wild plant (non-food plant). The residues constitute environmental nuisance if they are not burnt to dispose of them. In large-scale plantations, their offcuts (residues), pose problems for agricultural machines; there is therefore a need to find an alternative use for the residues.

2. Material and method

2.1 Feedstock

In this investigation, four biomass samples, viz: palm kernel shell (*Elaeis guineensis*), African bush mango wood and its shell (*Irvingia* gabonensis/wombolu), and the African border tree wood (*Newbouldia laevis*), were randomly selected for the study. The woody samples are counted as non-timber trees even though they can grow large trunks. The feedstock samples obtained within Nsukka town in South East, Nigeria, were air dried and milled to particles of about 1 mm using a Wiley milling machine. TGA was used to determine the devolatilisation data for plotting the TG and the derivative thermogravimetric (DTG) curves. The sample masses used were 24.989 mg, 14.284 mg, 18.840 mg, and 14.907 mg for PKS, African bush mango (ABM) wood, African bush mango (ABM) shell and African border tree (ABT) wood respectively while thermogravimetric analyser, model TGA Q500 was used in the temperature range of 30–750 °C under synthetic air at a temperature gradient of 30 °C.min^{-1}.

2.2 Kinetic study

Kinetic parameters of biomass materials such as activation energy, reaction order and pre-exponential (frequency) factor can be determined by many models. Several investigations have used the Arrhenius equation for the determination of the parameters in both oxidative and inert conditions because of its flexibility and simplicity, compared with other models (Munir et al., 2009; El may et al., 2012; Sait et al., 2012; Parthasarathy et al., 2013; Jeguirim et al., 2014). The Arrhenius model is used in this investigation in determining activation energy, reaction order and frequency factors that governed the decomposition of the feedstock in oxidative conditions. All models used for biomass kinetic studies are based on rate laws that obey Arrhenius rate expression in Equation 1:

$$K(T) = Ae^{-E/RT} \qquad (1)$$

where k(T) is temperature dependent reaction rate constant, A is pre-exponential or frequency factor, E is activation energy (J.mol^{-1}), R is the universal gas constant – 8.314 J.mol.$^{-1}$K^{-1}, and T is absolute temperature, K.

The activation energy is regarded as ‘the energy threshold that must be overcome before molecules can get close enough to react and form products’ (White et al., 2011).

The kinetics of biomass decomposition can be expressed by the relation in Equation 2.

$$\frac{D\alpha}{Dt} = k(T)f(\alpha) = Ae^{-E/RT}\,f(\alpha) \qquad (2)$$

where t is time, α is degree of conversion, $d\alpha/dt$ is rate of isothermal process, and $f(\alpha)$ is the conversion function that represents the model used which depends on the controlling mechanism, according to Equation 3.

$$f(\alpha) = (1 - \alpha)^n \qquad (3)$$

By definition, α can be expressed as the mass fraction of biomass substrate that has decomposed in a time t during the decomposition process or mass fraction of volatiles evolved as shown in Equation 4 (White et al., 2011).

$$\alpha = \frac{m_o - m}{m_o - m_f} \qquad (4)$$

where m_o, is the mass of the biomass substrate at the beginning of reaction or initial time, m is the mass of the biomass substrate at any time t, and m_f, is the mass of the biomass at the end of the reaction time. The unreacted mass or residue is accounted for in m_f.

For non-isothermal decomposition, the rate expression which represents reaction rates as function of temperature at a linear heating rate is given in Equation 5.

$$\frac{d\alpha}{dT} = \frac{d\alpha}{dt}\frac{dt}{dT} = \frac{A}{\gamma}e^{-E/RT}\,f(\alpha) \qquad (5)$$

where $\frac{d\alpha}{dT}$ is the non-isothermal reaction rate, $\frac{d\alpha}{dt}$ is the isothermal reaction rate and $\frac{dt}{dT}$ is the reciprocal of heating rate (γ^{-1}).

There are many methods to solve Equation 5. The Coats-Redfern (1964) method is the popular non-isothermal model fitting method used for the determination of the reaction processes (Shen et al., 2009).

Integral of both sides of Equation 5 results in the general solution given in Equation 6.

$$g(\alpha) = \int_0^{\alpha}\frac{d(\alpha)}{f(\alpha)} = \frac{A}{\gamma}\int_{T_0}^{T}\exp\left(-\frac{E}{RT}\right)dT \qquad (6)$$

Using Rainveil’s (1960) approximation, the right hand side of Equation 6 can be approximated to Equation 7.

$$g(\alpha) = \frac{ART^2}{\gamma E}\left[1 - \frac{2RT}{E}\right]e^{-\frac{E}{RT}} \qquad (7)$$

Further simplification of the rate Equation 7 results in the linear relationship between the reaction rate and temperature given in Equation 8.

$$ln\left[\frac{g(\alpha)}{T^2}\right] = ln\left[\frac{AR}{\gamma E}\left(1 - \frac{2RT}{E}\right)\right] - \frac{E}{RT} \qquad (8)$$

The term 2RT/E is usually small, however, hence the linear correlation between the kinetic parameters can be obtained by Equation 9.

$$ln\left[\frac{g(\alpha)}{T^2}\right] = ln\left[\frac{AR}{\gamma E}\right] - \frac{E}{RT} \qquad (9)$$

The plot of logarithmic rate of reaction, $\left[\frac{g(\alpha)}{T^2}\right]$, against reciprocal of temperature, T^{-1}, is a straight line whose slope and intercept are –E/R and $ln\left[\frac{AR}{\gamma E}\right]$ respectively. From these, activation energy E, reaction order n and frequency factor A can be estimated.

2.3 Combustion parameters

2.3.1 Reactivity

The reactivity of the biomass samples under oxidative condition was determined according to the method defined by Munir et al. (2009), El may et al. (2012), Park & Jang (2012) and Ghetti et al. (1996). The DTG curve height is a measure of the reactivity of the samples during decomposition stage, hence reactivity R_M is directly proportional to the maximum weight loss rate R_{DTGmax} and inversely proportional to its corresponding peak temperature T_{Peak}. This is given in Equation 10.

$$R_M = 100\sum\frac{R_{DTGmax}}{T_{DTGmax}} \qquad (10)$$

The summation takes account of any secondary peak or shoulder present in each of the regions considered.

2.3.2 Ignition and burn-out temperature

The ignition temperature T_i is the temperature at which major decomposition of the biomass samples began to take place. It is determined by the method described by Xiang-guo et al. (2006) according to Figure 1 using the TG and DTG plots of each sample. From the maximum DTG point A, in the oxidation stage, a line is drawn to touch the TG curve at point B. From this point a line BC is drawn as tangent to point B to meet an extended TG level line at C. From point C a vertical line is drawn to touch the temperature scale at point D. The value indicated by D is the approximate ignition temperature T_i.

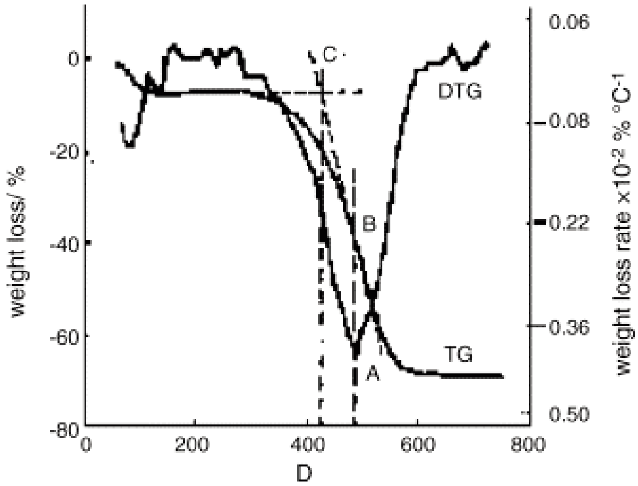

Figure 1: Ignition temperature determination sketch (Nie et al., 2001; Li et al., 2006).

