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CONFERENCE PAPERS

Reliability benefit of smart grid technologies: A case for South Africa

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Abstract
The South African power industry faces many challenges, from poor performing networks, a shortage of generation capacity to significant infrastructure backlog and an ageing work force. According to the Development Bank of South Africa (DBSA), the key challenge facing the industry is ageing infrastructure. Smart grid technologies are a class of technologies that are being developed and used by utilities to deliver electrical systems into the 21st century using computer-based remote control and automation. The main motive towards smart grid technologies is to improve reliability, flexibility, accessibility and profitability; as well as to support trends towards a more sustainable energy supply. This study identifies a number of smart grid technologies and examines the impact they may have on the distribution reliability of a test system. The components on the selected test system are the same as those found on a South African feeder. The bulk of the load in test system was modelled using load data collected in South Africa. This study will consider a number of different cases, with the base case incorporating the impact of aged infrastructure on the reliability of the system. The smart grid technologies were then introduced into the system and their impact on distribution reliability was determined. These different cases were also compared to the alternative of replacing the aged and worn out infrastructure with new infrastructure. The findings of this study indicate that the identified smart grid technologies improve the reliability of the system, mainly by decreasing the outage duration experienced by customers on the network. An even better performance was achieved when the ageing infrastructure was replaced with new infrastructure.

Keywords: distribution reliability, smart grid, feeder automation

1. Introduction

The distribution sub-system in South Africa, much like many other countries in the world, is still based on 20th century technology (DBSA, 2012). According to NELT (2007) and SANEDI (2012a), 20th century technology cannot efficiently sustain a 21st century economy, and power networks need to be 'modernized'. A report released in 2007 by the National Energy Regulator of South Africa (NERSA) on the state of the Electricity Distribution Industry (EDI) infrastructure, indicated that although there were pockets of good performance, assets needed urgent rehabilitation and investment (NERSA, 2007). A study conducted in 2008 by EDI Holdings on the state of the distribution grid of the country, revealed that the distribution grid infrastructure was ageing and poorly maintained, and that its state was steadily deteriorating. The study estimated that the maintenance, refurbishment and strengthening backlog in the distribution grid amounted to about 27.4 billion 2008 South African Rand (2008 ZAR). This backlog was growing at an alarming rate of 2.5 billion ZAR per annum (EDI Holdings, 2008). The same study pointed out that the current practices in the EDI do not promote business sustainability and economic growth. It also highlighted the fact that the increased use of an under-maintained distribution grid could be a potential risk to the industry.

A more recent report released in 2012 by the Development Bank of South Africa (DBSA) on the State of South Africa's Economic Infrastructure, identified ageing infrastructure as the key challenge for the electricity generation, transmission and distribution sectors. The other challenges faced in the South African power industry include: poor performance networks, shortage of generation capacity, significant infrastructure backlog, ageing work force, inability to effectively introduce renewable energy options into the grid, and the inability to effectively introduce demand response strategies (SANEDI, 2012b).

The term 'smart grid' refers to a class of technologies that are being developed and used by utilities to deliver electrical systems into the 21st century using computer-based remote control and automation (NELT, 2007). Smart grid technologies have been proposed as one of the possible means of implementing new technologies and techniques into the grids of different countries (SANEDI, 2012a). The main motive towards smart grid technologies is to improve reliability, flexibility, accessibility and profitability; as well as to support trends towards a more sustainable energy supply (Slootweg, 2009).

This paper will focus on the improvement smart grid technologies could have towards improving distribution reliability.

2. Distribution reliability

Reliability may be defined as the probability of a system performing its required tasks, adequately for a period of time and under set operating conditions (Billinton & Allan, 1992). This definition in itself highlights the uncertainty surrounding the ability of the power system to perform as desired, and therefore, the purpose of power system reliability evaluation and assessment, is to try and quantify the reliability of a system for planning and decision making.

Reliability indices are used extensively in the power system industry as a means to quantify and assess reliability. Reliability indices measure the frequency, duration and severity of disturbances on the network and give insight into the performance of the system. These indices can be regarded as being predictive indices or past performance indices. The indices considered in this study are System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Momentary Average Interruption Frequency Index (MAIFI) and Expected Energy Not Supplied (EENS). These indices are calculated as follows (Billinton & Allan, 1994; Brown, 2006):

$$\text{SAIDI} = \frac{\text{sum of customer interruption duration}}{\text{total number of customers}} \quad (1)$$

$$\text{MAIFI} = \frac{\text{total no customer momentary interruptions}}{\text{total number of customers served}} \quad (2)$$

$$\text{SAIFI} = \frac{\text{total no customer sustained interruptions}}{\text{total number of customers served}} \quad (3)$$

$$\text{EENS} = \Sigma\, L_i\, r_{i,j} \lambda_{i,j} \quad (4)$$

where: L_i is the average load at load point i
$r_{i,j}$ is the outage duration of load point i due to the failure of load point j
$\lambda_{i,j}$ is the failure rate of load point i due to the failure of load point j

In this study, a momentary interruption is defined as an interruption with duration greater than 3 seconds but not longer than 5 minutes, as defined by the NRS 048-6:2006 specification for the Electricity Supply Industry for medium voltage (MV) and low voltage (LV) systems (Chatterton *et al.,* 2006).

3. Smart grid technologies

Smart grid technologies refer to a group of improved technologies and concepts, that use digital and other advanced technologies, to monitor and manage the transmission of electricity from all generation sources, to meet the varying electricity demands of end users (IEA, 2011). In a broad sense, a "smart grid" refers to a conventional electric power system equipped with these technologies for the purpose of reliability improvement, ease of control and management, integrating of distributed energy resources and electricity market operations.

One of the most appealing advantages of smart grid technologies is the reduced reaction and restoration time. This is most apparent when a fault has occurred. Ordinarily when a disturbance causes a fault on the network, grid operators are unable to identify the exact location of the faulted section of the feeder. The repair crew are dispatched, and have to perform trial and error switching actions on circuit breakers and isolators, in an effort to find the exact location of the fault. This can take a considerable amount of time during the day and more especially at night or during unfavourable weather conditions, resulting in an increased outage duration (Kazemi, 2011). There are a number of smart grid technologies which have been developed in order to reduce the fault location time. These are discussed below:

i) Distance to fault estimator

Fault locators reduce the impact of faults as they speed up the restoration process, by allowing isolating and switching operations to be performed much faster (Morales-España et al., 2009). Distance to fault estimators, are an optional module of modern distribution protection equipment which can be used for estimating the fault location. When a fault occurs, this module calculates the fault location as a distance from the substation to the fault. It can also notify the control centre or utility repair crew of this information crew using a suitable communication medium. By using distance to fault estimators, a much smaller zone of the distribution network is inspected for faults. However, when a feeder has multiple taps, there might be several probable fault locations for the fault distance indicated by this module. In order to overcome this problem, distance to fault estimators should be used in conjunction with fault passage indicators (Kazemi, 2011).

ii) Fault passage indicators

Fault passage indictors are devices which are located at strategic points along the feeder, and are designed to indicate whether fault current has passed that particular point. They are usually installed at points where switching decisions can be made. Fault passage indicators are able to distinguish between fault current and load current. Several fault passage indicators installed along a feeder will enable quick identification of the passage of fault current. The status of these devices can be recognized remotely or by visiting its physical location. In the past, fault passage indicators could only be used in radial distribution networks, but there are new generation fault passage indicators which can be used in other electricity distribution networks (Newman, 1990; Kazemi, 2011; Nortech, 2013).

iii) Feeder automation

Feeder automation is an automatic control scheme that is used for automatic fault location, isolation, and service restoration (FLISR) in an electricity distribution network. Utilizing modern computer technology, micro-electronics and communication technology, modern feeder automation technologies conduct operations and risk assessments, in order to make decisions regarding the operation of the distribution feeders and the distribution grid as a whole (Huang *et al.*, 2012).

An automated grid is self-healing and recovers quickly from faults. When a permanent fault occurs, the customers affected by the fault may be categorized into two groups. The first group of customers are those who will have to wait until the faulted feeder section has been repaired. The second group includes those customers whose power supply has been interrupted, but can be restored through the main or alternate supplies by means of switching and isolating healthy and faulted feeder sections (Kazemi, 2011). In most cases, the second group is larger than the first group (Uluski, 2010; Kazemi, 2011).

In the case of manually operated distribution systems and feeders, the fault isolation and service restoration activities can only be done after the fault has been located. However, feeder automation can reduce the outage duration and restore supply to as many customers as possible by performing FLISR automatically. Automatic FLISR can restore service to customers in one minute or less, resulting in significant reliability improvement compared to traditional manual switching (Uluski, 2010; Kazemi, 2011).

4. Experiment design

4.1 Reliability model

The reliability model is required to evaluate the system indices, which give an indication on the reliability of a network.

i) Test system

A suitable test was needed and the RBTS (Roy Billinton Test System) was selected. Although it is not a South African test system, its system components are similar to those of the South African power system. It contains all the major elements of a distribution system and its simplicity allows for analysis using simulation techniques. Other advantages of the RBTS include the fact that is best suited for educational purposes; it is used extensively in research and it is well defined. Feeder 1 (F1) of bus 6 of the RBTS was selected. It is shown in Figure 1 (Billinton & Jonnavithula, 1996). The feeder components include overhead lines (O1 to O12), MV/LV transformers (T1 to T6), disconnector switches (S1 to S5) and load points (LP1 to LP6).

ii) Simulation technique

The time sequential Monte Carlo Simulation (MCS) technique selected for the evaluation of reliability. The availability of high speed computing facilities make it a more viable option because MCS yields more information on load point and system indices. Time sequential MCS is flexible and has a high reality potential. MATLAB, a high level technical computing language was used to execute the MCS. The

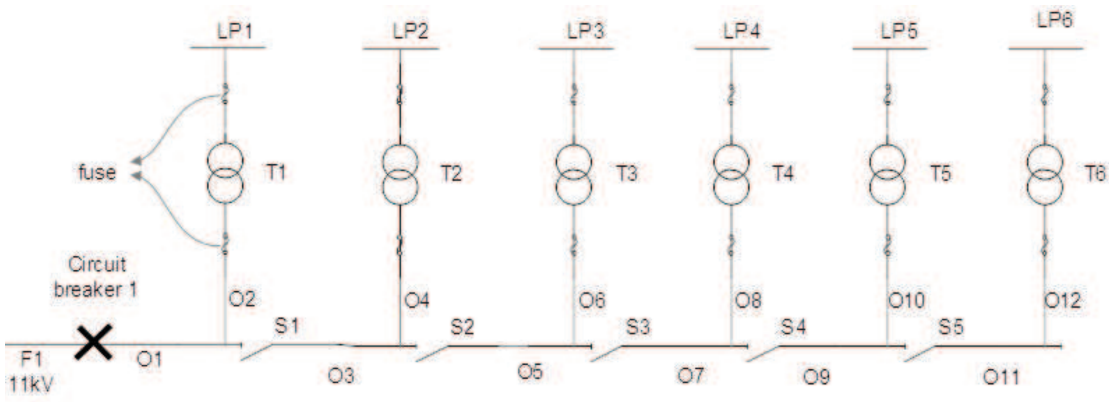

Figure 1: Diagram of selected test system – (Feeder 1 of Bus 6)
(Billinton & Jonnavithula, 1996)

simulation algorithm adopted, was based on the technique developed by Billinton & Wang (1999).

The failure rates for the different system components in the MCS are given in Table 1. The input parameters for the reliability study are given in Table 2.

Table 1: Component failure rates
(Allan et al., 1991)

System component	*Failure rate*
Circuit breaker 1	0.006 (failures/yr)
O1-O12	0.065(failures/yr.km)
T1-T6	0.259 (failures/yr)

Table 2: Input parameters

Input parameter	*Average (hours)*
Time To Locate Fault (TTLF)	1.5
Repair time (RT)	
overhead lines	5
breaker	4
transformer	200
Switching time	1
Reclosing time	1minute

4.2 Load model

The incorporation of a load model, allowed for the determination of how much energy was not supplied to customers as a result of the interruptions.

The customer load model was developed using data from the RBTS data sheet and NRS data collected in South Africa. This study only considered residential and commercial customers. The customers at each load point were defined as shown below.

Table 3: Customer distribution of test system

Load point	Number and type of customers
1	138 Residential
2	126 Residential
3	138 Residential
4	126 Residential
5	118 Residential+2 Commercial
6	118 Residential+3 Commercial
Total	**764 Residential+5 Commercial**

i) Residential load profile

NRS Load Research data was used in the development of a realistic residential load model, which could represent the load consumption of a South African household. NRS Load Research data comprises of the load consumption data collected in 5 minute intervals for different residential households in different locations in South Africa. This data was collected between 1994 and 2003.This data was used to develop a profile of the load consumption in amperes (A) of a residential customer residing in Claremont, Johannesburg, South Africa.

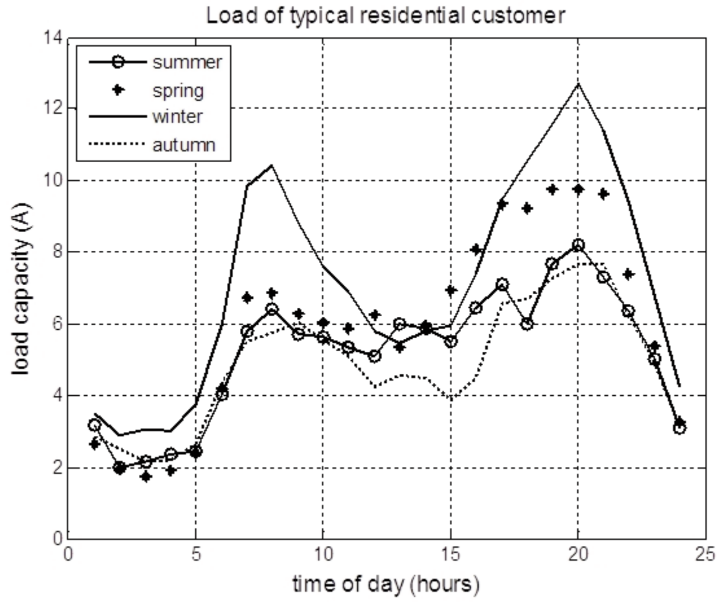

Figure 2: Residential 2oad profile
(NRS Load Research Group, 1994-2003)

ii) Commercial load profile

There are 5 identical commercial customers on the feeder. There are 3 commercial customers on LP5 and the remaining 2 on LP6. All 5 were assumed to be in the retail business. The loads of the commercial customers were time dependent and remained the same regardless of the season of year. The load of these customers was based on data given with the RBTS and this is indicated in Table 4.

Table 4: Commercial customer load profile
(Billinton & Jonnavithula, 1996)

Time of day	*Load per commercial customer (MW)*
00:00 -07:59	0.0497
08:00-17:00	0.085
17:00-23:59	0.0497

4.3 Cases

Six different cases were considered in this study. The abbreviated names of the different cases are given in parenthesis. In each case, an input value(s) from Table 1 and/or Table 2 was changed. All the six cases and the change(s) in input parameters for each case are discussed below:

i) Case 1: aged transformers (aged tr)

This is the base case to which all other cases will be compared.

The effect of aged equipment was incorporated into the system. The reason is that ageing infrastructure was outlined by the DBSA as the leading challenge facing the electricity industry. The effect of ageing was incorporated in the form of aged transformers. Transformers represent a significant cost to the electric utilities, both as a capital investment and as an ongoing operating expense. They can account for up to 20% of the total distribution capital spending per annum (Van Zandt & Walling, 2004). As transformers age, their internal condition deteriorates, increasing the risk of failure (Wang *et al.*, 2002; Bartley, 2011). According to Bartley (2011), ageing transformers are a huge risk to the electric power supply and could cause major losses.

All the transformers in this case were assumed to be aged and worn out. The average failure rate of transformers in this case was 0.259 failures/year based on data collected by Jagers & Tenbohlen (2009) on distribution transformers in South Africa.

ii) Case 2: Fault passage indicators and distance to fault estimators (FPI & DFE)

This case investigated the effect of fault passage indicators and distance to fault estimators on the system performance of the base case. These smart grid technologies assist in the location of faults after an interruption has occurred. Therefore, for this case the input parameter, TTFL, was reduced to an average of 0.5 hours (Kazemi, 2011).

iii) Case 3: Feeder automation (feeder auto)

The impact of feeder automation was investigated in this case. Feeder automation implemented automatic FLISR. This procedure results in a decrease in both the fault location time and switching time. In this case TTLF and switching time both had an average duration of 30 seconds (Uluski, 2010).

iv) Case 4: new transformers (new tr)

Case 4 investigated the performance of the system if all the transformers in the system were to be replaced with new transformers. Hence, a decreased average transformer failure rate of 0.035 failures/year (Jagers & Tenbohlen, 2009) was used in this case.

v) Case 5: new transformers, fault passage indicators, distance to fault estimators (new tr & FPI and FDE)

This case considered the inclusion of new transformers, fault passage indicators and distance to fault estimators. The purpose of this case is to determine the impact of fault passage indicators and distance to fault estimators on a network with non-aged transformers.

vi) Case 6: new transformers and feeder automation (new tr & feeder auto)

This case considered the inclusion of both new transformers and feeder automation.