The burnout temperature is defined as the temperature at which there is no noticeable weight loss in the TG and DTG curve.

2.3.3 Ignition index and combustion index

The ignition index D_i and combustion index S were calculated by Equations 11 and 12 according to methods used in previous research involving other biomass samples (El may et al., 2009; Vamvuka, 2011; Xiang-guo et al., 2006; Sahu et al., 2010).

$$D_i = \frac{R_{max}}{t_m t_i} \qquad (11)$$

$$S = \frac{R_{max}R_a}{T_i^2 T_b} \qquad (12)$$

where R_{max} = maximum combustion rate (%°$C^{-1}s^{-1}$) being the peak point on the DTG curve in the combustion zone, t_m and t_i = times (s) corresponding to maximum combustion rate and ignition temperature respectively, R_a is the average mass loss rate under oxidative conditions (%s^{-1}), T_i and T_b are ignition and burn-out temperatures (°C) respectively.

3. Results and discussion

3.1 TG and DTG analysis

The TG and the DTG of the samples are presented individually in Figure 2(a)-(d), which must be read together with Figures 3 and 4 to compare the TGs and DTGs of the respective samples. These results show that major thermal decomposition of all the samples followed a similar two stage structural decomposition. The first stage was from: 180 to 355 °C, for PKS (Figure 2a), 200 to 375 °C for ABM wood (Figure 2b), 200 to 350 °C for ABM shell (Figure 2c) and ABT wood (Figure 2d), which is the region of volatile decomposition (oxidative stage). This is the region of cellulose and hemicellulose decomposition. All the samples except PKS experienced greatest mass loss within this stage though at different temperatures due to differences in their structural composition, as can be seen in Table 1. The second stage from 355–500 °C (PKS), 350 – 475 °C (ABM shell), 375–500 °C (ABM wood) and 350–460 °C (ABT wood) region of char combustion.

Figures 2 and 3 show that the decomposition of the biomass samples followed a three step method with the initial mass loss between room temperature and about 110 °C being moisture loss (drying). The amount of moisture lost by each sample is presented in Table 2. There was mass loss observed for PKS and ABM wood between 100 °C and 200 °C before major structural decomposition of the samples. This can be attributed to light volatile release that was not present in other samples.

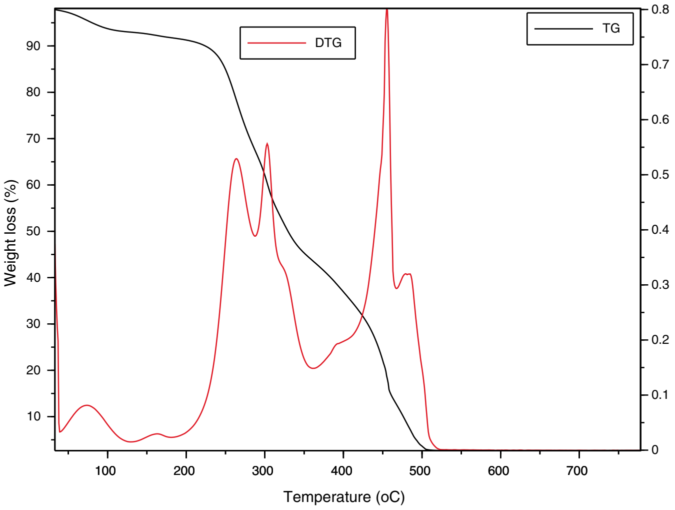

Figure 2a: TG and DTG of Palm kernel shell.

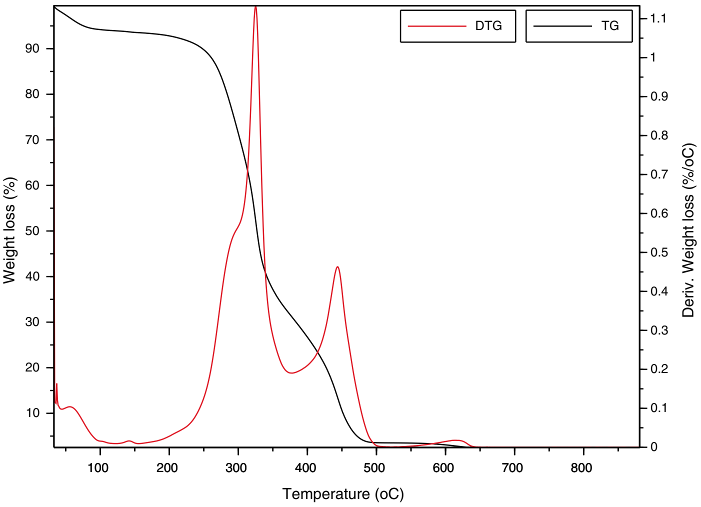

Figure 2b: TG and DTG of African bush mango wood.

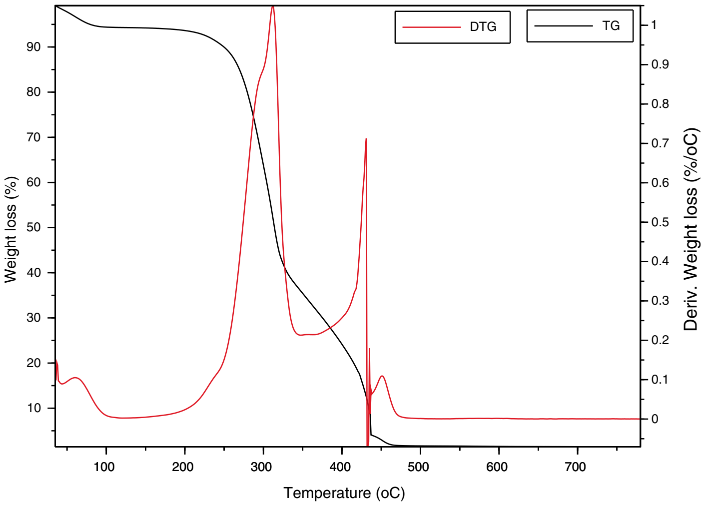

Figure 2c: TG and DTG of African bush mango shell.

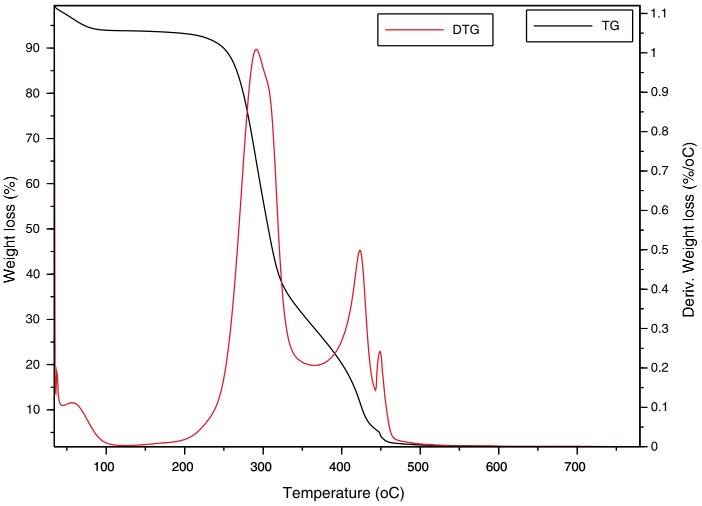

Figure 2d: TG and DTG plot of African border tree wood.

The second and last steps are the decomposition stages, during which the samples reached a complete combustion in the presence of oxygen, decomposing into volatile and ash release respectively. The mass fractions of these products are in Table 2 and Table 3. The TG and DTG profiles show distinctive regions of cellulose and hemicellulose decomposition in the PKS whereas there was no strong indication of this distinctive decomposition of the carbohydrates in the rest of the samples. The hemicellulose decomposition in ABM wood and shell is indicated by the shoulder peak by the left-hand end of their DTG curves while the shoulder peak at the right-hand end of ABT wood DTG shows its cellulose decomposition. The major mass loss in PKS at the combustion zone is confirmed by its large lignin content (Okoroigwe & Saffron, 2012). This is because lignin decomposition takes place over a large range of temperature usually from 180 – 900 °C (Luangkiattikhun, 2008).

3.2 Combustion parameters

3.2.1 Reactivity

The reactivity of the samples in the oxidative and char combustion stages is shown in Tables 2 and 3 respectively. The reactivity index R_M is a measure of

Table 1: Structural carbohydrate and lignin content of samples (Okoroigwe, 2014).

	Lignin (%)	***Cellulose (%)***	***Hemicellulose (%)***	***Inorganic materials (%)***
Palm kernel shell	53.85	6.92	26.16	13.07
African bush mango wood	35.96	40.19	11.47	12.38
African bush mango shell	36.18	36.12	8.77	18.93
African border tree wood	34.96	36.91	18.32	9.81

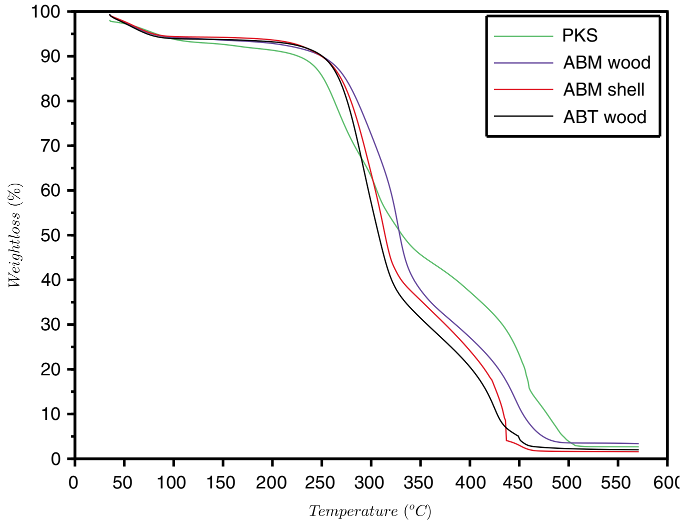

Figure 3: TG of all the samples.

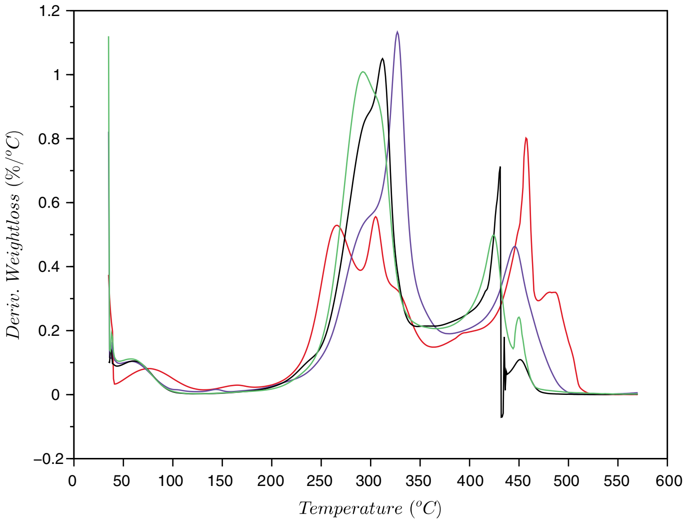

Figure 4: DTG of the samples.

the rate of decomposition of the structural components measured by the peak DTG profiles. The results show that within the volatile decomposition (oxidative) stage, PKS was the least reactive, while ABM shell was the most reactive sample in the mix. This is because the hemicellulose and cellulose components of PKS are small compared to its lignin content (Table 1). On the other hand during the char combustion stage, PKS became the most reactive. These are again expressed by the height of their DTG curves within the regions explained.

3.2.2 Ignition index and combustion index

The ignition and combustion indices of the samples are shown in Table 4, where ABT wood showed the least ignition temperature, $T_{i,}$ of 275 °C, while PKS showed the highest ignition temperature, $T_{\mathbf{i},}$ of 293 °C and least ignition index of 1.068 x10^{7}% °C $^{-1}$s^{-2}. All these could be attributed to the low reactivity of the sample due to its high lignin content. It is not quick to ignite PKS but it releases enormous heat during combustion owing to its high heating value (Okoroigwe & Saffron, 2012). The ABM wood and

Table 2: Combustion parameters during oxidative degradation.

Biomass	Moisture loss (%)	T_{peak} (°C)	Volatiles (%)	Temperature range (°C)	Max. weight loss rate (%°C $^{-1}$)	Reactivity R_M x10^3 (%°C $^{-1}$s^{-1})	Av. weight loss rate R_a (%°C $^{-1}$)
Palm kernel shell	6.0	305	89.0	180 - 355	0.55	0.48	0.2675
African bush mango wood	5.5	325	89.0	200 -375	1.10	0.91	0.3462
African bush mango shell	5.5	315	88.5	200 -350	1.25	1.10	0.3862
African border tree wood	6.0	291	89.0	200 -350	1.01	0.59	0.4098

Table 3: Combustion parameters during char combustion.

Biomass	Temperature range (°C)	T_{peak} (°C)	R_{max} (%°C $^{-1}$)	Average weight loss rate R_a	Reactivity R_M x10^3 (%°C^{-1}s^{-1})	Ash (%)
Palm kernel shell	355–500	455	0.80	0.2822	2.45	5.0
African bush mango wood	375–500	445	0.48	0.2267	0.17	5.5
African bush mango shell	350–475	430	0.71	0.2055	0.29	6.0
African border tree wood	350–460	423	0.49	0.2580	0.20	5.0

Table 4: Combustion characteristics of the samples.

Sample	T_i (°C)	t_i (s)	R_a (%°C^{-1})	R_{max} (%°C^{-1})	t_{max} (s)	T_b (°C)	$D \times 10^7$ (%°C^{-1}s^{-2})	$S \times 10^9$
Palm kernel shell	293	2300	0.2822	0.8019	3264	500	1.068	5.272
African bush mango wood	290	1648	0.2267	0.4632	2627	495	1.070	2.522
African bush mango shell	285	1672	0.2055	0.7129	2496	475	1.708	3.797
African border tree wood	275	1606	0.2580	0.4986	2489	475	1.247	3.581

its shell have close ignition temperature but have varying ignition index and combustion index. The larger combustion index of the shell might not be unconnected with the larger lignin content than its wood.