5. Results and analysis

5.1 SAIDI

The results of SAIDI for the different cases described above are given in Table 5. SAIDI gives an indication of the average number of hours each customer on the feeder experiences with no electricity supply in a calendar year due to a component in the network failing.

Table 5: SAIDI results

SAIDI (hours/customer year)		
Case	*Magnitude*	*Percentage difference*
1. aged tr (base case)	9.10	-
2. FPI & DFE	8.83	-2.9%
3. feeder auto	8.19	-10.0%
4. new tr	0.27	-97.0%
5. new tr & FPI & DFE	0.24	-97.3%
6. new tr & feeder auto	0.20	-97.8%

From Table 5, it is evident that the base case has the highest magnitude of SAIDI. A decrease in SAIDI is experienced when fault passage indicators and distance to fault estimators are introduced into the system. These smart grid technologies assist in decreasing the time it takes the repair crew to locate a fault. The impact of this is reflected in the decrease in SAIDI.

An even greater decrease is realised when feeder automation is implemented. Feeder automation detects and isolates faults within 1 minute, allowing customers whose energy supply can be immediately restored via switching, to be reconnected in a shorter period of time. It also facilitates in the quick identification of faults to be attended to by the repair crew. These operations are responsible for the decrease in SAIDI. For example, previously in the base case, the failure of component O7 from Figure 1, would result in customers of LP1 incurring an outage of about 2.5 hours but with the implementation of automatic FLISR, this duration is reduced to 1 minute.

Case 4 explored replacing the aged transformers with new transformers, which have a much lower failure rate. From Table 5, it is observable that a large decline in SAIDI is experienced from the base case to case 4. The main reason is the failure rate of the transformers. The transformers in the base case are assumed to be worn out and aged, and therefore they are more prone to failure. Transformers also have the longest repair time of about 200 hours, followed by overhead lines, with a repair time of about 5 hours. Therefore, a decreased transformer failure rate, as experienced in the case 4, results in a tremendous decrease in the outage duration experienced by customers. This drastic decrease in outage duration is reflected in SAIDI.

The incorporation of the selected smart grid technologies and new transformers was explored in cases 5 and 6. A further decrease in SAIDI from case 4 was experienced, but the bulk of the decrease is attributed to the implementation of the new transformers.

5.2 SAIFI & MAIFI

The results of SAIFI for the different cases are given in Table 6. SAIFI is the average number of sustained interruptions each customer on the feeder experiences in a calendar year due to a component in the network failing. The magnitude of the frequency of momentary interruptions, MAIFI, is depicted in Table 7.

Table 6: SAIFI results

SAIFI (interruptions/customer year)		
Case	*Magnitude*	*Percentage difference*
1. aged tr (base case)	0.73	-
2. FPI & DFE	0.73	0%
3. feeder auto	0.49	-32.8%
4. new tr	0.56	-23.3%
5. new tr & FPI & DFE	0.56	-23.3%
6. new tr & feeder auto	0.34	-53.4%

Table 7: MAIFI results

Case	*Magnitude*
1. aged tr (base case)	0.00
2. FPI & DFE	0.00
3. feeder auto	0.23
4. new tr	0.00
5. new tr & FPI & DFE	0.00
6. new tr & feeder auto	0.22

The highest magnitude of SAIFI is experienced in the base case. The magnitude of MAIFI in the base case is 0, meaning all interruptions experienced in this case were sustained. The implementation of passage indicators and distance to fault estimators had no impact on SAIFI and MAIFI. These two technologies do not affect the state or condition of the main system components, but instead assist in the location of faults, after an interruption has occurred. They do not help to prevent the occurrence of faults. Therefore, no impact on both SAIFI and MAIFI is observed in case 2. On the other hand, the implementation of feeder automation resulted in a decrease in SAIFI and an increase in MAIFI. Feeder automation implements fault detection, location and isolation. It then restores electrical energy supply to customers who need not be disconnected from the main supply. This group of customers instead experience a momentary interruption, where they previously would have experienced a sustained interruption. Therefore, the implementation of feeder automation sees a decrease in SAIFI and an increase in MAIFI.

The magnitude of SAIFI in the case 4, where new transformers were introduced into the system, is much lower than that of the base case. This is attributed to avoided interruptions due to the decreased transformer failure rate of the new transformers. No momentary interruptions were experienced in case 4. The magnitude of both SAIFI and MAIFI in case 5 is the same as that of cases 2 and 4. As already mentioned, fault passage indicators and distance to fault estimators, have no impact on the frequency of interruptions, therefore, the addition of these technologies to case 4, would result in no impact to both SAIFI and MAIFI as observed in case 5.

SAIFI in case 6 dropped to less than half its magnitude in the base case. The implementation of new transformers resulted in avoided interruptions, whereas feeder automation increased momentary interruptions and decreased sustained interruptions by carrying out FLISR.

5.3 EENS

Table 8 compares the average amount of energy not supplied to the customers on the feeder in one calendar year.

Table 8 EENS results

EENS (kWh/ year)		
Case	*Magnitude*	*Percentage difference*
aged tr (base case)	58 848.92	-
FPI & DFE	54 555.47	-7.30%
Feeder auto	53 656.91	-8.80%
new tr	11 392.73	-80.6%
new tr & FPI & DFE	10 923.03	-81.4%
new tr & Feeder auto	9 434.54	-83.9%

The base case has the highest EENS because the EENS is directly related to the outage duration as given in equation 4. Therefore, the greater the decrease in outage duration and failure frequency, the greater the decrease in EENS. Once the aged transformers in the system were replaced with new transformers, a decrease of about 80% was realized in the unsupplied energy. The further integration of smart grid technologies into the system with new transformers, results in an additional but smaller decrease in the EENS magnitude.

The EENS represents the amount of energy that the customer could have consumed, but could not because they were disconnected from supply. This could translate to different things for different sectors. For example in the commercial sector it could mean a loss of sales and for the industrial sector, it could translate to the loss of production.

6. Conclusions

In this study, the reliability benefit of a number of smart grid technologies was examined. A feeder containing all the fundamental components of a distribution grid i.e. fuses, transformers, overhead lines, circuit breaker and disconnector switches, was selected from the RBTS and used as a test system. The load of the system consisted of mainly residential customers and a few commercial customers. The loads of the residential customers were defined using load data collected in South Africa. A number of cases were considered where the identified smart grid technologies were implemented. These were compared to the base case which contained aged transformers, since ageing was identified as the key challenge the South Africa power industry is facing.

The key findings of this study point to following:

i) The high failure rate of the transformers in the base case contributed significantly to the failure frequency. This is clearly indicated by the decline in SAIFI when these aged transformers are replaced with new transformers. The aged transformers also significantly increased the outage duration because the average repair time of the transformers is very large (about 200 hours) compared to that of the other components in the system. This observation was apparent in the comparison of SAIDI for the base case and case 3. Each time a transformer failed, an outage duration equivalent to the repair time of 200 hours was incurred. This drastically increased SAIDI.

ii) Distance to fault estimators and passage fault indicators do not have an impact on SAIFI. This is because these technologies do not contribute towards the prevention of faults. On the other hand, feeder automation has a positive impact on SAIFI and MAIFI. Feeder automation resulted in a significant decrease in SAIFI and an increase in MAIFI. The main reason for this would be the speed at which feeder automation locates and isolates faults and then restores customers not directly impacted by a fault. This group of customers, not directly impacted by a fault, would experience a momentary interruption instead of a sustained interruption.

iii) The identified smart grid technologies had an impact on the reduction of TTLF. This impact was carried through to SAIDI. Feeder automation had a more of an impact on SAIDI than the distance to fault estimators and fault passage indicators. Feeder automation prevents customers not directly impacted by the failure of a component from experiencing a sustained interruption. Therefore, a potential outage duration of about 2.5 hours for a customer was reduced to 1 minute.

iv) The decrease in feeder outage duration, as a result of the implementation of the identified smart grid technologies, is carried through to the EENS of the feeder. The cases with higher outage duration also experienced a higher EENS, because it is dependent on outage duration.

v) The findings have highlighted that the identified smart grid technologies have no impact on the frequency and rate of interruptions, but decrease the total outage duration of the feeder. They also pinpointed that a network with aged infrastructure has a much higher failure rate, and that this increase is carried through to the increased outage duration of the system. When the aged transformers were replaced with new transformers, the SAIDI, SAIFI and EENS decreased drastically and with some of these indices, it more than halved. None of the selected smart grid technologies had as much of a positive impact on the system reliability as the new transformers. This therefore stresses the importance of first identifying and correcting the root causes of the underlying problems in the system before investing in further technologies, which may not address these fundamental problems adequately.

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Low-income resident's preferences for the location of wind turbine farms in the Eastern Cape Province, South Africa

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1. Insight Analysis
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Abstract
There is a general consensus that South Africa should be generating more power through harnessing renewable energy resources, such as wind power. However, there is no consensus with regard to the location of such generating projects. This paper describes a wind farm project proposed for development in the Kouga Local Municipality, reports low-income local residents' preferences on its nature and applies choice modelling to analyse these preferences. A questionnaire was presented to each respondent, the discrete choice experiment component of the questionnaire included two different onshore wind energy development scenarios and a status quo option. The scenarios differed by the combination of four elements: the distance of the wind turbines from residential areas, job creation, the number of turbines and a subsidy allocated to each household.
Keywords: wind, energy, underprivileged, welfare, preference, choice

1. Introduction

South Africa is the 12th largest emitter of greenhouse gasses in the world and responsible for almost half of all emissions in Africa (EDF, 2014) in large part because the majority of electricity in South Africa is produced from coal. In order for South Africa to reduce its carbon emissions and comply with the UN Framework Convention on Climate Change and the Kyoto Protocol, Eskom, its leading electricity supplier, is committed to diversifying its energy mix (DEA, 2011; SAinfo Reporter, 2008; UNEP, 2009; Gets & Mlanga, 2013). The quest to reduce carbon emissions has led to a drive to increase the percentage of energy produced by renewable and sustainable sources. The most prominent of these sources today is wind energy. There are wind farms currently being developed in South Africa in both the Western Cape and Eastern Cape provinces of South Africa.

The reason wind is favoured as a source for the generation of electrical energy is because wind resources are easily harnessed through the use of wind turbine technology (Edkins, Marquard & Winkler, 2010). By the end of 2010, wind energy projects in South Africa had an installed capacity of 10 MW (WWEA, 2011). The goal of the South African government was to generate approximately 10 000 GWh of electricity through renewable energies by 2013 (Edkins *et. al.* 2010; Eskom, 2015). This would require the installed capacity of wind power to be increased dramatically. The introduction of a Renewable Energy Feed-In Tariff (REFIT) in 2009 incentivised independent power producers to propose different renewable power projects throughout South Africa. Several of these proposals have caused concern for coastal communities. The majority of these concerns are environmental and location related.

Their concerns are that wind turbines may (Binopoulos & Haviaropoulos, 2010):

- increase road development in ecologically sensitive areas;
- detract from the visual appeal of an area, thus affecting real estate values, and impacting a region's culture and heritage;
- increase industrial noise in the area in which they are erected;
- negatively impact on fauna and flora, e.g., discourage bird migration into the area; and
- reduce other development opportunities, e.g. flight paths for airports.

The negative externalities of wind energy are of greatest concern to the communities in the vicinity of the wind farms – this is because wind turbines are site specific (Pasqualetti, 2011). These communities may also derive benefits from wind energy in the form of employment creation, increased electricity supply and increased tourism to the area. The communities that are located nearest to big industry developments (factories, power stations etc.) are characterised as poor or low income or underprivileged (Siegfried, 2014; PRB, 1998). Such locations may be chosen by pure coincidence. Or, it may be that these communities tend to underestimate the negative environmental costs related to these projects, relative to the new jobs prospect benefit claimed for such developments, thus more easily enabling development in these areas than in more well-to-do areas. Whatever, the case, the preferences of low income residents and how their happiness is influenced by various features of wind farm construction near their places of residence clearly matter. For this reason, this paper has selected to focus attention on this issue.

A number of studies have been conducted to assess the positive and negative environmental and social impacts that arise from the construction of wind farms (Wolsink, 2007; Pasqualetti, 2011; Slattery, Johnson, Swofford & Pasqualetti, 2012). These studies highlight the issues pertaining to wind farms through analysis of public opposition with Pasqueletti (2005) indicating that there are five key issues (immobility, immutability, solidarity, imposition and place). Krohn and Damborg (1999) and Slattery *et al.* (2012) are in agreement that proponents of wind energy focus on the benefits as opposed to opponents that share a negative attitude towards the aspects of wind energy, with the overarching view that public opinion on the issues is not straightforward and is complex in nature. A number of studies have also attempted to quantify the effects of the erection of wind turbines in specific locations (Ek, 2002; Krueger, 2007; Ladenberg & Dubgaard, 2007; Hanley *et al.,* 2001; Alfarez-Farizo & Hanley, 2002).

The way in which these studies compare the costs and benefits of wind turbine erection in certain locations is through an analysis of the trade-offs residents in the area of the prospective wind farms would be prepared to make in their assessment of various potential impacts. A methodology for estimating these trade-offs is the choice experiment variant of the Choice Modelling Technique (Hensher *et al.,* 2005). This paper aims to estimate some of these trade-offs by offering an analysis of a survey on the different aspects of wind energy developments conducted with underprivileged residents of the Kouga Local Municipality.

2. A proposal to harness wind energy in the Kouga Municipality

The Eastern Cape Province has attracted a number of proposals for the construction of wind turbine farms; one of which is by a company called Red Cap Investments to build a 121 wind turbine farm in the Kouga Local Municipality. The generating capacity of this wind farm is proposed to be approximately 300 MW, enough to power approximately 54 200 households with electricity (Red Cap Investments, 2011). [1] The wind farm will span over three locations; the 'Eastern Cluster', located near Aston Bay and Paradise Beach, the 'Central Cluster', located near St. Francis Bay and the 'Western Cluster', located near Oyster Bay (Red Cap Investments, 2011 – see Figure 1 for map showing location).

The areas that will be most affected by the wind farm development are Paradise Beach, Oyster Bay, Umzamozethu, St. Francis Bay, Port St. Francis, Sea Vista, Kwanomzamo and to a lesser extent, Humansdorp, Jeffrey's Bay and Aston Bay.

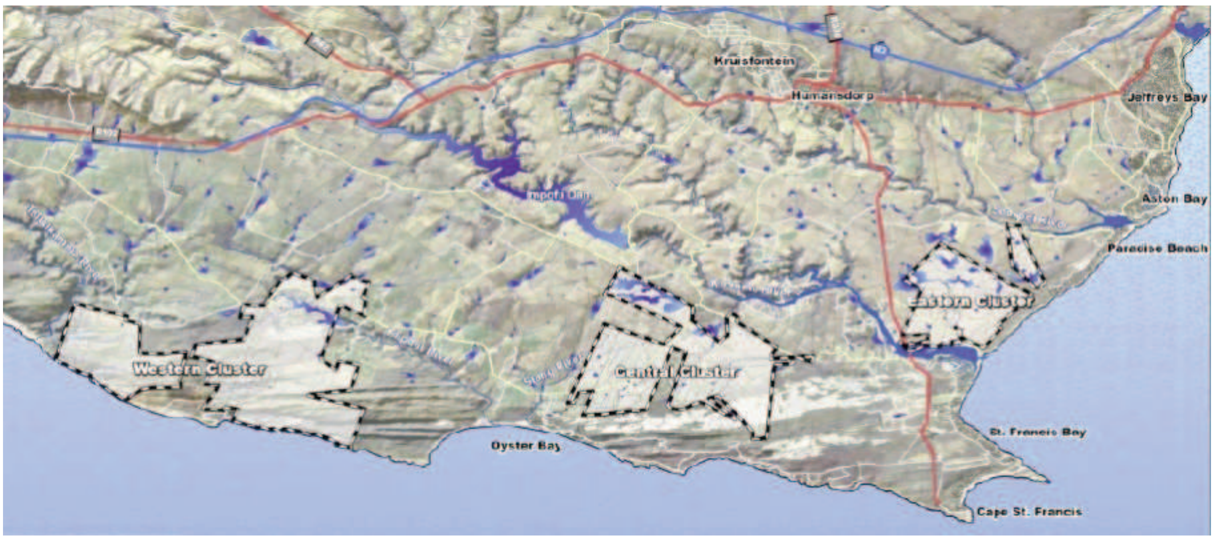

Figure 1: Map of Red Cap Investments wind farm locations
Source: Red Cap Investments Pty (Ltd) (2011)

Resistance to the erection of the turbines at certain locations has come from the better-off residents and businesses in the area (Meeting with St Francis Bay Residents Association, 2012). Many of the opponents to the wind turbine erections in the Kouga municipality support the drive for cleaner energy but they are unhappy at the prospect of wind farms dominating the area surrounding them (this is characterised as the NIMBY syndrome) (Pasqualetti, 2011).