3.2.3 Burn-out temperature

Burnout temperature has been applied by researchers to characterise combustion properties of some fuels (Lu & Chen, 2015; Son & Sohn, 2015; Moon et al., 2015). It is defined as a temperature where the rate of weight loss consistently decreases to less than 1%.min^{-1} (Wilson et al., 2011). At this temperature, the sample decomposition can be assumed to be nearly complete and there is no further noticeable mass loss in the form of volatiles. The burnout temperatures, T_b, of the biomass samples used are presented in Table 4. Usually, low burnout temperatures indicate how readily the sample combusts; the lower the burnout temperature, the more readily the fuel is burned (Rostam-Abadi et al., 1988). Among the four samples, ABM shell and ABT wood exhibited the lowest burnout temperature (475 °C) which implies that they can combust more readily than others (Zang et al., 1992; Alvarez & González, 1999) as a result of the samples composition of softer tissues and lower lignin material, as shown in Table 1. Despite the higher content of lignin in ABM shell than the ABM wood, as shown in Table 1, its burning was aided by the oil content of the kernel (housed in the shell). The burnout temperatures were, however, higher than 377, 365, 364, 378 and 382 °C obtained by Wilson et al. (2011), for mill bagasse, palm stem, cashew nut shells, coffee husks and sisal bole biomass species found in the tropics. In spite of these being all tropical plants, two different biomass samples are most likely to differ in their thermal characteristic behaviour due to agronomical differences. The burnout temperature results reported in this investigation can be attributed to the morphological and agronomical differences of the samples used. It can,

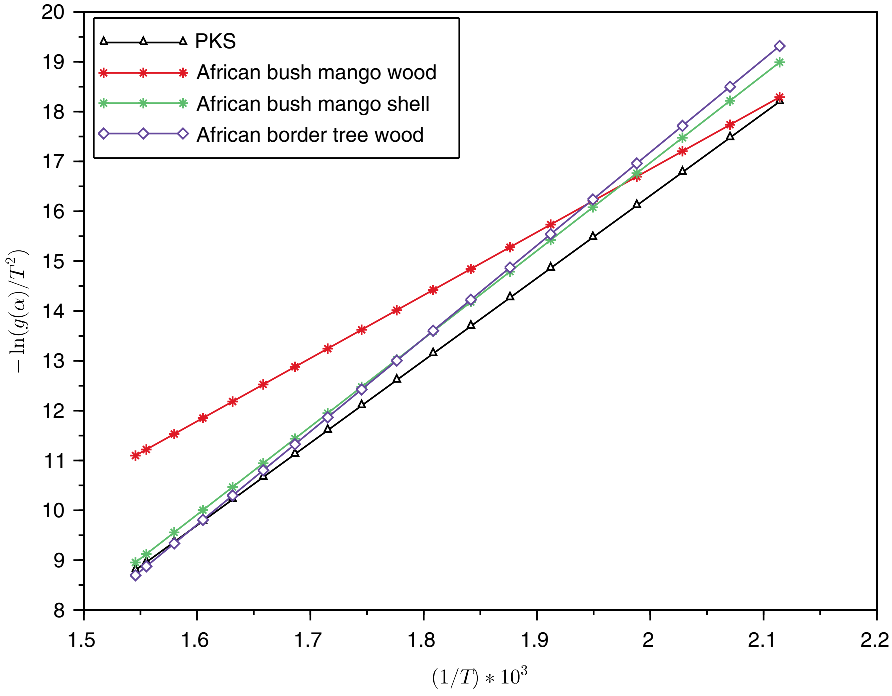

Figure 5a: Plots of $\left[\frac{g(\alpha)}{T^2}\right]$ against T^{-1} for all samples during oxidative stage.

therefore, be inferred that the mill bagasse, palm stem, cashew nut shells, coffee husks and Sisal bole are more readily combustible than the current samples being studied.

3.3 Kinetic parameters

The plot of logarithmic rate of reaction $\left[\frac{g(a)}{T^2}\right]$ against reciprocal of temperature, T^{-1}, (Equation 9) for all the samples during oxidative and char combustion stages is shown in Figure 5 and the summary of the parameters estimated using the intercept and slope of each sample's plot for the two stages are presented in Tables 5 and 6.

The activation energy of any sample undergoing chemical reaction is usually the threshold energy the particles would overcome before the reaction can proceed (White et al., 2011). Applied here, activation energy is the minimum energy required to start the decomposition reaction.

As observed from Tables 5 and 6, the activation energy of each sample varied as reaction moved from volatile decomposition stage to char combustion stage. Volatile decomposition is a low-temperature reaction relative to a high-temperature combustion reaction, hence the lower energy requirement at the oxidation stage. Comparison of the activation energy of the samples shows that ABM wood had the lowest activation energy, of 99.03 kJ.mol^{-1}, while ABT wood had the highest activation energy, of 124.35 kJ.mol^{-1}. During the combustion stage PKS had the lowest value, of 155.62 kJ.mol^{-1}, while ABM shell experienced the highest value, of 403.78 kJ.mol^{-1}. The two-stage structural decomposition process showed that the activation energy values were proportional to the process reaction order and the same for frequency factors. There is limited literature on the activation energy of the current samples, except for PKS, whose activation energy is within the range reported by Idris et al. (2012) despite using different experimental methods by them. The activation energy of the four samples were compared with those of other biomass samples reported (Wilson et al., 2011; Shen et al., 2009), as presented in Table 7.

Table 7 shows that the average activation energy values of current samples differ from those reported by other researchers for different biomass samples at different heating rates. Heating rate, particle size, model employed in the analyses, and the experimental medium are among the factors that can affect the combustion parameter estimation. Insufficient and/or lack of research in the reactivity behaviour of samples similar to the current ones and perhaps their heterogeneous nature, might be responsible for the differences in comparison with others. The values obtained in this investigation can, therefore, be accepted in the context of the associated experiment and can be used to predict the combustion behaviour of the feedstock. Generally, however, the values obtained here are lower than those reported by Wilson et al. (2011) for palm stem, cashew nut shells, coffee husks and sisal bole, even though they differ in morphology and plant family. They are also higher than those of oak, aspen, birch and pine reported by Shen et al. (2009). The implication is that less energy is required to convert the samples in this work to bioenergy than the samples reported by Wilson et

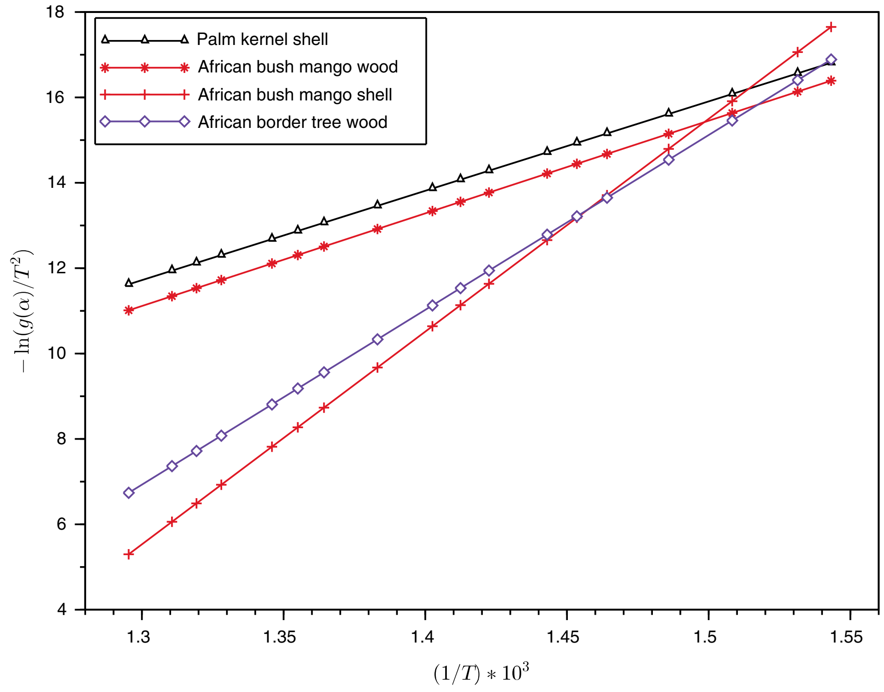

Figure 5b: Plots of $\left[\frac{g(\alpha)}{T^2}\right]$ against T^{-1} for all samples during char combustion stage.

Table 5: Summary of the estimated kinetic reaction parameters representing the volatile decomposition stage.

Sample	***Reaction order, n***				***Reaction kinetic parameters***		
	Factor of correlation, R^2				*Determined reaction order*	*Activation energy, E*	*Frequency factor, A*
	0	*1*	*2*	*3*	*n*	*(kJ.mol^{-1})*	*(min^{-1})*
Palm kernel shell	0.8291521	0.9331554	0.9780643	0.9516838	2	124.35042	11926.583
African bush mango wood	0.9406571	0.9852757	0.9659244	0.9002804	1	99.035323	7124.4312
African bush mango shell	0.9118338	0.9732715	0.9847963	0.9453636	2	135.50204	13644.02
African border tree wood	0.895209	0.9628088	0.989191	0.961295	2	144.3738	15141.96

Table 6: Summary of the estimated kinetic reaction parameters representing the char combustion stage.

Sample	***Reaction order, n***				***Reaction kinetic parameters***		
	Factor of correlation, R^2				*Determined reaction order*	*Activation energy, E*	*Frequency factor, A*
	0	*1*	*2*	*3*	*n*	*(kJ.mol^{-1})*	*(min^{-1})*
Palm kernel shell	0.8722524	0.9553034	0.9359161	0.868101	1	155.62467	14301.637
African bush mango wood	0.8145269	0.9657425	0.9140365	0.836295	1	163.90929	15925.278
African bush mango shell	0.7673127	0.9587005	0.9658252	0.926689	2	403.78535	59633.139
African border tree wood	0.6956617	0.9252994	0.9846007	0.955613	2	318.29011	43503.998

Table 7: Comparison of average activation energy of the samples with those of other biomass samples.

Sample	***Activation energy (kJ.mol^{-1})***	***Heating rate (k.min^{-1})***	***Particle size used (mm)***	***Reference***
Palm kernel shell	139.988	30	1	Current
African bush mango wood	131.472	-30	1	Current
African bush mango shell	269.643	30	1	Current
African border tree wood	231.332	30	1	Current
Mill bagasse	460.60	10	Not given	Wilson et al., 2011
Palm stem	542.07	10	Not given	Wilson et al., 2011
Cashew nut shells	293.48	10	Not given	Wilson et al., 2011
Oak	104–125	10–100	<0.5	Shen et al., 2009
Aspen	104–125	10–100	<0.5	Shen et al., 2009
Pine	104–125	10–100	<0.5	Shen et al., 2009
Birch	104–125	10–100	<0.5	Shen et al., 2009

al., but may require more energy than those reported by Shen et al. In addition to using different samples from the ones reported by Wilson et al. and Shen et al., geographical location, climatic conditions and biomass origin can contribute to the variation in the parameters obtained.

4. Conclusions

The combustion characteristics and decomposition kinetics of the biomass samples under oxidative conditions were studied. The thermal decomposition process showed distinctly the regions of moisture loss, structural decomposition and char combustion stages.

At the heating rate of 30 °C.min^{-1} the volatile release stage was the most critical of the degradation process in all the samples because the greater mass loss was observed in this region, with the exception only of PKS. The greater combustion process of the samples, except for PKS, would, therefore, most likely take place at this temperature region, with lower degree of combustion taking place at the higher temperatures.

The samples were characterised by low activation energies and decomposed at low energy input compared with some biomass samples reported in literature under combustion conditions but different heating rate and particle size. The samples also displayed high reaction rates during the structural decomposition stages with high volatile release.

Under an oxygenated medium, the combustion processes of the samples was complete, leading to low-carbon emission, which is a good attribute of biomass combustion for bioenergy production.

Owing to lack of reports on oxidative and combustion characteristics of the biomass samples studied in this research, further investigation involving varying particle size, heating rates, pre-treatments, cultivation, location and biomass age (maturity) are proposed. This will not only provide additional information on the combustion properties of the samples but also validate the results presented in this research.

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Ranking South African provinces on the basis of MERRA 2D surface incident shortwave flux

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Abstract
The main objective of the present study is to rank South African provinces on the basis of incoming solar radiation. The surface incident shortwave flux (SW_{Flux}, Wm^{-2}) of NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA 2D) reanalysis data for the period 1980–2009 over South Africa was analysed on annual, seasonal and monthly scales. The monthly mean ± standard deviation values of SW_{Flux} for the period revealed that, Northern Cape received the most (267.38 ± 4.32 Wm^{-2}) incoming solar radiation throughout the year, followed by North West (263.37 ± 7.13 Wm^{-2}) and Free State (259.20 ± 7.66 Wm^{-2}). The northern region of Limpopo also showed a good amount of incoming solar radiation (257.95 ± 6.16 Wm^{-2}) at the surface. KwaZulu-Natal received least (232.99 ± 7.02 Wm^{-2}) amount of mean monthly solar radiation in comparison with other provinces. On an annual scale, the Northern Cape ranked first, and on seasonal and monthly scales North West ranked first. Limpopo and Free State also performed well in the present study.

Keywords: *solar radiation, solar energy, reanalysis data*

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1. Introduction

Solar radiation mainly reaches the earth's surface in the form of shortwave radiation. With a changing climate, the amount of solar radiation reaching the earth's surface is also changing. In this regard, the monitoring and analysis of solar radiation over a region is important. Satellite data is good for the analysis of solar radiation because of its better spatial coverage compared to the ground measurements.

The sun is also the source of solar energy. Efficient use of solar energy not only decreases reliance on fossil fuels, but will also reduce environmental degradation associated with fossil fuels (Atilgan and Azapagic, 2015; Singh et al., 2011). Its availability over the earth's surface varies from place to place due to factors including latitude, elevation and cloud cover. The geographic location of South Africa is highly favorable for solar energy-based applications. Previous studies (Schulze and McGee, 1976; Drummond and Vowinckel, 1957) indicate that over South Africa daily insolation may reach up to 29 MJm^{-2}. The population of South Africa is over 50 million and to satisfy energy demand sustainably renewable energy is necessary. Development of any country's renewable energy potential is important for sustainable development. Solar energy is considered as the most reliable renewable energy resources (Kleissl, 2013). It is freely available, but collecting and transforming it is not very much cost-effective (Kougias et al., 2016). Means of collecting solar energy include photovoltaic systems (PV), solar thermals (solar water heaters, solar hot water panel, solar hot water collector), and solar thermal and PV working together. Before installing any solar energy collecting device at any site it is advisable to perform a detailed analysis of the site, as any wrong information may lead to sub-optimal performance and unexpectedly poor economic returns. For example, the size and design of PV systems to be installed at any site should be decided after proper solar resource assessment (Munzhebdi and Sebitosi, 2009). To assess a site's solar energy potential, long-term solar radiation data is needed. Typical meteorological year (TMY) data have been also used in many solar resource assessment studies (Kleissl, 2013) - that is, a long-term average of solar irradiance. TMY data, which represent the typical conditions, might be less useful where substantial variability and extremes in weather are observed.

While information related to incoming solar radiation is valuable, observational solar radiation data is sparse. Radiometric stations provide data for single locations and sometime for a relatively short duration. In this case, satellite data are reliably sourced. There is no doubt that *in situ* observations are valuable but satellite data are arguably a better option due to their better spatial coverage. It is necessary to understand the characteristics of data carefully in order to use them for solar resource assessment, as requirements for different projects vary. The focus of solar radiation project on a PV installation requires mainly global horizontal irradiance (GHI) dataset, while concentrating solar power needs a direct normal irradiance (DNI) dataset. For some solar projects, exceedance probabilities (P10, P50, P90, P95 and P99) of GHI and DNI are also calculated. The present study aims to study SW_{Flux}, from MERRA 2D reanalysis data (1980–2009) over the nine provinces (see details in Section 2). SW_{Flux} data were analysed in all the provinces separately to understand its variation on provincial scale. The provinces were also ranked on the basis of available SW_{Flux}. Studies based on rank are useful to convert large information into digestible information and it is easier to remember and present rank than actual values. In many renewable energy studies ranking method has been used (Şengül et al, 2015; Mohamadabadi et al. 2009; Goumas and Lygerou, 2000). Solar energy studies that focus on provinces can help governmental decision-making on a provincial scale. This study can also assist small-to-large solar energy investors, construction engineers, tourism industries and architects to plan activities and make decisions in their respective areas. It can also serve as a baseline for further studies related to solar energy potential using MERRA 2D data.