3. Background

Local critics have asserted that the wind farm development in the Kouga Local Municipality will negatively impact on the visual attractiveness of the land (landscape character), abundance of bird life, employment and in some cases property values in the area (St Francis Bay Residents Association, 2010). These impacts are typically cited as relevant in environmental impact assessments (EIA) of wind farms and clearly are important elements to consider in any comprehensive assessment of the merits of building a wind farm (Dimitropoulos & Kontoleon, 2008). However, such factors are not of uniform importance across all communities. They differ according to social factors and general beliefs held in the community (Alvarez-Farizo & Hanley, 2002).

For a given community it is possible to assess this relative importance by means of discrete choice experiment (DCE) methodology (or conjoint analysis) (Hensher *et al.*, 2005). It is a stated preference technique that employs questionnaires in which respondents are required to choose between hypothetical scenarios. Typically these scenarios include a monetary payment or acceptance of some form of compensation element. By this inclusion it is possible to estimate willingness to pay or acceptance of compensation for marginal changes to the given scenario. DCE is a method frequently used to determine the values of the environmental impacts that are based mainly on perception. The technique is useful in determining a scenarios impact on a population in the absence of market trades that would otherwise reveal the preferences of the population and therefore the impact.

3.1 Discrete choice experiments

Choice experiments are based on two fundamental theories. The first is Lancaster's theory which states that a *good* is made up of several attributes and that the utility one derives from the usage or consumption of the *good* is determined by the attributes of the *good* and not from the consumption of the *good* as a whole (Lancaster, 1966). The second is based on random utility theory which proposes that not all utility derived from a *good* is observable to the analyst (Hensher, Rose & Greene, 2005). The combination of the two theories allows one to decompose utility of any *good* into two parts, an observable and an unobservable part:

$$U_i = V_i + \varepsilon_i \quad [1]$$

where U_i represents the overall utility of a specific choice alternative i, V_i represents the observable utility component and ε_i represents the unobservable or stochastic utility component (Hensher *et. al.*, 2005).

We can define the observable utility component in a linear form:

$$V_i = \beta_{0i} + \beta_{1i} f(X_{1i}) + \beta_{2i} f(X_{2i}) + \beta_{3i}(X_{3i}) + \dots + \beta_{ni}(X_{ni}) \quad [2]$$

where β_{1i} is the parameter associated with X_1 and alternative i and β_{0i} is the alternative specific constant associated with the i^{th} alternative (Hensher *et. al*, 2005).

In order to model individuals choices with only the available or observed data an analyst has to determine the probabilities associated with each alternative (choice) presented to the individual. If the individual k faces j alternatives (where $j = 1, \dots, i$) the individual will evaluate each alternative $U_1, U_2, \dots, U_j \dots, U_J$, and select the one that yields the highest utility. It is assumed that the probability of the individual selecting alternative i is equal to the probability that the utility of alternative i is greater than or equal to the utility of alternative j after comparing all alternatives in the choice set of $j = 1, \dots, i, \dots, J$ alternatives (Hensher *et. al.*, 2005):

$$Prob_k(chooses\ i) = Prob\big(U_{ki} > U_{kj}\big)\ \forall\ i \neq j \quad [3]$$

or

$$Prob_{ki} = Prob[(V_{ki} + \varepsilon_{ki}) \geq (V_{kj} + \varepsilon_{kj})]\ \forall\ i \neq j \quad [4]$$

which, when rearranged to separate the unobserved components from the observed components, becomes:

$$Prob_{ki} = Prob\big[(\varepsilon_{kj} - \varepsilon_{ki}) \leq (V_{ki} - V_{kj})\big]\ \forall\ i \neq j \quad [5]$$

Assuming that the unobserved components are independent and identically distributed with a Gumbel distribution, allows for use to be made of the multinomial logit (MNL) model to determine the probability of choosing alternative i over alternative j (Hanley, Mourato & Wright, 2001):

$$Prob\big(U_{ki} > U_{kj}\big) = \frac{e^{(\mu V_{ki})}}{\sum_{j=1}^{J} e^{(\mu V_{kj})}}\ \forall\ i \neq j \quad [6]$$

where μ is a scale parameter that confounds the direct determination of the β parameters. This equation states that the probability of an individual k selecting alternative i over alternative j in the set of J alternatives is equal to the ratio of e to the exponent of the observed utility of i to e to the exponent of the sum of all the observed utility indices for all J alternatives (Bergmann, Hanley & Wright, 2006).

The trade-offs between the attributes that a respondent makes can be determined by the estimated coefficients of the attributes from Equation 2. This trade-off is estimated by maximising the log-likelihood function of Equation 6. A monetary attribute (usually a price or subsidy) combined with another attribute permits an estimate of willingness-to-pay (receive) of respondents for changes in the attribute levels to be calculated. This can be determined as shown by Ek (2002):

$$implicit\ price = -\left(\frac{\beta\ attribute}{\beta\ monetary\ attribute}\right) \quad [7]$$

In order to incorporate taste variation among the respondents, a random parameters logit model (RPL) can be used for estimation. This model assumes that the preferences of the respondents are distributed by some known statistical distribution $\eta_k \sim f(\eta_k|\bar{\eta}, \sigma_\beta)$. The unobserved component of utility is $e_{ki} = \eta_k z_{ki} + \varepsilon_{ki}$, where ε_{ki} is assumed to be IID Type I extreme value, z_{ki} is a vector of individual specific characteristics and η_k is a vector of random terms that varies across individuals k according to a known distribution $f(\eta_k|\bar{\eta}, \sigma_\eta)$ (Glasgow, 2001). Estimation of the variance σ_β provides an indication of heterogeneity in the model (Glasgow, 2001). With the new assumptions on the random component, the utility that individual k derives from choosing alternative i can be reformulated:

$$U_{ki} = \beta X_{ki} + \eta_k z_{ki} + \varepsilon_{ki} \quad [8]$$

If there is preference homogeneity $\eta_k = 0$ and $\eta_k z_{ki} = 0$, the model is of the conditional logit specification. The random component of utility is assumed to be IID extreme value Type 1. The unconditional choice probability that decision maker k will choose alternative i becomes:

$$Prob_{ki}(\eta) = \int L_{ki}(\eta) f(\eta|\bar{\eta}, \sigma_\eta) \partial(\eta) \quad [9]$$

and the unconditional probability of respondent k choosing alternative i (Equation 3.9) can be reformulated as:

$$Prob(U_{ki}) = \int \left[\frac{e^{\beta X + \eta X}}{\sum_{n=1}^{N} e^{(\beta X + \eta X)}}\right] f(\eta_k|\bar{\eta}, \sigma_\eta) \partial(\eta) \quad [10]$$

where X contains all attributes and socio-economic characteristics of the individuals. Standard maximum likelihood theory cannot be used to evaluate Equation10 as the integral does not have a closed form. For this reason, a simulated maximum likelihood technique must be used (Glasgow, 1999). The logit probability of each draw is calculated, a process repeated several times, and the mean of the draws taken as the unbiased estimator of the unconditional choice probability of respondent k choosing alternative i. The underlying utility function of respondent k is:

$$U_{ki} = V_{ki} + \varepsilon_{ki} = ASC_i + \sum_n \beta_{nki} X_{nki} + \sum_n \eta_{nk} X_{nki} + \varepsilon_{ki} \quad [11]$$

where the k is the respondent $k(1, \ldots, K)$ and i is the alternative option selected *(i = Option A, Option B, Option C…)*, n is the number of attributes $(1, \ldots, N)$ and X_{nki} is the vector of explanatory variables including the attributes of the alternatives, socio-economic characteristics of the respondents, decision context and choice task in choice set (Hensher *et al.*, 2005). The non-random component of utility V is assumed to be a function of n choice-specific attributes X_{nki} with parameters β_{nki}. The coefficient vector η_{nk} varies across the population with density $f(\eta_k|\bar{\eta}, \sigma_\eta)$, where $\bar{\eta}$ is the vector of actual parameters of taste variation (Baskaran *et al.*, 2009).

Using a RPL model is advantageous in that the model eliminates the bias due to heteroscedastic error terms (Glasgow, 1999). Additionally, the model allows for a statistical test of heterogeneity of respondent preferences for attributes by assessing the significance of the standard deviation of the η_{nk} estimates (Mazzanti, 2001). A significant standard deviation of the η_{nk} parameter would indicate heterogeneity in the preferences for an attribute (Mazzanti, 2001).

3.2 Compiling the questionnaire

An essential part of a DCE is creating an effective survey tool that can provide relevant information about the respondents and their preferences. The questionnaire is constructed in four phases. Firstly, the researcher creates a description of all possible characteristics that define the *good* to be analysed. Then a focus group is convened to ensure that only the relevant characteristics of the *good* are incorporated into the questionnaire. The third phase is a pilot study which is used to test the understanding and ease of the survey as well as identifying the appropriate bounds and levels for the cost attribute (Bateman and Willis, 1999). The last phase involves finalising the main questionnaire and administering the survey.

As this study was conducted in South Africa, a developing country, it is important to note that the distinct difference between this study and similar studies conducted in industrialised nations is that the target respondent group for this study were low-income residents. This group was selected for two main reasons. The first was that South Africa has significant inequalities in income distribution and an economy with dualistic features (Rosset, Patel & Courville, 2006). In a dual economy the behaviour of people varies according to the group to which they belong. The second is that low-income respondents are rarely included in studies of preference, so there is a gap in describing their preferences to the relevant literature in South Africa. A possible reason for this gap is a perception that these respondents are overwhelmingly influenced by price and job income prospects, rather than other factors, such as environmental impacts.

A focus group was conducted to address the main concerns of the wind farm development and compile a provisional list of important wind farm attributes for inclusion in the choice experiment. Consultation with international literature and discussions with informed residents resulted in the refinement to four key attributes, with three levels each (Table 1).

Table 1: Attributes and levels included in the DCE

Attribute	*Levels*
Size of wind farm	10, 20, 53 turbines
Jobs Created	5, 20, 40
Proximity to residential areas	0.5km , 2km , 6km
Subsidy per household per month	ZAR 3.25, ZAR 13, ZAR 19.5

Two physical wind farm characteristics were included – one for the size of the wind farm in terms of number of turbines and proximity of the turbines to residential areas in kilometres. An attribute for employment possibilities from the wind farm development was highlighted as an important attribute for the low-income respondents and was also included in the DCE. The monetary attribute included was in the form of a subsidy, indicating willingness to accept (WTA) compensation as opposed to a price, indicating willingness to pay (WTP). A subsidy was chosen over a price for renewable energy because it was assumed that wind farm developments impose negative presence costs on the residents in the surrounding areas, and the residents surrounding the wind farm development were likely to have municipal property rights that would be infringed upon were the wind farm to be built in proximity to their residence (Dimitropoulos & Kontoleon, 2008). The subsidy took the form of providing free (basic) electricity (South African Government Information, 2011).

Once the attributes and the levels were defined, a main-effects-only, orthogonal and balanced design for the experiment was created in SPSS (version 12.01). As there were four attributes, each with three corresponding levels, a total of $3^4 = 81$ possible treatment combinations of attribute levels were identified. A fractional factorial design was used to reduce this number to 27 treatment combinations. These combinations were randomly paired into 108 choice sets (Hensher *et. al*., 2005). A total of 27 unique questionnaires were created, each questionnaire containing four choice tasks. A status quo option was added to each choice task.

The body of the questionnaire had four sections. The first two sections elicited information about the respondents' understanding of wind energy. The third section contained the choice experiment. Four pages were shown to the respondents. Each page contained two choice cards and each attribute on the choice cards was represented by a picture. The respondents were asked to choose between option A, B and C, where option C was the *status quo*. The fourth section contained questions about the socio-economic characteristics of the respondents. The questionnaire was simplified. Pictures were used to guide respondents with specific questions and to explain the differences between the levels of the attributes. The survey team was comprised of members with fluency in either English or Afrikaans or isiXhosa.

A pilot survey was conducted to test the comprehension and validity of the questionnaire. The pilot survey included 27 respondents.

3.3 Sample description

A stratified sample of randomly selected heads of households in the informal areas (townships) of Kwanomzamo, Sea Vista, Tokyo Sexwale, Ocean View and Umzamowethu was included in the study. A total of 270 personal interviews of low-income bracket households in the Kouga Local Municipality were conducted during a week in October 2012. The average household gross annual income for the sample was R30 800.89 or R2 600 per month. Table 2 shows the distribution of age, income and education of the sample group. The majority of the respondents were aged between 18 and 30 years old and had a low level of education.

4. Results

The econometric software NLOGIT (version 10) was used to compute the relevant utilities of the alternatives. The data matrix was in the form (Bergmann *et. al.,* 2006):

Option A:

$$V_a = \beta_{0a} + \beta_1 X_{size} + \beta_2 X_{cluster/job} + \beta_3 X_{distance} + \beta_4 X_{subsidy} \quad [12]$$

Table 2: Sample characteristics for the sample respondent group

Age		*Income*		*Education*	
Underprivileged Sample					
Range	*Sample*	*Range*	*Sample*	*Level*	*Sample*
18 to 30	38.4%	R0 to R15 000	17%	Primary	23%
31 to 40	29%	R15 001 to R50 000	42%	Secondary	48.5%
41 to 50	19.6%	R50001 to R200 000	19%	Matriculation	22.5%
51 to 80	13%	R200 001 to R750 000	0 %	Tertiary	6%
Kouga Local Municipality					
Age		*Income*		*Education*	
Range	*% Kouga Population*	*Range*	*% Kouga Population*	*Level*	*% Kouga Population*
18 to 30	24%	R0 to R19 600	41.7%	Primary	53.6%
31 to 40	14%	R19 601 to R76 400	36.1%	Secondary	30.9%
41 to 50	12.3%	R76 401 to R307 600	17.2%	Matriculation	9.7%
51 to 80	18.5%	R307 601 to R1 228 800	4.5%	Tertiary	1%

Option B:

$$V_b = \beta_{0b} + \beta_1 X_{size} + \beta_2 X_{cluster/job} + \beta_3 X_{distance} + \beta_4 X_{subsidy} \quad [13]$$

Status quo option:

$$V_{SQ} = \beta_1 X_{size} + \beta_2 X_{cluster/job} + \beta_3 X_{distance} + \beta_4 X_{subsidy} \quad [13]$$

where V is the observed utility and β_0 is the alternative specific constants for options A and B. The status quo (non-option) level was used as the base level.

The estimation results of a conditional logit model are shown in Table 3. The influence of each attribute on the choice probabilities can be determined by the magnitude and sign of the coefficients (Krueger, 2007). The size attribute is insignificant at the 5% level, suggesting that the respondent group were indifferent in their preferences for wind farm size. The attributes for job and distance were positive and significant, indicating that the respondents derived greater utility from an increasing change in the level of these attributes, i.e. through creating more job opportunities and locating the wind farm further away from residential areas.

The pseudo R^2 is 0.12, indicating a comparable OLS model fit of 30%. This level of fit is acceptable because this model only includes the attributes as parameter estimates and does not account for individual characteristics or external determinants of choice.

A test to determine whether a violation of the IIA assumption was conducted using the Hausman test. The status quo was omitted from the data and the restricted model estimated. The resulting test statistic was 16.09 and the p-value for this test was 0.0003, sufficient evidence to reject the null hypothesis that the IIA assumption is violated.