2. Study area and datasets

South Africa lies between 22°–34° S latitude and 16°–32° E longitude. On the west it is bounded by the Atlantic Ocean; on the south and east by the Indian Ocean; on the North by Namibia, Botswana and Zimbabwe; and by Mozambique and Swaziland on the north-east. There are nine provinces: Free State, Northern Cape, Western Cape, Gauteng, Mpumalanga, North West, Limpopo, KwaZulu-Natal and Eastern Cape (Figure 1). There are four primary climatic zones: desert (Northern Cape, North-Eastern parts of Western Cape); arid (Lim-

Figure 1: The provinces of South Africa.

popo, Mpumalanga, North-West, Free State, the western parts of KwaZulu-Natal and the Eastern Cape); sub-tropical wet (coastal strip of KwaZulu-Natal and the Eastern Cape); and Mediterranean winter rainfall (south-western coastal strip of Western Cape) (JWAF, 1999).

Monthly MERRA 2D datasets going back to 1979 were released in 2010 by the NASA, with data generated using Version 5 of the Goddard earth observing system atmospheric model and data assimilation system (Rienecker et al., 2011). These datasets are widely used in the scientific community (Chand et al., 2016; Bosilovich et al., 2011; Robertson et al., 2011; Schubert et al., 2011). The spatial resolution of the datasets is 2/3° (longitude) x 1/2° (latitude). More details on MERRA 2D data can be found at http://giovanni.sci.gsfc.nasa.gov/giovanni/. The present analysis used MERRA 2D monthly SW_{Flux}.

3. Methodology

SW_{Flux} data (1980–2009) were used to calculate long-term annual, seasonal and monthly means along with standard deviation (SD). These data were separated into three decades 1980s (1980-1989), 1990s (1990-1999) and 2000s (2000-2009) and analysed for annual, monthly and seasonal averages. Three metrics were calculated in order to compare the solar energy potential (based on the mean values) of provinces: solar energy potential number (SEPN), total solar energy potential number (TSEPN), and solar energy potential rank (SEPR). SEPN was calculated first by determining the mean values of SW_{Flux} for each province, and those with maximum (minimum) SW_{Flux} were given a SEPN value of 1 (9), respectively. The same procedure was applied for annual, seasonal and monthly time scales. TSEPN was calculated as the sum of all the SEPNs. The smallest TSEPN was given the first rank and the largest TSEPN was given the last rank. The provinces where the values of SW_{Flux} were equal were given equal rank.

4. 4. Results and discussions

4.1 Spatial variation of SW_{Flux} from 1980 to 2009

Solar radiation at any location depends upon the land elevation, sunshine duration, cloud cover, moisture and dust content (Singh et al., 2013; Drummond and Vowinckel, 1957). Figure 2 shows spatial variation of the annual mean SW_{Flux} in South Africa from 1980 to 2009, where it can be clearly observed that the north and north-west regions of South Africa receives more solar radiation than the south and south-east. Annual, monthly and seasonal means are presented as mean ± SD. The monthly mean values of SW_{Flux} (1980–2009) show that Northern Cape received the highest (267.38 ± 4.32 Wm^{-2}) incoming solar radiation throughout the year, followed by the North West (263.37 ± 7.13 Wm^{-2}) and Free State (259.20 ± 7.66 Wm^{-2}); Limpopo also received a good amount of SW_{Flux} (257.95 ± 6.16 Wm^{-2}), while KwaZulu-Natal received the least (232.99 ± 7.02 Wm^{-2}). The mean magnitude of percentage difference with respect to Northern Cape was also calculated (Table 1). The maximum was recorded by KwaZulu-Natal at 12.86% and the minimum by North West at 1.50%.

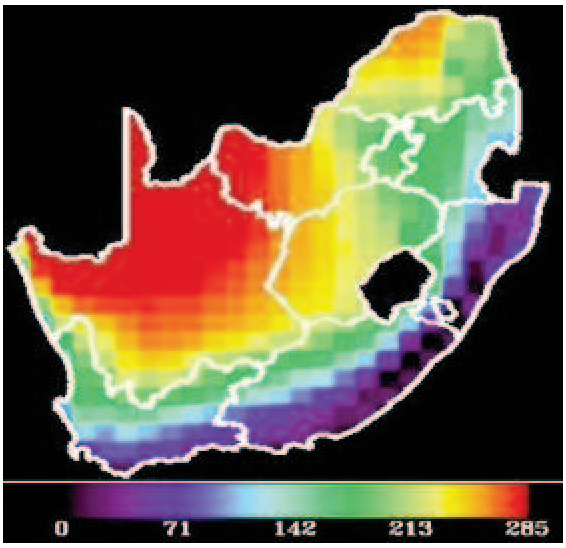

Figure 2: Variation of annual mean of SW_{Flux} (surface incident shortwave flux, Wm^{-2}) from 1980 to 2009.

Table 1: Mean with standard deviation (mean ± SD) of SW_{Flux} in nine provinces and magnitude of percentage difference with respect to Northern Cape.

Province	***1980–2009 (Mean ±SD)***	***% difference from N. Cape***
Free State	259.20 ± 07.66	3.06
Northern Cape	267.38 ± 04.32	0.00
Western Cape	244.34 ± 03.10	8.62
Gauteng	252.78 ± 07.46	5.46
Mpumalanga	247.49 ± 06.46	7.44
North West	263.37 ± 07.13	1.50
Limpopo	257.95 ± 06.16	3.53
KwaZulu-Natal	232.99 ± 07.02	12.86
Eastern Cape	236.06 ± 05.98	11.71

4.2 Variation of SW_{Flux} in different seasons

Figures 3 and 4 show that, SW_{Flux} varied from season to season for the nine provinces. Northern

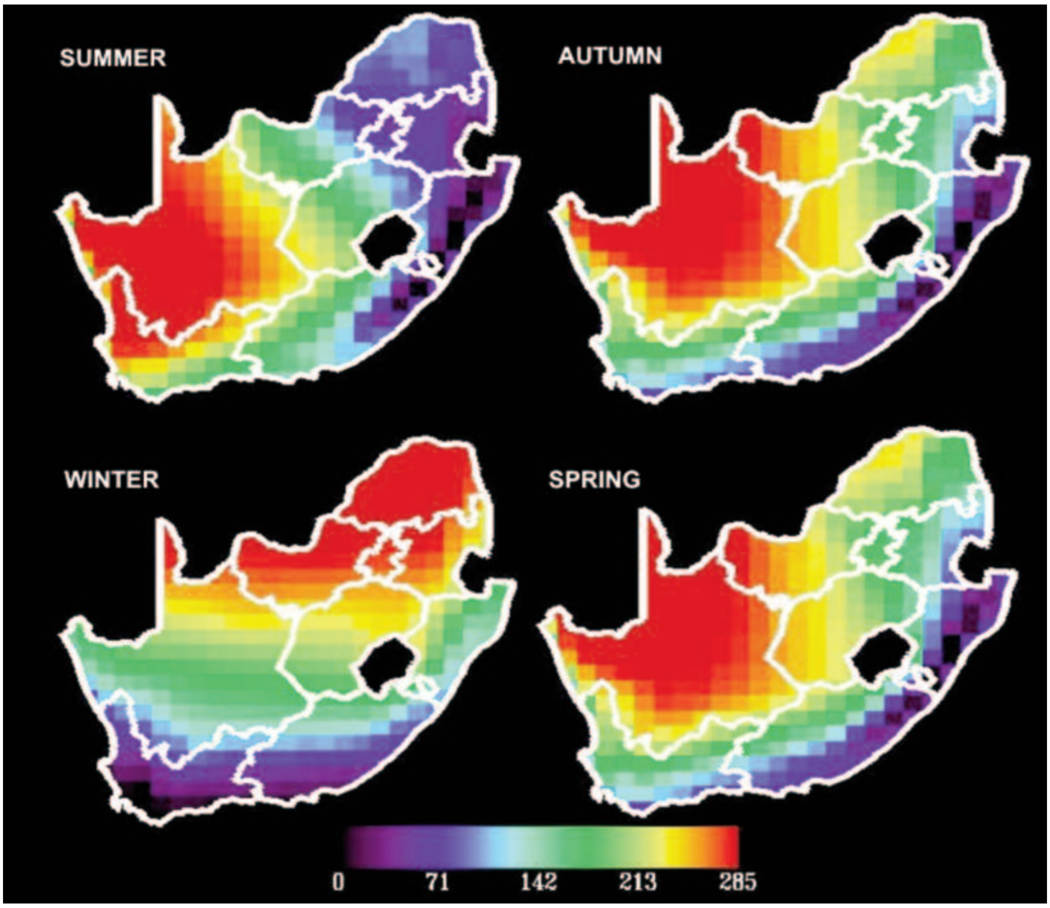

Figure 3: Climatological mean of monthly means of SW_{Flux} (surface shortwave incident flux, W/m^2) from MERRA 2D reanalysis (1980–2009), by season.

Cape showed more SW_{Flux} in summer than any other provinces, while Limpopo had more SW_{Flux} in autumn (235 ± 4.61 Wm^{-2}) and winter (201.60 ± 4.7 Wm^{-2}). During summer, autumn, winter and spring the maximum (minimum) SW_{Flux} was in Northern Cape, 357.57 ± 7.51 Wm^{-2} (KwaZulu-Natal, 288.714 ± 10.02 Wm^{-2}), Limpopo, 235 ± 4.61 Wm^{-2} (Eastern Cape, 199.74 ± 11.36 Wm^{-2}), Limpopo, 201.60 ± 4.39 Wm^{-2} (Western Cape, 141.31 ± 8.57 Wm^{-2}), and Northern Cape, 310.40 ± 6.9 Wm^{-2} (KwaZulu-Natal, 264.41 ± 10.76 Wm^{-2}), respectively, as shown in Figure 4. Most areas in the Northern Cape during the winter showed less amount of SW_{Flux} .The monthly mean of SW_{Flux} with SD for 1980–2009 in the nine provinces is presented in Table 2, which shows that during the winter and autumn months Limpopo had higher SW_{Flux} than other provinces. Present studies of SW_{Flux} results on annual and seasonal scale show similarity to the maps generated using the United States National Renewable Energy Laboratory database (Fluri, 2009). These maps show that the solar radiation was higher in Northern Cape during summer and spring and lower in winter. The monthly mean values of SW_{Flux} (1980-2009) with SD are presented in Table 2. In almost all the provinces the SW_{Flux} was higher in December and lower in June.

4.3 Spatial variation of SW_{Flux} over three decades

SW_{Flux} was analysed spatially over the three decades of the datasets – the 1980s, 1990s and 2000s (Figure 5). SW_{Flux} in Northern Cape was higher than in any other province in all three

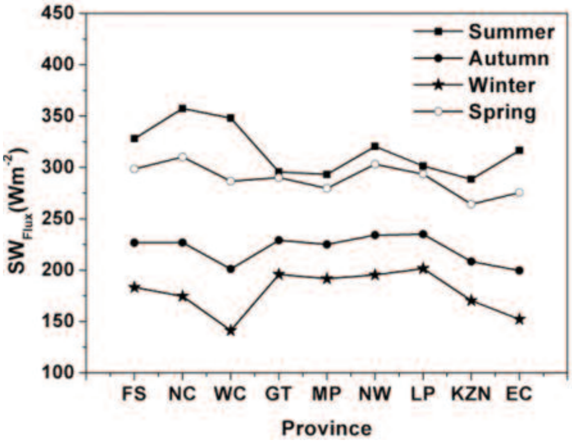

Figure 4: Seasonal variation of surface incident shortwave flux (SW_{Flux}), Wm^{-2} in the nine provinces of South Africa. (FS, NC, WC, GT, MP, NW, LP, KZN and EC stand respectively for Free State, Northern Cape, Western Cape, Gauteng, Mpumalanga, North West, Limpopo, KwaZulu-Natal and Eastern Cape).

Table 2: Monthly mean of surface incident shortwave flux, Wm^{-2} with a standard deviation (SD) for 1980–2009 in the nine provinces of South Africa.

	SW_{Flux} (Mean ±SD)					
Province	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
Free State	334.45 ± 16.57	305.80 ± 8.36	270.28 ± 3.97	225.09 ± 3.60	184.94 ± 5.54	163.31 ± 6.03
Northern Cape	366.74 ± 8.41	330.39 ± 7.31	279.72 ± 5.12	223.46 ± 8.61	177.27 ± 11.56	153.94 ± 12.59
Western Cape	359.65 ± 11.46	319.92 ± 12.70	261.91 ± 11.65	195.73 ± 9.81	145.71 ± 8.77	121.94 ± 7.84
Gauteng	297.93 ± 5.37	285.93 ± 2.90	260.82 ± 2.99	229.67 ± 1.06	197.02 ± 1.28	177.01 ± 1.82
Mpumalanga	325.53 ± 3.14	286.72 ± 3.87	258.23 ± 3.32	224.53 ± 4.35	192.55 ± 4.25	173.56 ± 4.29
North West	325.53± 16.50	300.26 ± 9.77	271.14 ± 5.73	234.22 ± 2.37	196.98 ± 3.30	175.69 ± 3.47
Limpopo	304.72 ± 2.70	294.37 ± 4.39	267.59 ± 4.38	234.93 ± 4.91	202.48 ± 4.54	183.21 ± 3.82
KwaZulu-Natal	291.84 ± 9.83	277.56 ± 8.78	246.21 ± 8.77	207.06 ± 8.52	172.13 ± 7.85	152.87 ± 7.38
Eastern Cape	324.41 ± 19.17	291.27 ± 14.21	248.47 ± 11.67	196.00 ± 11.11	154.00 ± 11.30	133.03 ± 11.02
	July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Free State	174.53 ± 6.16	212.17 ± 4.76	264.44 ± 3.74	299.65 ± 6.32	331.56 ± 12.86	344.23 ± 17.85
Northern Cape	164.82 ± 12.07	205.33 ± 11.80	261.02 ± 9.65	314.41 ± 5.65	355.76 ± 5.43	375.58 ± 6.81
Western Cape	131.78 ± 8.61	170.58 ± 9.26	229.78 ± 9.41	291.69 ± 10.39	338.63 ± 10.43	365.10 ± 11.00
Gauteng	187.96 ± 1.69	223.07 ± 1.51	270.49 ± 0.99	294.46 ± 2.04	305.63 ± 5.79	303.35 ± 7.13
Mpumalanga	183.88 ± 04.68	217.58 ± 05.28	261.84 ± 06.38	284.33 ± 06.24	293.24 ± 06.74	295.68 ± 05.96
North West	186.90 ± 03.50	223.97 ± 02.80	273.58 ± 02.06	305.86 ± 04.94	330.08 ± 13.18	336.19± 18.52
Limpopo	193.37 ± 04.33	228.22 ± 05.04	272.31 ± 05.95	301.59 ± 06.48	306.96 ± 6.84	305.62 ± 5.29
KwaZulu-Natal	162.67 ± 08.01	195.61 ± 09.17	238.45 ± 11.29	267.42 ± 09.56	287.35 ± 11.42	296.75 ± 11.45
Eastern Cape	143.85 ± 11.42	179.89 ± 12.80	231.28 ± 13.11	279.38 ± 12.91	316.07 ± 14.82	334.25 ± 18.46