An RPL model was also fitted to the data to determine whether there was heterogeneity in the parameter estimates for the sampled population around the mean parameter estimate (Hensher *et al.*, 2005). The dispersion of the job attribute, represented by the derived standard deviation of 0.089, was statistically significant, with a Wald statistic of 3.81 and a p-value of 0.0001. Different dis-

Table 3: Conditional logit model results for low-income respondents

Variable	*Coefficient*	*Standard error*	*Wald statistic*	*p-value*
Subsidy (X_1)	0.0288***	0.0068	4.2400	0.0000
Size (X_2)	0.0035	0.0026	1.3650	0.1721
*ln*Distance (X_3)	0.1815***	0.0469	3.8660	0.0001
Jobs (X_4)	0.0410***	0.0033	12.4670	0.0000
ASC(status quo)	-1.3382***	0.2564	-5.2200	0.0000
Maximum likelihood estimates				
No. of observations	1080	Base LL function	-965.487	
No. of parameters	5	Pseudo R^2	0.12	
Estimated LL function	-863.4402	AIC	1.608	

tributions were assigned to the job attribute to determine the best model fit (Hensher *et al*., 2005). The normal distribution provided the best model fit. All other attributes did not have a significant dispersion around the mean.

Interaction terms were included in the RPL model to explain the heterogeneity in the job attribute (the explanatory variables were interacted with the job attribute). Interaction terms for gender of the respondent (dummy coded, 0 for males, 1 for females), age of the respondent, and knowledge of wind energy (two different measures) were included in the model. The results of the RPL model with interaction terms included to explain the heterogeneity about the mean of the parameter estimate for the job attribute is shown in Table 4.

The likelihood ratio test value is 19.05, indicating that the model is a significant improvement on the first model. The overall model is statistically significant, as evidenced by the Chi-squared value of 685.9 with 10 degrees of freedom. The pseudo R^2 value is 0.289, a good fit for this class of model (Hensher *et al*., 2005).

The differences in the marginal utilities held for the job attribute are in part explained by differences in respondent gender. The negative and statistically significant ‘’ parameter indicates that male and female respondents chose different levels of the attribute for job prospects.

The WTA measure for the distance attribute was calculated differently to the job attribute. It was calculated for moving the wind farm from the baseline of 0.5 km to 2 km, 6 km and the status quo of 120 km away from the residential areas. The WTA measures were estimated using Equation 15 (Krueger, 2007).

$$WTA = \frac{\beta_{ln(distance)}(lnX_i - ln(0.5))}{-\beta_{subsidy}} \quad [15]$$

In Equation 15, the X_i represents the distance *i* from the residential areas (2 km, 6 km and 120 km away) and $\beta_{subsidy}$ represents the coefficient for the subsidy attribute.

The negative WTA compensation measures pertaining to the distance attribute indicate that the sampled respondents were willing to accept a reduction in subsidy the further away the wind farm was located from their residential areas. The sampled respondents were willing to accept a reduction in subsidy of ZAR 21.38 per month if the wind farm was moved from the base level of 0.5 km away to 2 kms away from the residential areas. Similarly, the negative WTA measure for the jobs attribute indicates that the sampled respondents were willing to accept a reduction in compensation for increases in the number of jobs created by the wind farm.

Moving the wind turbines so far away from residential areas that they are no longer visible, is not always the best practice or feasible. It may be a better alternative to compensate. For this purpose, it is useful to assess the marginal willingness to accept (MWTA) measures. MWTA compensation measures were calculated for the significant attributes, by taking the difference of the two WTA measures and dividing it by the difference in the corresponding change in distance (Krueger, 2007; Ladenburg and Dubgaard, 2007).

A reduction in MWTA compensation measures was higher for distances closer to the residential areas, indicating that the majority of the sampled respondents would derive social benefit from moving the wind turbines more than 0.5 kilometres away from residential areas. The MWTA compensation measures were consistent indicating that the sampled respondents derive the same amount of utility for each increase in the job prospects created by the wind farm.

As the parameter estimates for the distance attribute were also significant, WTA measures could also be calculated with respect to distance.

The underprivileged respondents were WTA a reduction in the subsidy each month of ZAR 14.25 per kilometre distance from the base-line distance of 0.5 km to 2 km away from the residential areas. The MWTA a reduction in subsidy each month drops to ZAR 4.23 per kilometre between 2 km and 6 km away from residential areas. This indicates that as the wind turbines are moved a considerable distance away from the residential areas, the perceived benefit is increased and therefore the residents are willing to accept a reduction in subsidy.

As the distance between the residential areas and the wind turbines increases, the sampled population is prepared to accept less and less of a reduction in compensation until the full subsidy value is accepted. The MWTA a reduction in subsidy is below one at a distance of 120 km away from residential areas. This rate of change indicates that for the underprivileged respondent group the benefits are minimal for locating the wind turbines at a distance greater than 120 km away. The greatest social benefit is derived for the initial movement of the turbines further than 0.5 km from residential areas.

5. Conclusions

The choice experiment methodology has been used extensively in marketing (conjoint analysis) and in valuing environmental resources that do not readily reflect in market values. Through the use of personal surveys, the residents of the Kouga Local Municipality were asked to make choices between several hypothetical wind energy scenarios defined by a selection of attributes at different levels. The selection of attributes and levels was based on the findings reported in similar international studies and through focus group sessions.

Table 4: RPL model with interactions included

Variable	*Coefficient*	*Standard Error*	*Wald Statistic*	*p-value*
		Random parameters in utility functions		
Jobs	0.121	0.027	4.527	0.000*
		Non-random parameters in utility functions		
Subsidy	0.036	0.008	4.258	0.000*
Size	0.005	0.003	1.634	0.102
Distance	0.223	0.059	3.791	0.000*
ASC(status quo)	-1.723	0.328	-5.258	0.000*
		Heterogeneity in mean, Parameter: Variable		
Jobs: Gender	-0.036	0.011	-3.165	0.002*
Jobs: Know1	-0.014	0.011	-1.251	0.211
Jobs: Know2	0.002	0.006	0.356	0.722
Jobs: Age	-0.001	0.000	-1.413	0.158
		Derived standard deviations of parameter distributions		
Jobs	0.082	0.018	4.509	0.000*
		Maximum likelihood estimates		
No. of observations	1080	Pseudo R^2	0.2890	
No. of parameters	10	Chi-squared	685.9032	
Log-Likelihood function	-843.5497	Degrees of freedom	10	
Base LL function	-1186.501	AIC	1.5807	

* 1% level of significance

The magnitude, sign and significance of all the estimated coefficients of the attributes were similar for each of the models. The negative signs for the attributes of distance, jobs and size indicate that the respondents were WTP for increases in the attribute levels. The respondents preferred to have the wind farm located at least 2 km away from residential areas, have more wind turbines and more jobs created.

There was heteroscedasticity in preference for jobs among the underprivileged respondent group. This heteroscedasticity was explained by gender. The preference for the jobs attribute was similar for individuals of the same gender.

The number of new jobs created by the wind farm development was an important indicator of choice for the underprivileged respondent choices. This job creation potential needs further investigation as there may be job losses as well, caused by discouragement of affluent resident settlement in the area or lost recreational value.

Notes:

1. An average household uses ± 1.1 MWh per month (Eskom, 2011) or 12.12 MWh per annum (In one year the Red Capp investments wind energy development will generate approximately 657 000 MWh (300MW x 24 x 0.25 x 365), which can supply approximately 54 200 households with electricity each month.

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Identification and characterisation of performance limiting defects and cell mismatch in photovoltaic modules

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Abstract

The performance and longevity of photovoltaic (PV) modules can be severely limited by cell mismatch occurring when a solar cell in a series-connected string produces a lower current than the other cells in that string. The current output of the entire string is limited by the weakest cell in the string so shading or damage to a single cell in a module can affect the entire module's current output. Electroluminescence (EL) occurs when a positive current and voltage are applied to a solar cell and is used to identify damage and defects in the cell. In this study, the cell mismatch in three single crystalline silicon modules was investigated using EL and current-voltage (I-V) characterisation techniques. Two modules have a white discolouration that affects the majority of the cells in the module and also have signs of mechanical damage, while the third module acts as a reference as it has no discolouration and appears undamaged. The EL signal intensity is related to cell performance and identifies material defects, bad contacts and broken cells. Cell mismatch in a module results in a decrease in the performance parameters obtained from the I-V characteristic curve of the module. The I-V curves indicate the presence of current mismatch in the degraded modules, which is supported by the EL images of these modules. The use of EL images, in conjunction with the I-V curves, allows the degradation in the modules to be characterised.

Keywords: photovoltaics, cell mismatch, current-voltage characterisation, electroluminescence, degradation

1. Introduction

The reliability and longevity of photovoltaic (PV) modules is a key factor in the success of solar energy as an alternative energy source. Cell mismatch arises from unbalanced current production of some cells in a series-connected string. This mismatch results from degradation in the cell due to mechanically damaged cells or shading due to shadows or the accumulation of dirt (Meyer and van Dyk, 2004). Cell mismatch affects the current production of the cell and, hence, the string.

The objectives of this investigation are to identify and characterise cell mismatch in PV modules by comparing the results of the current-voltage (I-V) characteristics with electroluminescence (EL) images. EL is a useful solar cell characterisation technique as it is fast, non-destructive and sensitive to the effects of shunt and series resistances and recombination parameters. This luminescence is dependent on the optical, electrical and resistive properties of the solar cell.

EL imaging is very effective in detecting defects in modules such as cracks, broken fingers and broken cells (Mansouri *et al.*, 2012). For this reason, it is extensively integrated into module production lines and module testing systems and highlights features that are missed during visual inspection (Camino-Villacorta *et al.*, 2012). The EL images allow defective cells in a module to be identified and these defects can be related to reduced output power.

1.1. Current-voltage (I-V) characteristics and cell mismatch

Cell mismatch has a substantial effect on the current-voltage (I-V) curve of the whole module. A cell with a current output lower than the rest of the cells in the string of series-connected cells is referred to as a 'weak cell'. When cells are connected in series, the voltages of the individual cells add and the total current is limited by the weakest cell.

Figure 1(a) shows a representation of two cells connected in series and the cells are current matched, so the total current flowing through the circuit is equal to the current generated by each cell. At short-circuit the voltage of each cell is zero. Figure 1(b) illustrates the I-V curves of the two cells and how they are combined, with the voltages of each cell adding and the short-circuit current (Isc) is equal to the Isc of each cell. The curves were plotted using a modelling programme called PVSim (King *et al.,* 1996) which includes a statistical variation of parameters of the cells resulting in the I-V curves of cell 1 and cell 2 being slightly different.

If a cell is shaded by leaves or dirt it generates less current than the other cells in the series-connected string, as illustrated in Figure 2(a). Under short-circuit conditions cells 2 and 3 generate current, I, however the current that can flow through the circuit is limited by cell 1, which is only generating half as much current, ½I, thus the excess current flows through the diodes in cells 2 and 3, forward biasing them. At short-circuit the voltages of all the cells must add up to zero and since cells 2 and 3 are forward biased, cell 1 is reverse biased by an equivalent voltage. Cell 1 thus changes from a power generator to a power dissipater (Vorster and van Dyk, 2005). The cell generates heat that may damage the cell by creating a hot-spot which can cause the cell to crack or delaminate from the encapsulation material. The combined output of the series connected cells is dependent on the reverse voltage behaviour of the weak cell (Alonso-García and Ruíz, 2006). Figure 2(b) illustrates the effect on the I-V curve of the weak cell, the Isc of the series connected string is limited by the weak cell.

The effects of cell mismatch can be mitigated by using bypass diodes connected in parallel over a series connected cell or string of cells, illustrated in Figure 3(a). The bypass diode is activated when the weak cell is reverse biased by a voltage equal to the transmission voltage of the diode (Vorster and van Dyk, 2005). Cells 2 and 3 are only slightly forward biased and the current of the series-connected

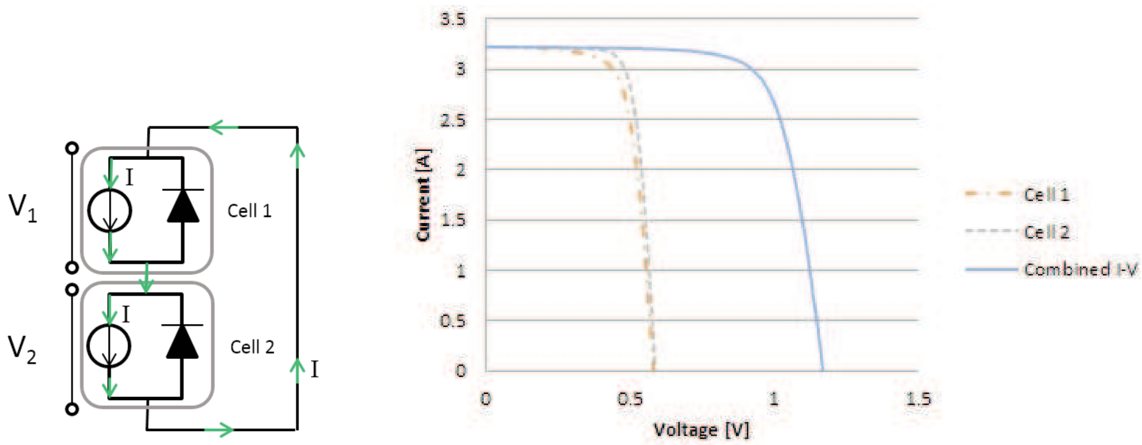

Figure 1: a) The equivalent circuit of two matched solar cells in short-circuit. b) Simulation of the I-V curves of two matched cells and their combined I-V curve. The curves were plotted using a modelling programme called PVSim[2], which includes a statistical variation of parameters of the cells resulting in the I-V curves of cell 1 and cell 2 being slightly different

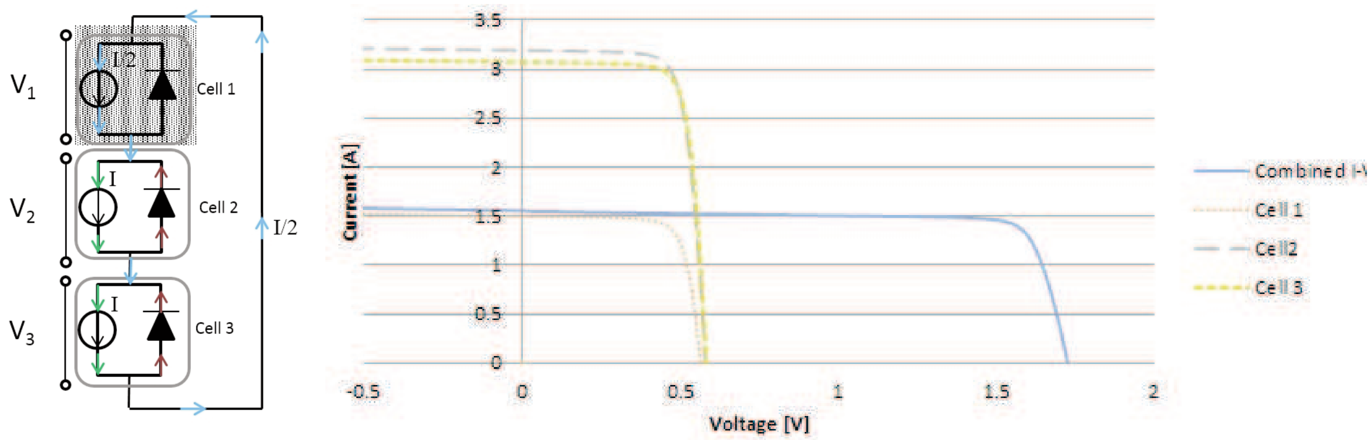

Figure 2: a) The equivalent circuit of three cells in series with one shaded cell. b) The simulated I-V curves of the three cells and the combined I-V curve of all the cells in series

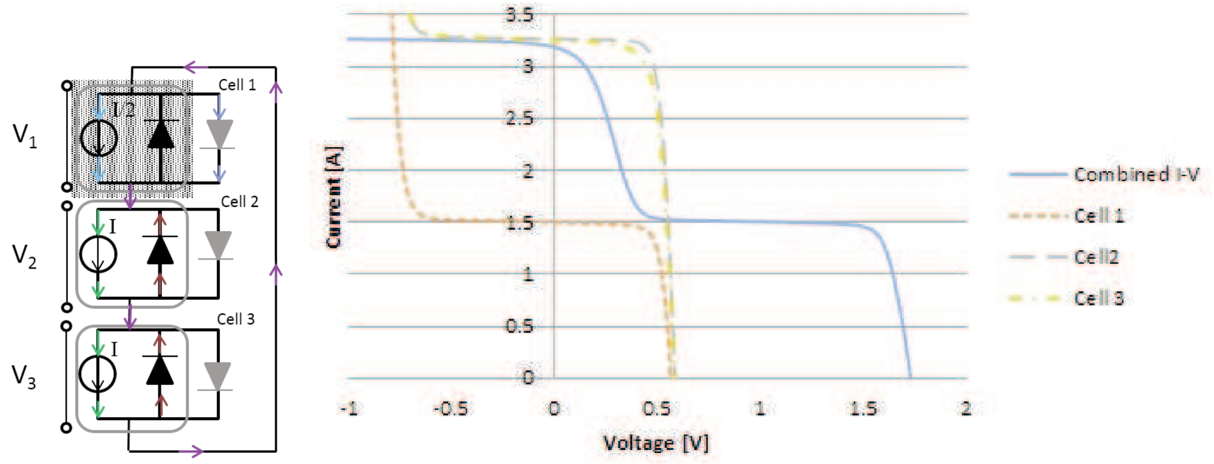

Figure 3: a) The equivalent circuit of three cells in series with one shaded cell with bypass diodes connected in parallel across each cell. b) The simulated I-V curves of the three cells and the combined I-V curve of all the cells in series

string is not limited by cell 1. The activation of the bypass diode results in a step in the I-V curve visible in Figure 3(b). The relative position of the step in the I-V curve is related to the behaviour of the weak cell in reverse bias (Alonso-García and Ruíz, 2006). When cells are connected together in modules, it is impractical to have bypass diodes over each cell so they are connected over strings of series-connected cells.

1.2. Electroluminescence

A solar cell or a LED can be represented as a device with electrical or optical terminals, (Kirchartz *et al.,* 2009). A solar cell receives an optical input in the form of the incoming light and outputs an electrical current. Conversely, a LED receives an electrical input resulting in an optical output. EL occurs in a solar cell when it is forward biased, receiving an electrical input and outputs an electromagnetic emission spectrum. The emission spectrum from silicon is in the infrared region of the electromagnetic spectrum. Luminescence is defined as the emission of light not due to heating so electroluminescence is the emission of light due to an applied bias.

When a silicon solar cell is forward biased, the applied potential difference injects additional carriers into the junction. When some of the carriers recombine radiatively, energy is emitted in the form of electromagnetic radiation, EL, in a range of 1000 to 1200 nm. The intensity of the EL signal is related to the material properties such as the surface recombination velocity, minority carrier lifetime and diffusion length (Fuyuki *et al.*, 2005; Fuyuki *et al.*, 2007; W□rfel *et al.*, 2007; Fuyuki and Kitiyanan, 2008). Extrinsic defects that have occurred in the cell or module during the manufacturing process can also be detected as they result in areas of low or absent EL signal. The EL signal is detected using a cooled silicon charge-coupled device (CCD) camera which provides a grey scale spatial representation of defects in the cell. EL imaging is a very fast, efficient and non-destructive technique for identifying the causes of cell mismatch in PV modules.

Since the initial research of EL of silicon solar cells was completed by Fuyaki *et. al.* (2005), EL has developed into a very successful defect identification and module characterising technique (Mansouri *et al.*, 2012; IEAPVPS, 2014). EL can effectively identify the micro-cracks that are not detected during visual inspection. Micro-cracks can occur during the soldering process (Gabor *et al.*, 2006), during the handling and installation of the modules (Sander *et al.*, 2013; Köntges *et al.*, 2014). The occurrence and distribution of icro-cracks has also been studied in detail (Köntges *et al.*, 2011; Paggi and Sapora, 2013; Kajari-Schröder *et al.*, 2011). Similarly breaks in contact finger, which run perpendicular to the busbars across the cell, are visible in EL. A break across the finger results in that area of the cell having decreased electrical contact. These defects are visible in the EL image as the area around the broken finger appears darker in the image (Chaturvedi *et al.*, 2013; Mansouri *et al.,* 2012). The busbars and solder strapping in a cell provides electrical contact to the cells.

2. Experimental procedure

I-V curves were measured using a calibrated outdoor I-V tracer, which consists of a programmable power supply and an electronic load that allows the output current to be measured through a range of voltages. The current produced by the module is measured at each applied voltage and these data points are plotted as the characteristic I-V curve of the module. The irradiance and the back-of-module temperature were measured during the I-V curve measurements and the results were corrected to standard operating conditions of 25°C and 1000 W/m^2. I-V curves of the modules were measured with and without bypass diodes and the I-V curves of the individual strings were measured, allowing the current mismatch in the module to be fully identified and characterised.

The EL images were measured by applying a forward bias of 30 V such that a current greater than Isc passes through the module, in this case approximately 4 A. The wavelength of the emitted luminescence of a silicon sample has a peak at about 1150 nm and a portion of this peak can be detected by a silicon CCD camera which has a detection range of 300-1000 nm. The camera's CCD chip is cooled to -50 °C to improve the signal-to-noise ratio. In order for the electroluminescence signal to be detected, the setup must be placed in a dark room to prevent ambient light from being detected. The CCD camera is fitted with an infrared filter and an objective lens for focusing. The module is forward biased using a DC power supply and the CCD camera is connected to a computer with camera control software. The exposure time for each image is about 2.5 seconds. ImageJ (NIH, 2004), image processing software was used to analyse the EL images.

Three single crystalline silicon modules were used in this investigation, all with the same cell material and configuration. Photographs of the three modules are shown in Figure 4. The modules are labelled 1, 2 and 3 with module 1 serving as a reference. The modules have 44 cells connected in two strings of 22 series-connected cells with bypass diodes connected in parallel across the strings. Two of the modules have a visible grey-white discolouration affecting the majority of the cells in the module. This is thought to be due to degradation in

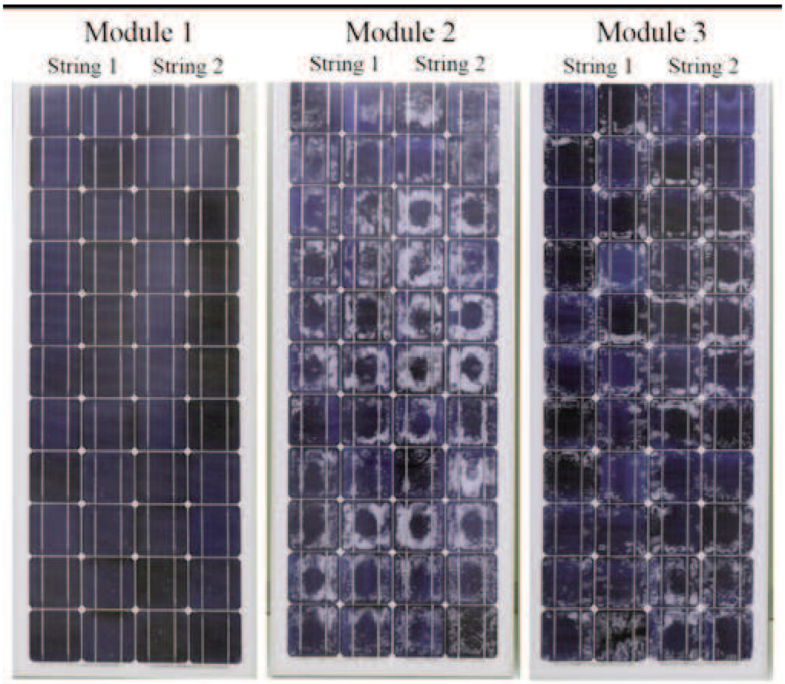

Figure 4: Photographs of Module 1 (reference), Module 2 and Module 3

the anti-reflective coating on the cell surfaces. The effects of this degradation can be determined by comparing these modules with a third reference module that has no visible degradation. The modules have a specified maximum power (P_{max}) of 65 W, open circuit voltage (V_{oc}) of 25 V and short-circuit current (I_{sc}) of 3.6 A.

3. Results

3.1. Outdoor I-V curves

The performance parameters of the three modules and the manufacturer's specifications are given in Table 1. The reference module 1 has the best power and current output as expected, with a measured P_{max} of 64.6 W. The variation from the specified 65 W is most likely due to the small micro-cracks that were only visible in the EL image.

Table 1: The performance parameters of the three modules with the manufacturer's specifications

	V_{oc} [V]	I_{sc} [A]	P_{max} [W]
Module 1	25.4	3.6	64.6
Module 2	25.8	3.4	55.1
Module 3	25.7	3.4	54.1
Manufacturer's specifications	25.0	3.6	65.0

The I-V curves of the three modules, with bypass diodes connected, and those of the individual strings without bypass diodes are shown in Figure 5. Module 1 has no visible damage or degradation as seen in the photograph of the module, Figure 4. The I-V curves of module 1 with bypass diodes and its individual strings are shown in Figure 5. The cells in each string of module 1 are evenly matched and produce the same current and thus the I-V curves of each string are identical. When the strings are current matched the same current is generated, so the bypass diodes that are parallel connected across the cell strings are not activated. The voltages of the two strings add at equal currents, resulting in the I-V curve of the whole module. The module is, therefore, used as a reference module for comparison of the performance and cell mismatch of the other modules.

The I-V curves of module 2 and its cell strings are shown in Figure 6. String 1 has a lower current and power output than string 2, resulting in current mismatch between the two strings. String 1 is reverse biased by a voltage greater than the bypass diode's turn-on voltage, which activates the bypass diode across string 1. The step in the module I-V curve, at about 7 V, is due to the activation of the bypass diode and the bypassing of string 1 and thus the Isc of the module is determined by the Isc of string 2. If bypass diodes are not used the module's Isc will be limited by string 1's Isc and thus by the

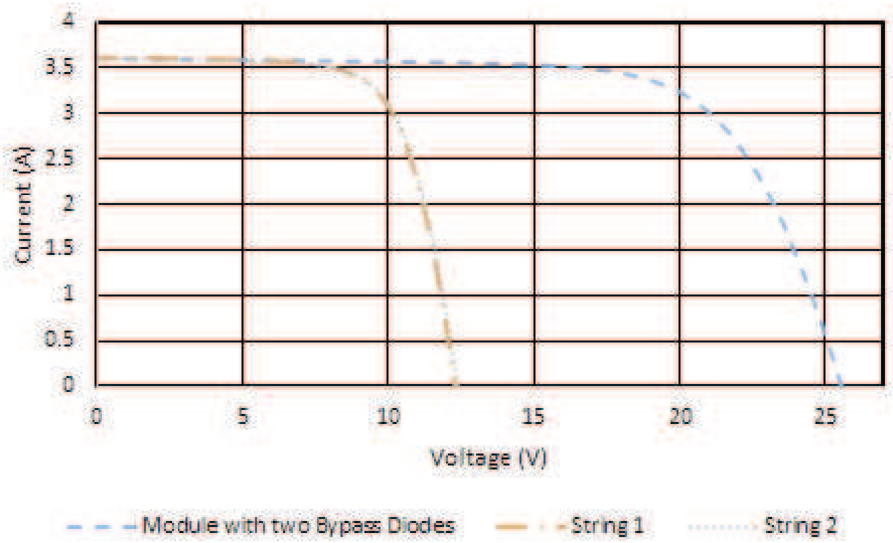

Figure 5: The I-V curves of module 1 and its individual strings

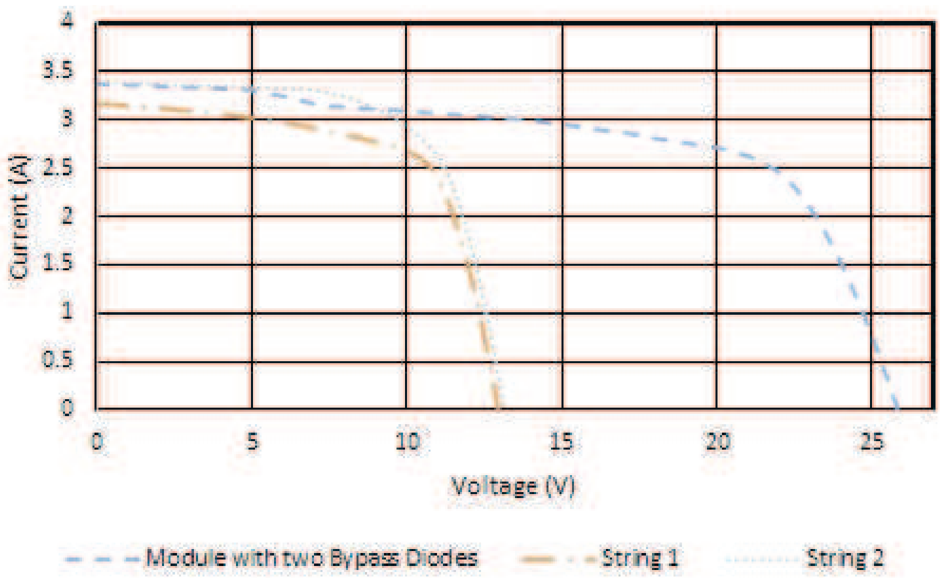

Figure 6: The I-V curves of module 2 and its individual strings

weakest cell in the string.

The I-V curves of module 3 and the individual strings are shown in Figure 7. The current of the two strings is matched at Isc and thus neither of the bypass diodes are activated. However, in the region before the "knee", between 2 and 11 V, the current of string 1 is lower than string 2. This could be due to a combination of cell mismatch effects and shunt resistance as this region of the I-V curve is influenced by shunt resistance in the cell and module. In an ideal solar cell, the resistance due to shunting across the p-n junction should be infinite but due to manufacturing defects shunting can occur. Low shunt resistance results in an alternative current path for light generated current thus reducing the current of the cell. At low voltage levels the impact of parallel shunt resistance is significant.

3.2. EL images

The EL images of all the modules in the study are shown in Figure 8. Figure 8(a), the EL image of module 1, corroborates the results of the I-V curve as there are no large severely damaged areas visible and the two cell strings are evenly matched. Common cell defects, such as finger defects and micro-cracks that affect small areas can be detected. Finger defects occur due to a break across the contact fingers across the cell resulting in the area between the fingers of the cell having decreased electrical contact and appearing darker in the EL image. Finger defects occur in the majority of the cells in this module, possibly due to problems in the manufacturing process. Micro-cracks are visible in highlighted cells C8 and C9 in module 1. The micro-cracks indicated in C9 are visible in the EL

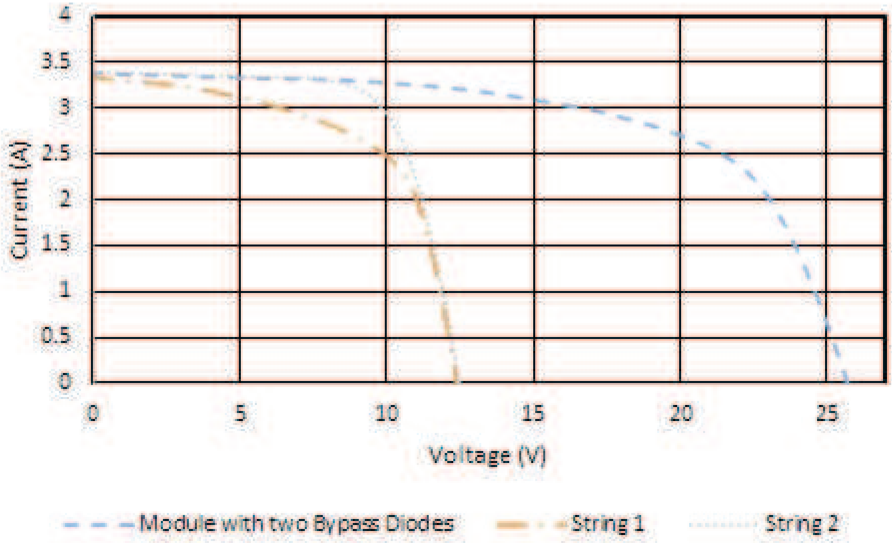

Figure 7: The I-V curves of module 3 and its individual strings

but do not cause inactive areas in the cells (Köntges *et al.*, 2011). This type of crack most likely occurred during the manufacturing process and would not be detected in the I-V module testing process as they do not result in a significant drop in cell performance. With time and thermal cycling these cracks have the potential to spread and result in performance degradation. The micro-cracks in the corner of the cell C8 completely removes an area of the cell from electrical contact resulting in a completely dark area in the EL image. This inactive area indicates that this area of the cell has poor photo-response lowering the performance of the cell. This decrease, however, does not significantly affect the performance of the module because of the small area affected and is therefore not observed in the I-V curve.