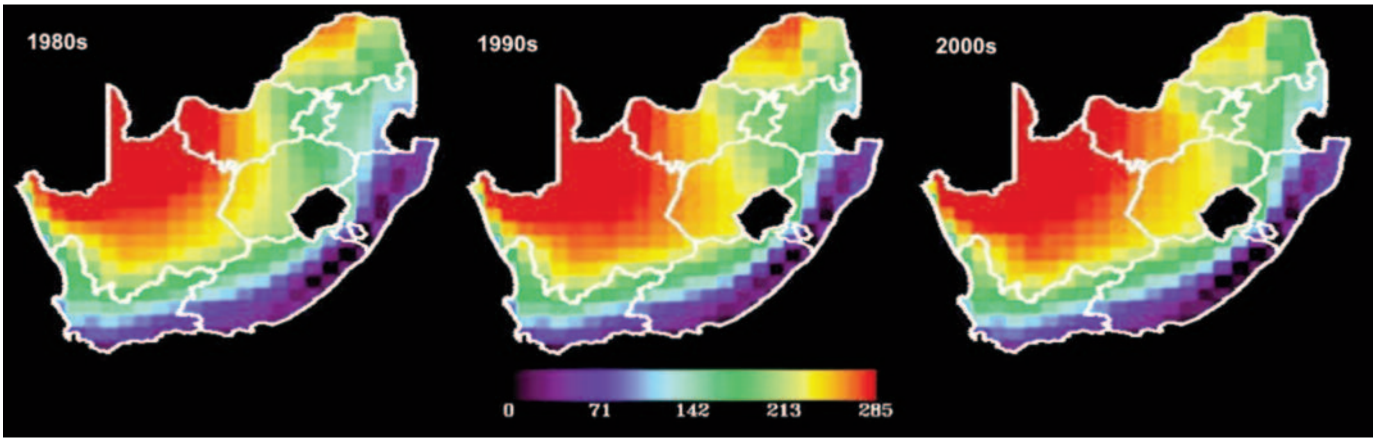

Figure 5: Spatial variation of SW_{Flux} (surface incident shortwave flux, Wm^{-2}) in the last three decades over South Africa.

Table 3: Mean SW_{Flux} (surface incident shortwave flux, Wm^{-2}) with a standard deviation in the last three decades over South Africa.

Province	***1980s***	***1990s***	***2000s***
		(Mean ±SD)	
Free State	259.27 ± 11.90	260.00 ± 4.93	258.34 ± 4.66
Northern Cape	269.44 ± 5.60	267.21 ± 3.26	265.49 ± 2.33
Western Cape	245.47 ± 4.73	244.17 ± 2.04	243.37 ± 1.40
Gauteng	251.46 ± 9.88	254.19 ± 5.94	252.69 ± 6.51
Mpumalanga	246.46 ± 8.50	249.48 ± 4.85	246.53 ± 5.71
North West	265.56 ± 9.66	262.62 ± 5.82	261.92 ± 5.33
Limpopo	259.98 ± 5.05	259.61 ± 6.08	254.24 ± 6.07
Kwa Zulu-Natal	233.48 ± 11.12	233.90 ± 4.07	231.59 ± 3.98
Eastern Cape	237.12 ± 9.22	237.29 ± 2.98	233.76 ± 3.57

decades, the 1980s (269.44 ± 5.60 Wm^{-2}), the 1990s (267.21 ± 3.26 Wm^{-2}) and the 2000s (265.49 ± 2.33 Wm^{-2}) (Table 3). The spatial variation of SW_{Flux} show that the amount of solar radiation decreased each decade, a trend shared by other five provinces (North West, Limpopo, KwaZulu-Natal and Eastern Cape) (Figure 5). This could be attributed to increasing air pollution, which reduces the amount of solar radiation reaching the earth's surface (Gan et al., 2014, Singh et al., 2012).

4.4 SEPR for the nine provinces of South Africa

SEPR was calculated on annual, seasonal and monthly scales. Annually, the Northern Cape ranked first, followed by North West (Table 4). Seasonally the North West ranked first, followed by Northern Cape and Limpopo. The monthly scale showed that North West again ranked first, followed by Limpopo. KwaZulu-Natal did not performed well on annual, seasonal and monthly. The good solar energy potential of Northern Cape was reported previously (Fluri, 2009). The present study found that North West and Limpopo also showed good solar energy potential (Table 4). Concentrating solar power and PV are important for harvesting solar radiation from the recognised high solar energy potential areas.

5. Conclusions

In order to contribute to better understanding the solar energy potential of different provinces of South Africa, annual, seasonal, and monthly variability in SW_{Flux} was studied using MERRA 2D data (1980–2009). On an annual scale, SW_{Flux} was found to be the highest for Northern Cape (267.4 ± 4.32 Wm^{-2}), followed by North West (263.3 ± 7.13 Wm^{-2}) and Free State (259.2 ± 7.66 Wm^{-2}). Seasonal scale SW_{Flux} was highest in Northern Cape only during summer (357.57 ± 7.51 Wm^{-2}) and spring (310.40 ± 6.9 Wm^{-2}). Limpopo had the highest value of SW_{Flux} in winter and spring; and some of its areas also received a good amount of solar radiation that could serve as good sites for solar energy based applications. SEPR analysis showed that the Northern Cape ranked first on an annual basis, while North West ranked first in seasonal and monthly analyses. The amount of SW_{Flux} over Northern Cape was high. However, North West, Limpopo and Free State also received good amount of solar radiation.

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Table 4: Solar energy potential number (SEPN), total solar energy potential number (TSEPN), and solar energy potential rank (SEPR) on annual, seasonal and monthly scales in the nine provinces of South Africa.

	Free State	*N. Cape*	*W. Cape*	*Gauteng*	*Mpumalanga*	*North West*	*Limpopo*	*KwaZulu-Natal*	*E. Cape*
$\text{SEPN}_{\text{Annual}}$	3	1	7	5	6	2	4	9	8
$\text{TSEPN}_{\text{Annual}}$	3	1	7	5	6	2	4	9	8
$\text{SEPR}_{\text{Annual}}$	3	1	7	5	6	2	4	9	8
$\text{SEPN}_{\text{Summer}}$	3	1	2	7	8	4	6	9	5
$\text{SEPN}_{\text{Autumn}}$	5	4	8	3	6	2	1	7	9
$\text{SEPN}_{\text{Winter}}$	5	6	9	2	4	3	1	7	8
$\text{SEPN}_{\text{Spring}}$	3	1	6	5	7	2	4	9	8
$\text{TSEPN}_{\text{Seasonal}}$	16	12	25	17	25	11	12	32	30
$\text{SEPR}_{\text{Seasonal}}$	3	2	5	4	5	1	2	7	6
SEPN_{Jan}	3	1	2	7	8	4	6	9	5
SEPN_{Feb}	3	1	2	8	7	4	5	9	6
SEPN_{Mar}	3	1	5	6	7	2	4	9	8
$\text{SEPN}_{\text{April}}$	4	6	9	3	5	2	1	7	8
SEPN_{May}	5	6	9	2	4	3	1	7	8
$\text{SEPN}_{\text{June}}$	5	6	9	2	4	3	1	7	8
$\text{SEPN}_{\text{July}}$	5	6	9	2	4	3	1	7	8
SEPN_{Aug}	5	6	9	3	4	2	1	7	8
$\text{SEPN}_{\text{Spet}}$	4	6	9	3	5	1	2	7	8
SEPN_{Oct}	4	1	6	5	7	2	3	9	8
SEPN_{Nov}	3	1	2	7	8	4	6	9	5
SEPN_{Dec}	3	1	2	7	9	4	6	8	5
$\text{TSEPN}_{\text{Monthly}}$	47	42	73	55	72	34	37	95	85
$\text{SEPR}_{\text{Monthly}}$	4	3	7	5	6	1	2	9	8

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