The EL image of module 2 is shown in Figure 8(b) and reveals several defects and large inactive areas due to broken cells. The effect of the degradation in the anti-reflective coating is visible in the EL image as areas that have been discoloured correspond with areas of lower EL signal intensity. This could be due to the discolouration of the anti-reflective coating that blocks the EL signal from being detected. Either way, this degradation results in poor photo-response and, ultimately, performance degradation in the affected areas. In cell B4 a micro-crack has prevented electrical contact between the one side of the cell and the other. The high current density in the one third of the cell results in a higher intensity EL signal. Cells A7, B7, B8, C8 are severely cracked. These cracks cause large inactive areas which result in lower performance of these cells. The cause of this damage is most likely due to mechanical damage as the cracks line up with scratches that have been observed

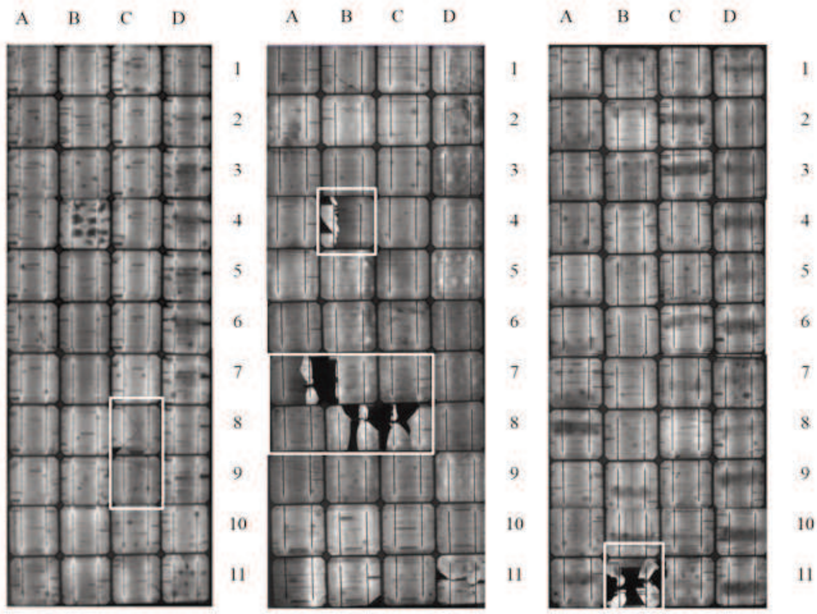

Figure 8: The EL images of a) module 1, b) module 2 and c) module 3

along the back surface of the module. The EL images explain the mismatch seen in the I-V curves of the two strings as string 1 has more inactive cell area than string 2 and thus lower current output.

The EL image of module 3 is shown in Figure 8(c). Cell B11 is the severely damaged with cracks resulting in large inactive areas which lower the performance of the module. This damaged cell is responsible for the lower performance of string 1 compared with string 2 obseved in the I-V curves. While this damaged cell doesn't lower the Isc of string 1, it does contribute to the cell mismatch and shunting observed in the I-V curve.

4. Summary and conclusion

Electroluminescence is used as a fast and effective technique in identifying defects and degradation in these three PV modules. It is able to quickly detect cell defects that would not be detected in visual module inspection or I-V curve measurement. These defects can explain why some modules, such as module 1, appear undamaged but have lower power output than expected. Defects in a module can be detected at the manufacturing stage enabling manufacturers to increase the reliability of PV modules. Cell mismatch can be observed in the I-V curves of a module but the EL image of the module allows the identification of cell defects and the exact nature and position of the defects may also be determined.

Despite the EL of module 2 indicating that it has several severely cracked cells, the performance parameters of modules 2 and 3 are very similar. The bypass diodes in module 2 increases the Isc of module 2, and thus the power outputs of module 2 and 3 are very similar despite module 2 having more damaged cells. The EL images of module 2 clearly indicate that the cell mismatch which is seen in the I-V curve of the module is due to cracked cells and inactive areas. These defects result in a lower current output in one string which is visible in the I-V curve. Similarly, a damaged cell only visible in the EL image of module 3 could be responsible for the lower performance and shunting visible in the I-V curve of the module.

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A perspective on South African coal fired power station emissions

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Abstract
This paper investigates trends of historical and projected future South African coal-fired power station criteria (total primary Particulate Matter (PM), Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x)) and Carbon Dioxide (CO_2) emissions. It was found that an energy restricted environment has an increasing effect on emissions, as emissions per energy unit increased from the onset of the South African energy crisis. PM emissions particularly, increased during the energy crisis period, due to increased pressure on PM abatement and lowered maintenance opportunity. Projections of future coal-fired power station criteria and CO_2 emissions are made for four different future scenarios for the period 2015 to 2030. Three of the four scenarios are based on the lower projected energy demand baseline case as published in the updated Integrated Development Plan (IRP). The difference between these three scenarios is different retrofit rates of power stations with emissions abatement technologies. The fourth scenario is a worst case scenario and assumes high energy demand (and therefore no decommissioning of power stations), high emission rates (similar to worst past emission rates during the period 1999-2012) and no further abatement of emissions above and beyond current mitigation efforts. This scenario gives an indication of what South African coal-fired power station emissions could look like if the energy crisis persists. There is a marked difference between projected best and worst case PM emissions during the entire projected period, but especially during 2030 when worst case PM emissions compared to a 2015 baseline value are expected to rise by 40% and best case PM emissions are projected to decline by 40%. Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030. Worst case SO_2 emissions are predicted to increase by around 38% in 2030 and best case emissions are expected to decrease by around 20% in 2030 from a 2015 baseline value. Relative emissions used in the projection of future CO_2 emissions in this paper differ from that used in the energy demand and energy mix modelling done for the updated IRP baseline case. The reason for this is that the modelling for the updated IRP assumed relative CO_2 emission factors for supercritical boilers, whereas only Kusile and Medupi fall in this category and relative emissions from all other stations are, in fact, between 5% and 16% higher. For this reason, it seems unlikely that the South African climate commitment target for 2030 will be made.

Keywords: coal-fired power station emissions; energy crisis; South Africa; emissions projection; climate commitments

1. Introduction

The South African energy sector is currently faced with a number of challenges. Residential energy consumption dramatically increased (by 50%) during the period 1994 to 2007 due to the implementation of a Free Basic Electricity Policy in 2001. This meant that 50 kWh of electricity was supplied per household to poor households per month, free of charge (Inglesi and Pouris, 2010). Since 2007 the country has been experiencing an ongoing energy crisis. The main reason for this was the delay by government in making a decision to fund the building of a new power station after being warned of an energy crisis approaching in 1998, combined with an increase in demand as a result of economic growth and the implementation of the Free Basic Energy Policy (Department of Minerals and Energy (DME), 1998; Inglesi and Pouris).

During the energy crisis period, energy demand was met by means of delaying maintenance on the generation fleet. This led to the decline in performance of the fleet, which in turn, negatively impacted the effectiveness of the fleet to meet future demand (Integrated Resource Plan for Electricity (IRP), 2013). Three older power stations that were mothballed during the 1980's and early 1990 were returned back to service to alleviate the pressure on existing stations. It is believed that the energy demand/supply balance will remain vulnerable until Medupi and Kusile, two new power stations currently under construction, come fully online expectedly between 2018 and 2020 (Eskom, personal communication), although uncertainty still remains on the exact commissioning dates. In 2010 the South African Department of Environmental Affairs (DEA) promulgated a set of Minimum Emission Standards (MES) for criteria pollutants that will come into effect in 2015 and 2020, and is expected to decrease emissions (Department of Environmental Affairs (DEA), 2010a). However, a number of industries, including Eskom and Sasol, the two major role players in the combustion of coal in South Africa have filed applications for the postponement of, and in some cases, exemption from the MES (Iliso Consulting, 2013; SRK Consulting, 2013). The reasons for this are the high cost of compliance with the MES (with a capital cost of around 6% of the South African nominal Gross Domestic Product (GDP) for 2013) (Eskom, personal communication, 2014; *Statistics* South Africa, 2014), and the inflexibility of the MES by not taking the ambient air quality and exposed population surrounding power stations into account. This means that stations are expected to comply with the MES even if the national ambient air quality standards are met before compliance. It is further envisaged that a Carbon tax as an instrument to encourage carbon mitigation will come into effect in 2016 (Greve, 2013).

The energy sector in South Africa is the biggest contributor to SO_2 and NO_x emissions and second highest contributor to PM emissions of all sources of air emissions in the country (70%, 55% and 36%, respectively) compared to industrial, commercial & institutional fuel burning (27%, 23% and 44%), vehicle emissions (2%, 21%, 5%), biomass burning (0%, 0.3%, 6%) and domestic burning (0.8%, 0.2%, 9%) (DEA, 2012; Scorgie *et al.,* 2004). However, several studies have shown that power station emissions are not the main cause of adverse health impacts from air quality in South Africa. Past studies have found that domestic burning has by far the largest impact on human health (Friedl *et al.,* 2008; Scorgie *et al*., 2004). Domestic burning of wood, coal and paraffin is practiced by the very poor, living in informal settlements, in South Africa. In 2011, the number of households living in informal households was in the order of 1.25 Million, of which 57% of these households did not have access to electricity. Of the 43% of households that did have access to electricity, many opted to still making use of domestic burning of wood, paraffin and coal for their cooking and heating needs (Housing Development Agency (HDA), 2013).The reason for the large negative impact of domestic burning emissions on human health is the close proximity of emissions to humans (at ground level), the concomitance of peak emissions with periods of poor atmospheric dispersion (early morning, night time and winter time) and the release of these emissions within areas of dense population exposure to both indoor and outdoor pollution concentrations (Scorgie *et al*., 2004). On the other hand, power station emissions are emitted through tall stacks and therefore usually dilute in the atmosphere before reaching human lungs. It is believed that cost and unreliable supply are the main factors that keep the South African poor from switching to electricity (Friedl *et al.,* 2008).

In the past, regional CO_2 and NO_x emission factors for the power sector in Southern Africa were determined both theoretically and from continuous in-stack measurements for comparison to the Intergovernmental Panel on Climate Change (IPCC) default emission factors (Zhou *et al.* 2009). It was found that Southern African CO_2 emission factors were on the upper end of the IPCC default emission range whereas NO_2 emission factors were below the low end of the range. In 2013, a document was published on the outlook of the coal value chain in South Africa. Emissions projections for South African coal-fired power stations were made up until 2040 for four different future scenarios, namely a lag behind, more of the same, at the forefront and low carbon world scenario (South African Coal Roadmap (SACRM), 2013). However, this document is already outdated in terms of the decommissioning schedules of existing power stations and the projection of future South African energy demand (and therefore the building program of new power stations to meet this demand) (IRP, 2013). Currently there are no publications focusing on the current and future status of coal fired power station emissions in South Africa – taking into account the effect the energy crisis had on emissions, the most updated information on the decommissioning schedules of stations, the commissioning of stations currently under construction, the building of new stations and the retrofitting of stations with new, more efficient, emissions abatement technologies in the future.

The aim of this paper is to give a perspective on the contribution of South African coal-fired power stations to a wide range of pollutants, including criteria pollutants (PM, NO_x, SO_2) and CO_2. Historical emissions were investigated in order to establish a relationship between an energy restricted environment and emission trends. Estimations of future coal-fired power plant criteria and CO_2 emissions from 2015 to 2030 in South Africa are made for worst case, business as usual, intermediate and best case scenarios which are based on different predicted future energy demand outlooks and retrofit scenarios of stations with emissions abatement technologies.

1.1 The South African power sector

South Africa generates 32% of total energy on the African continent. Eskom, one of the largest energy utilities in the world, is responsible for the generation of approximately 95% of South African electricity and 45% of Africa's electricity (Eskom, 2010). Eskom power is exported to Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe. Eskom-owned coal-fired power plants, all of which are base load plants, include Arnot, Duvha, Camden, Grootvei, Hendrina, Kendal, Komati, Kriel, Lethabo, Majuba, Matla, Matimba and Tutuka (Eskom, 2012). The remaining 5% of South African electricity is generated by coal-fired power plants owned by the private sector (Kelvin power plant), municipalities (Rooiwal, Pretoria West and Bloemfontein power plants) and Sasol. Currently two additional Eskom plants are under construction, namely Medupi and Kusile. It is expected that the first units of each will come online during 2015, although there is still uncertainty about the precise dates (Eskom, 2013a; Eskom, 2013b). It is evident that even though the South African government is trying to reduce the country's dependence on coal; it will remain a dominant source of energy in South Africa, at least in the medium term.

Most South African power plants consist of six to ten units with an average capacity of approximately 600 megawatt (MW) each. Eight of the thirteen base-load stations have generating capacities in excess of 3 000 MW. When compared to the approximate average sizes of thermal power plants in the United States (737 MW) (US Energy Information Administration (US EIA), 2013a), it is clear that South African power stations are extremely large when compared to their international counterparts.

South Africa has been at the forefront in the developing world in recognizing climate change and its role in addressing carbon dioxide emissions. The latest developments include the commitments made by the presidency at the 2009 Climate Summit, to a 'peak, plateau and decline' emissions path between 2010 and 2050. This means that carbon emissions are allowed to peak between 2020 and 2025 at 500 megatons (Mt) to 550 Mt CO_2 equivalent and then to remain constant at this level until 2035, where after it should decline to between 200 Mt and 400 Mt in 2050 (DEA, 2010; Department of Environmental Affairs and Tourism (DEAT), 2009). In January 2010 the country formally notified its climate change mitigation proposals with the United Nations Convention on Climate Change. These included a 34% reduction of emissions below 'Business as Usual' by 2020 and a 42% reduction by 2025. Whether or not these targets can be realistically met will be addressed in Section 3.3 of this paper when future CO_2 emissions projections for South Africa are discussed.

1.2 South African coal quality

South African coal has the general characteristics of the southern hemisphere Gondwana coal and therefore differs from northern hemisphere Laurasian coal in being variable between regions and seams and in possessing relatively high ash contents, low calorific values and low sulphur, sodium, potassium and chlorine contents (Falcon and Ham, 1988). The variability in the quality of South African coals is illustrated by the fact that the difference between the maximum and minimum ash contents, calorific values and sulphur contents burned at Eskom during the 1999 to 2012 historical period was 4%, 6 mega joules per kilogram (MJ/kg) and 19%, respectively (Eskom, 2006 - 2012). The average ash content, sulphur content and calorific values of South African fuel coals compared to those of China, United States (US), India, Russia and Germany, the major coal consumers in the world, are shown in Figure 1 (Chandra and Chandra, 2004; Eskom, 2006; 2007; 2008; 2009; 2011; 2012; European Association for Coal and Lignite (EURACOAL), 2013; Podbaronova, 2010; Sun, 2010 and US EIA, 2013b). The annual coal consumption of each country is also indicated in megatons per annum (Mtpa) (US EIA, 2014).

2. Methods

2.1 Historical South African power plant emissions

Historical South African coal-fired power station emissions were investigated in order to understand the effect of an energy restricted environment on emissions. Historical emissions and energy production information for Eskom power plants over the period 1999 to 2012 were obtained from the Eskom energy utility's annual reports (Eskom, 2006-2012). Total annual PM emissions reported in these reports were estimated by means of continuous opacity monitoring systems and estimated vol-

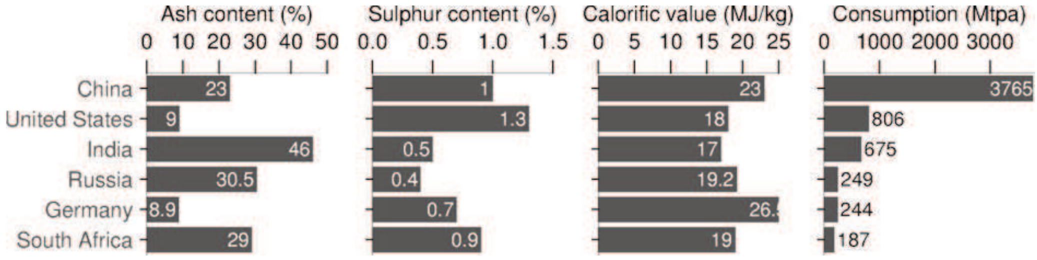


Figure 1: A comparison of average ash contents (%), calorific values (MJ/kg) and sulphur contents (%) of fuel coals from the major coal consumers in the world, namely China, US, India, Russia, Germany and South Africa (in descending order of coal consumption (Mtpa))

umetric flow rates of flue gas in power station stacks. NO_x, SO_2 and CO_2 annual emissions were estimated from mass-balance equations and annual coal consumption tonnages. Although Eskom does not currently calculate uncertainties associated with their emissions estimation techniques, it is estimated from similar operations elsewhere in the world that uncertainties associated with PM, NO_x, SO_2 and CO_2 emissions estimation at Eskom is around 10%, maximum 20%, maximum 20% and maximum 7.5%, respectively (Source Testing Association, personal communication; European Commission, 2012; Evans *et al.,* 2009). It was assumed that the coal-fired power plants not owned by Eskom followed the same emissions trends as the Eskom plants during this period. This assumption is valid as Eskom plants generate the major share of South African electricity (95%). Relative emissions from coal fired power stations were calculated by normalizing the absolute emissions (in units of mass per annum) for total electricity production per annum. It was assumed that all Eskom reported emissions originated from coal fired power stations as gas turbine stations (the only emitters apart from coal fired power stations) were responsible for only a fraction ($<<$ 1%) of total energy production and therefore have a negligible effect on total criteria and CO_2 emissions.

2.2 Future emission projections

Projections of future South African coal-fired power station emissions were made for the period 2015 to 2030. The decommissioning of power stations, the addition of Kusile and Medupi power stations and the building of new power stations in the future were included in the emissions projections. The decommissioning and new building schedules are strongly dependent on future energy demand, which in turn is dependent on numerous factors such as demand responses to higher electricity prices, structural changes in the economy, energy efficiency and population dynamics (Energy Research Centre, 2013; Department of Energy (DOE), 2012).

The projection of future South African energy demand is therefore associated with high relative uncertainties. However, the fact that this paper only looks at coal-fired power station demand projections simplifies this process to an extent. It is unlikely that Eskom will be able to construct another large scale coal-fired power station after the completion of Kusile and Medupi (Eskom, personal communication). Even if this is the case, the construction of such a power station will take time (Medupi and Kusile will take an estimated 15 years to be fully constructed) and therefore such a station will most likely only contribute to emissions after 2030 (the cut-off date of emissions projections in this paper). It is furthermore probable that the 50-year lifetimes of existing stations will be expanded instead of investing in new coal generating capacity as this will most likely be the more cost effective option. For this reason, the future coal-fired power station new building program and decommissioning schedules assumed in this study are based on the baseline projection as published in the updated IRP (IRP, 2013).

The baseline projection published in the IRP 2013 is the preferred power generation output of TIMES modelling done by the Energy Research Centre at the University of Cape Town (Energy Research Centre, 2013). The TIMES model makes use of a number of assumptions including demand projections, fuel prices and CO_2 emissions constraints in order to project the optimal energy mix to sustain future demand (Energy Research Centre, 2013). The baseline scenario published in the recently updated electricity resource plan (IRP, 2013) and based on the above mentioned modelling, proposes that the lifetimes of existing coal-fired power stations (excluding the return-to-service stations) will be extended beyond their 50 year operational time period and that 2 500 MW of new coal-fired capacity be added in the future. This is believed to be a more realistic scenario compared to an addition of 6 500 MW and no extensions of the lifetimes of power stations as proposed in the IRP 2010. Business as usual, intermediate and best case future projections of criteria and CO_2 emissions were based on the updated IRP baseline scenario (Table 1, black text), but an additional worst case scenario was included where high energy demand

Table 1: A summary of the decommissioning-, commissioning- and new build schedules for South African coal fired power stations for the period 2015 to 2030

(The total nominal capacity assumed in the worst case projected scenario (which assumes no decommissioning of power stations) is indicated in grey text whereas black text indicates the energy outlook as indicated by the IRP (2013) baseline case.)

Term	*Decommissioning schedule (MW)*	*Commissioning schedule (MW)*	*Total nominal capacity (MW)*
Short-term 2015-2020	Non Eskom (-180) Non Eskom (-90)	Medupi (+4800) Kusile (+4800)	49000, 49000
Medium-term 2020-2025	Non-Eskom (-170) Komati (-90) Camden (-1500)		46000, 49000
Long-term 2025-2030	Grootvlei (-1200)	New Coal (+2500),	48000, 49000

Table 2: A summary of the business as usual, intermediate and best case scenarios, used to make future projections of PM, SO_2, NO_x and CO_2 emissions. The worst case scenario assumes no retrofits and high energy demand

Pollutant	*Abatement nology required to comply with 2020 MES*	*Scenarios* *Business as usual*	 *Intermediate*	 *Best Case*
PM	Fabric Filter Plant (FFP).	No FFP's are retrofitted on existing stations in the future. Medupi, Kusile and new stations make use of FFP's.	FFP's are retrofitted at Duvha (the remaining 3 units) 2021-2023, Grootvlei (remaining 3 units) 2015-2017, Kriel (6 units), Matla (6 units) 2019-2024 and Tutuka (6 units) 2018-2023 at a reduced retrofit rate. Medupi, Kusile and new stations make use of FFP's.	FFP's are retrofitted at Duvha (the remaining 3 units) 2018-2020, Grootvlei (remaining 3 units) 2015-2016, Kendal (5 units) 2020-2025, Kriel (6 units) 2016-2020, Lethabo (6 units) 2015-2021, Matla (6 units) 2013-2017 and Tutuka (6 units) 2014-2019, at an aggressive retrofit rate. Medupi, Kusile and new stations make use of FFP's
NO_x	Low NO_x burner (LNB). Emissions are assumed to average 700 mg/Nm^3 at 10% O_2 after retrofits.	No existing stations are retrofitted with LNB's. Medupi, Kusile and new stations make use of LNB's.	LNB's are retrofitted at 3 existing stations, namely Tutuka 2020-2025, Matla 2012-2015 and Majuba 2020-2025. Medupi, Kusile and new stations make use of LNB's.	LNB's are retrofitted at 4 existing stations, namely Tutuka 2020-2025, Matla 2021-2015 and Majuba 2020-2025 and Kriel 2020-2025. Medupi, Kusile and new stations make use of LNB's.
SO_2	Flue Gas Desulfurization Plant (FGD). It was assumed that a dry FGD has 40% removal efficiency and a wet FGD 90%.*	No FGD's are retrofitted on existing stations. Kusile makes use of a wet FGD. Medupi is retrofitted with a dry FGD. New stations make use of dry FGD's.	Dry FGD's retrofitted at Medupi 2019-2022 and Kendal 2021-2026. Kusile makes use of a wet FGD. New stations make use of dry FGD's.	Dry FGD's retrofitted at Kendal 2021-2026, Majuba 2028-2030, Lethabo 2024-2028, Tutuka 2027-2032, Duvha 2025-2030, Matla 2022-2027, Kriel 2023-2028 and Medupi 2019-2022. Kusile makes use of a wet FGD. New stations make use of dry FGD's.
CO_2	None	Dry FGD's retrofitted at Kendal 2021-2026, Majuba 2028-2030, Lethabo 2024-2028, Tutuka 2027-2032, Duvha 2025-2030, Matla 2022-2027, Kriel 2023-2028 and Medupi 2019-2022.	Dry FGD's retrofitted at Medupi 2019-2022 and Kendal 2021-2026. Kusile makes use of a wet FGD. New stations make use of dry FGD's.	No FGD's are retro fitted on existing stations. Kusile makes use of a wet FGD. New stations make use of dry F GD's.

* According to the United States Environmental Protection Agency (US EPA) (2003) removal efficiencies of calcium-based dry FGD systems are in the order of 50% to 60% and wet FGDs in excess of 90%. In order to be conservative it was assumed that the removal efficiency of dry FGD's are 40% and wet FGD's 90%.

was assumed (and therefore that no power stations will be decommissioned) (Table 1, grey text). The worst case emissions scenario can be seen as an estimation of an upper limit of emissions if rapid economic growth occurs and the pressure on the South African energy system remains high.

The business as usual, intermediate and best case scenarios are based on different retrofitting rates of power stations with newer, more efficient abatement technologies. Mitigation strategies for different pollutants are independent of one another and are all tied with different technologies, capacities and infrastructure development pathways. The abatement technologies include the retrofitting of Electrostatic Precipitators (ESPs), the current abatement technologies used at around half of the existing power stations with Fabric Filter Plants (FFP's) (which have higher efficiencies than ESPs) for reducing PM emissions, Low NO_x Burners (LNB) for reducing NO_x emissions, and Flue Gas Desulfurization Plants (FGD) for SO_2 emissions reductions. The business as usual scenarios assume retro-fitments only on new stations whereas the intermediate and best case scenarios assume less aggressive and aggressive retro-fitment rates, respectively. There is no emissions abatement planned for CO_2 emissions reductions at present; however CO_2 emissions are influenced by the FGD retrofit scenario as CO_2 is a direct by-product of the wet FGD process and the additional auxiliary power requirements of the FGD system of around 1% of annual power generation by the station (E-ON Engineering, 2007). CO_2 emission scenarios are therefore slightly influenced by the SO_2 retrofit scenario. The effect of LNB's on CO_2 emissions was considered to be negligible (there are some who believe it will impact CO_2 emissions by changing the thermal efficiency of a power station, but information on this is scarce). A summary of the retrofit schedules assumed in the business as usual, intermediate and best case scenarios are given in Table 2. Retrofit rates and schedules were possible scenarios proposed by Eskom (Eskom, personal communication).

Intermediate and best case emissions were calculated by making use of relative emissions for the different retrofit scenarios (Table 3) based on the efficiency of emissions abatement technology and projected future load factors (Eskom, personal communication). Retrofits of FFP's, LNB's and FGD's take place at a rate of one unit per year and therefore relative emissions were allowed to gradually decrease during the retrofit period. Business as usual criteria emissions projections were calculated from the current emission limits to which stations adhere (see Table 4) (Eskom, personal communication). Relative CO_2 emissions for the business as usual, intermediate and best case scenarios were assumed to be 1 000 kg/MWSO for all power stations where no FGD retrofits take place (Eskom, personal communication). The annual increase in CO_2 emissions that would result due to the installation of an FGD plant at a given power station were obtained from Eskom's applications for postponement or exemption from the MES (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i). Worst

Table 3: Relative emissions and average load factor values used for the projection of intermediate- and best case emissions scenarios before and after the instalment of emissions abatement

Station	*PM Relative emissions (kg/MWh)*		*NO_x Relative emissions (kg/MWh)*		*SO_2 Relative emissions (kg/MWh)*		*Average load factor*
	Before FFP	*After FFP*	*Before LNB*	*After LNB*	*Before FGD*	*After FGD*	
Arnot	0.13-0.2		4300		6600		70
Duvha	0.25-0.33	0.07-0.12	4300		7200	720	80
Hendrina	0.08-0.09		4300		10300		72
Kendal	0.2	0.12	3600		8100	820	83
Kriel	0.8-1	0.12	6200	3600	6600	660	76
Lethabo	0.35-0.44	0.15	4500		7900	790	79
Majuba	0.09-0.11		5500	3300	6800	680	62
Matimba	0.12-0.19		2500		11500		85
Matla	0.45-0.69	0.12	5200	3900	8400	840	81
Tutuka	0.75-0.83		5300	4000	9400	940	72
Camden	0.12		4300		9500		52
Grootvlei	1.06-1.44	0.2	4400		8600		57
Komati	0.35-0.65		5600		6900		55
Medupi		0.09-0.12		1700	10700	1000	81
Kusile		0.09		1700		900	80
New Coal		0.09		1700		900	86

case scenarios were calculated by making use of the highest relative emissions of the power generation fleet during the historical period 1999 to 2012 (see Figure 4) and the projected generating capacity based on a high future energy demand scenario assuming that no power stations are decommissioned during the projected period (grey values in Table 1).

Table 4: Current emission limits for Eskom power stations (mg/Nm^3) under normal conditions of 10% O_2, 273 Kelvin and 101.3 kPa

Power station	*PM (mg/Nm^3)*	*NO_x (mg/Nm^3)*	*SO_2 (mg/Nm^3)*
Arnot	50	760	1400
Duvha	75	1100	2100
Hendrina	50	1100	2700
Kendal	100	860	2100
Kriel	125	1100	2100
Lethabo	100	900	2100
Majuba	50	1100	1900
Matimba	100	760	3300
Matla	175	1100	2400
Tutuka	250	1100	2100
Camden	50	990	2400
Grootvlei	300	1500	3000
Komati	100	1200	1600
Medupi	50	750	750
Kusile	50	750	750

The formula used to calculate total emissions from relative emissions is as follows:

$$E = h \sum_i \sum_j R_{ij}.C_j L_j$$

Where E is total annual emissions of a specific pollutant, i, in tons/year, h is the total hours in a year, R is the relative emission in tons per megawatt hour sent out (t/MWhSO), C_j is the total nominal capacity of power station j (MW), and L_j is the generation load factor of power station j (%) as planned by Eskom (Eskom, personal communication). The following formula was utilized to calculate total emissions from emission limits and the volumetric flow rates of power stations:

$$E = h \sum_i \sum_j V_j.L_j.EL_{ij}.n_j.10^{-9}$$

Where V_j is the specified gas volume flow rate in normal cubic metres per hour (Nm^3/h) for a single boiler at power station j, EL_{ij} is the emission limit of pollutant i in milligrams per normal cubic metre (mg/Nm^3) with which power station j comply and n_j is the number of boilers at power station j.

Even though South African legislation dictates that emissions information should be available to the public of South Africa, the reality is that information is relatively inaccessible. It was therefore not possible to obtain current information from Sasol, Kelvin power station and the municipal power stations. Emissions estimations for these non-Eskom plants were made by assuming that they have similar emissions to Eskom plants of similar ages and operational conditions, making use of similar emissions abatement technologies. This is the same approach taken in the SACRM (2013). The future energy projections further assumed that future fuel coal quality will remain constant and similar to current values.

3. Emissions trends and projections

3.1 South African power plant emissions during the energy crisis

Electricity reserve is the amount of reserve energy in an electric power system left after consumer supply has been met at all times. The electricity reserve is required in order to operate reliably in the face of possible unplanned equipment outages and fluctuations in demand due to occurrences such as unusually cold weather conditions (DOE, 2010). Electricity reserve can therefore be used as an indicator of how much pressure an electricity generation system is under. When electricity demand is greater than supply, there will be very little spare electricity in the system. The decline in the electricity reserve of the South African energy system from 1999 to 2007 marks the approach of the energy crisis (Figure 2) (Eskom, 2006-2012; Eskom 2014). During the period leading up to the energy crisis and during the energy crisis itself, the electricity reserve fell well below the Eskom aspiration of 15%. Internationally, percent electricity reserve requirements usually fall in the range of 15% to 25% (DOE, 2010). The electricity reserve curve was skewed after 2008, when the implementation of load shedding increased the electricity reserve artificially. During 2011 and 2012, the reserve was increased by means of the application of power buy-backs by Eskom, in which certain energy intensive consumers were paid not to use energy during this period. From the end of 2014 onwards, the reserve was again increased by means of the implementation of load shedding and Eskom urging large consumers to cut back their electricity consumption by 10%.

Three older power plants (Camden, Grootvlei and Komati) that were mothballed during the late 1980's and early 1990's had to return back to service during 2004 to 2013 in order to help alleviate the pressure on operational plants. These older plants have lower thermal efficiencies and, in most cases, make use of older, less effective particulate matter abatement technologies. Since the load

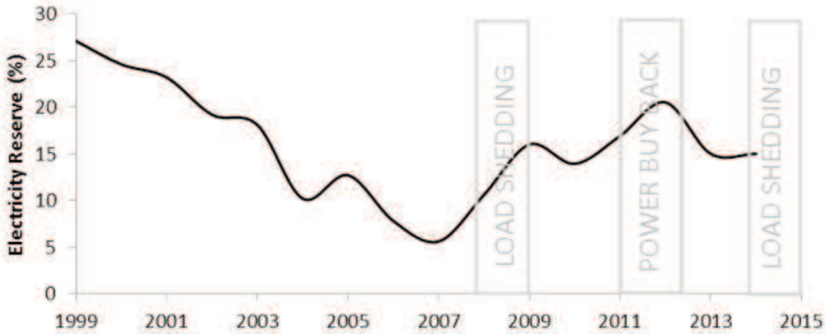


Figure 2: The electricity reserve (%) of the South African coal fired power station fleet during the period 1999 to 2014

shedding that occurred during 2008, electricity demand could be met by means of delaying maintenance on the generation fleet, which led to the decline in performance of the fleet (IRP, 2013). This deteriorating effect is evident in the fact that the IRP (2011) assumed the fleet to have an average availability of 86%, but in reality the actual performance declined to less than 80% (IRP, 2013). The combination of the above mentioned factors contributed to the decline of approximately 3% in the overall thermal efficiency of the fleet between 2007 and 2012 (Eskom, 2006; 2007; 2008; 2009; 2011; 2012). The energy crisis therefore had a negative effect on the overall thermal efficiency of South African power plants, which meant that more coal had to be burned in order to produce the same amount of energy. The decline in the thermal efficiency of the fleet led to an increase in coal burn of approximately 8% per annum relative to energy output from 2008 onwards as indicated in Figure 3 (Eskom, 2006-2012; Eskom 2014).

The relative (emissions per energy output) and absolute (total annual emissions) criteria- and CO_2 emissions for South African power plants for the period 1999 to 2012 are shown in Figure 4 (Eskom, 2006-2012). Absolute emissions are a multiplication function of the relative emissions and annual energy sent out. Therefore it is important that absolute emission trends be seen against the annual energy sent out (Figure 3).

PM emissions are mainly a function of the ash content of the coal burned and the efficiency of the PM abatement technology used (United States Environmental Protection Agency (US EPA), 1993). Approximately half of South African thermal power plants currently make use of ESPs for PM control and the other half make use of FFP's. In general, the FFP removal efficiencies are higher than those of ESP's, by design. In South Africa, plants making use of ESP's experience additional difficulties associated with the low sulphur content of coal fuels (and therefore low resistivities of fly ash), and various operational and maintenance challenges. In order to mitigate the problem of low resistivity fly ash, flue gas conditioning (by means of SO_3 injection) is done at the majority of plants that make use of ESPs.

The sharp increase in relative PM emissions from 2007 to 2010 is explained by the increase in relative PM emissions due to the increased pressure on PM abatement equipment during this period. From 2010 onwards, relative PM emissions started to decline, albeit not to pre-energy crisis levels. This reduction is explained by the major modifications that were completed on particulate emission abatement equipment in 2010 (Eskom, 2010). Absolute emissions mainly followed the same trend as that of relative emissions, thereby showing that the absolute emissions were strongly affected by the increase in relative emissions during the energy cri-

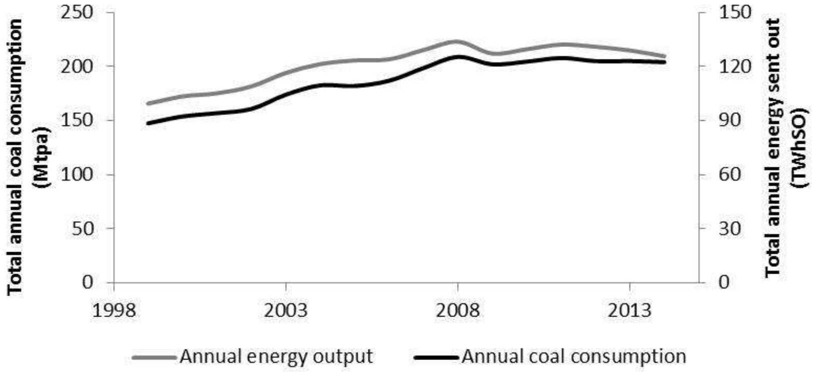


Figure 3: The total annual coal consumption (Mtpa) and annual energy output in terawatt hour sent out (TWhSO) of the South African coal-fired power station fleet during the period 1999 and 2014

sis period. Absolute PM emissions almost doubled between 2007 and 2010 (from 43 ktpa to 84 ktpa) when energy output only increased by approximately 0.3% during the same period. It is therefore clear that PM emissions were highly affected by the energy crisis. The reason for this is the fact that abatement technology experienced tremendous strain during the energy-restricted period and maintenance opportunity was low. PM is the only pollutant that is currently controlled by means of abatement, but in the future FGD's and LNB's maybe installed to control SO_2 and NO_2 emissions, respectively. It can be argued that, if the energy crisis persists in the future, removal efficiencies of these abatement technologies will probably be lower than expected, as in the case of PM abatement during the historical energy crisis period (2007 to 2012).

The absolute and relative NO_x emissions during the period 1999 to 2012 are indicated in Figure 4. NO_x emission factors are governed by a number of different factors, including the thermal efficiency of the plant, fuel quality, boiler type and emission control level (US EPA, 1993). Currently, none of the South African thermal power plants make use of NO_x abatement technologies. From 2006 onwards, absolute NO_x emissions increased by 10% (from 877 ktpa to 977 ktpa) whereas energy output only increased by 6%.

Uncontrolled SO_2 emissions from conventional pulverized combustion are almost exclusively a function of the sulphur content in the fuel and SO_2 abatement (US EPA, 1993). Currently there are no operational power stations using SO_2 abatement. The absolute and relative SO_2 emissions from the South African coal fired power station fleet during the period 1999 to 2012 are shown in Figure 4. Relative SO_2 emissions (kg/MWhSO) remained relatively stable during the energy crisis period, and absolute emissions mainly followed the energy sent out trend of Figure 3. This can be explained by a decrease in average sulphur content in coals burned during the period 2007 to 2012 of around 10% (Eskom 2007-2012).

The amount of CO_2 emitted by a thermal power

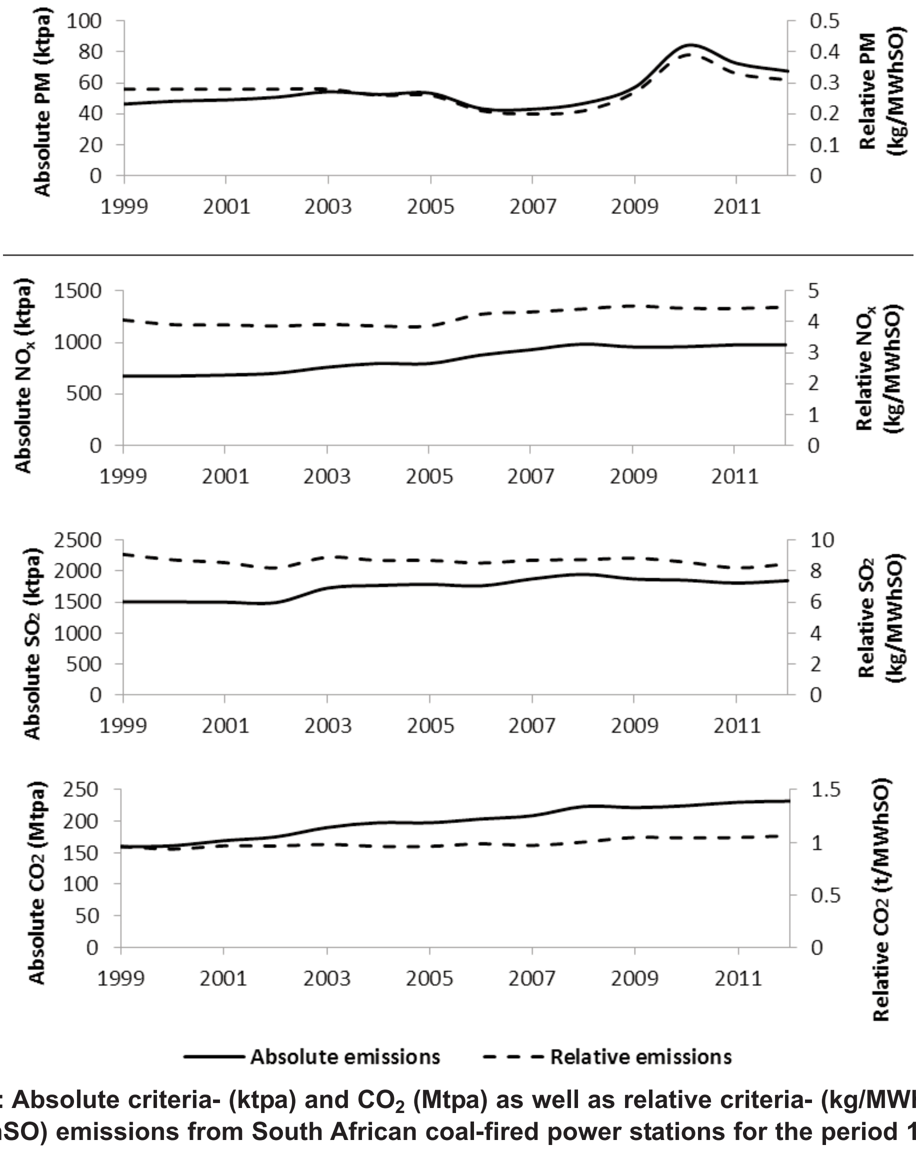


Figure 4: Absolute criteria- (ktpa) and CO_2 (Mtpa) as well as relative criteria- (kg/MWhSO) and CO_2 (t/MWhSO) emissions from South African coal-fired power stations for the period 1999 to 2012

plant depends on the thermal efficiency of the plant and the extent to which the energy content of the coal can be converted into electrical energy without losses. Absolute CO_2 emissions increased by 15% (from 200 Mtpa to 230 Mtpa) during the 2006-2012 period (Figure 4) whereas energy output only increased by 6% (Figure 3). The reason for this increase was the reducing effect the energy crisis had on the overall thermal efficiency of the fleet.

3.2 Emissions projections

Future projections of absolute criteria coal-fired power station emissions indicated as a percentage growth against a 2015 baseline are depicted in Figure 5. It is important to note that projections for 2015 differ and that for this reason not all projections intercept zero. Real projected values (not normalized for a 2015 baseline case) are tabulated in Table 5 and are supplied for input to prospective modelling endeavours.

There is a marked difference between projected best- and worst case PM emissions during the entire projected period, but especially during 2030 when worst case PM emissions are expected to rise by 40% from a 2015 baseline value and best case PM emissions are projected to decline by 40% from the same value (Figure 5). Eskom plans to retrofit FFP's at five existing stations and Medupi and Kusile will also make use of FFP's (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i). If this plan goes forward, future PM emissions will most probably follow the intermediate scenario trend which means that PM would have decreased by around 28% in 2030 compared to a 2015 baseline value (Figure 5). However, if pressure on the energy system remains high and maintenance opportunities are continually missed, retrofits may not be possible and emissions may follow the business as usual or even the worst case scenario trends.

Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030. There is not a marked difference between predicted best case and intermediate emissions trends. Eskom undertakes to install LNB's at four of its existing stations (Medupi and Kusile will both also make use of LNB's) (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i), if this is done and if the current pressure on the energy system decreases, emissions will follow the approximate best case NO_x emissions trend, which means that emissions are expected to decline by approximately 10% between 2015 and 2030.

There is a marked difference between worst- and best case SO_2 emissions during 2030 (Figure 5), where worst case emissions are predicted to increase by around 38% from a 2015 baseline in 2030 and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value. Eskom undertakes to retrofit one FGD at Medupi power station (although some uncertainty exists on this). FGD systems are major infrastructure investments with high complexity of operation and are associated with high capital and operational costs. This means that the most probable SO_2 emissions trend is the business as usual scenario (which is projected to stay relatively constant

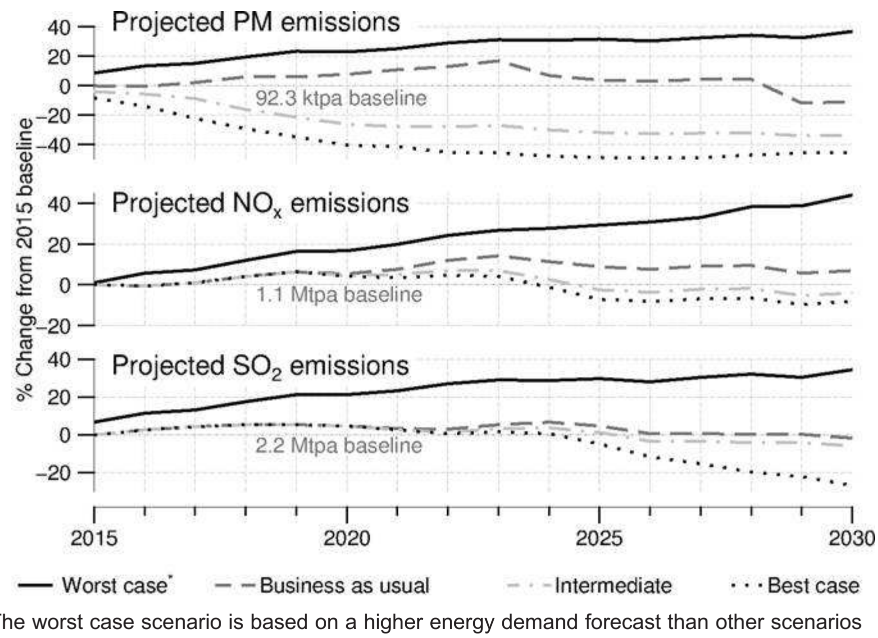


Figure 5: Future projections (in % change from a 2015 baseline) of absolute criteria emissions for 2015 to 2030 for four different future scenarios, namely worst case, business as usual (BAU), intermediate and best case scenarios

between 2015 and 2030) or the worst case scenario, if pressure on the energy system persists.

Table 5: Absolute emissions projected for criteria pollutants (ktpa) for different scenarios in 2015, 2020, 2025 and 2030

Scenarios	*Worst case*	*Business as usual*	*Intermediate*	*Best case*
		PM (ktpa)		
2015	100	92	89	85
2020	115	97	68	55
2025	127	96	63	47
2030	135	82	62	50
		NO_x (ktpa)		
2015	1160	1094	1094	1094
2020	1334	1155	1145	1139
2025	1470	1192	1067	1017
2030	1559	1172	1052	1005
		SO_2 (ktpa)		
2015	2336	2186	2186	2186
2020	2652	2295	2295	2295
2025	2839	2293	2216	2086
2030	2946	2155	2063	1605

3.3 CO_2 emissions projections and South African climate commitments

Absolute emission projections for CO_2 are given in Table 6 whereas CO_2 projections in % change from a 2015 baseline value are shown in Figure 6. The difference between CO_2 scenarios assuming different retrofit rates of FGDs (business as usual, intermediate and best case scenarios) was negligibly small and was therefore indicated as a single line in Figure 6 (namely IRP Baseline, because of the fact that these scenarios assume the updated IRP baseline future energy demand and energy mix). The worst case- and IRP baseline projected CO_2 emissions in 2015 differ because of the fact that they have assumed different relative CO_2 emissions, and for this reason both lines do not intercept zero.

One of the assumptions of the TIMES energy demand/energy mix modelling was that CO_2 emissions are capped at 275 Mtpa from 2025 onwards in order to follow a peak, plateau and decline trajectory (Energy Research Centre, 2013). However, use was made of relative CO_2 emissions for supercritical boilers in the modelling (IRP, 2013). Only Medupi and Kusile fall in this category, whereas all 13 other base load stations as well as Sasol and municipality-owned stations do not. Relative CO_2 emissions assumed for supercritical boilers in the TIMES modelling and IRP (2013) are 947 kg/MWhSO, whereas the Eskom average for the period 2002 to 2012 was 1002 kg/MWhSO and projections in this publication assumed 1000 kg/MWhSO. This means that CO_2 emissions were underestimated during the energy forecast modelling for the updated IRP.

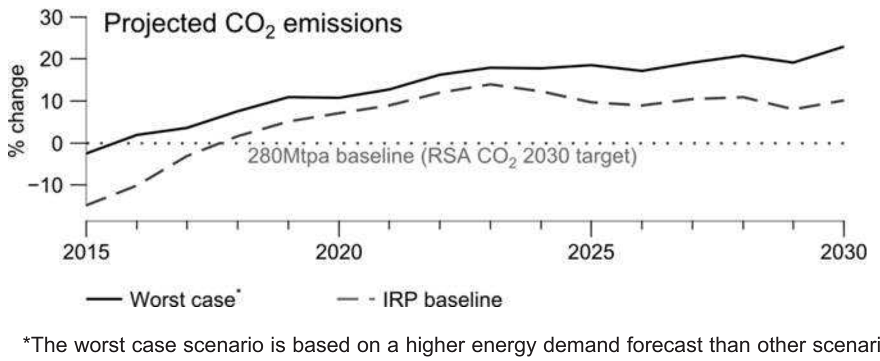
When a 45% contribution of the electricity sector (and specifically coal fired power stations) to total carbon emissions in South Africa is assumed, the upper limit carbon emissions of the electricity sector, according to South Africa's climate change commitments, should be in the order of 280 Mt by 2030 (IRP, 2013). From the CO_2 projections in this study (Table 6) it is clear that it is unlikely that this target will be met, unless economic growth and energy demand dramatically decrease in the future.

Table 6: Absolute emissions projected (Mtpa) CO_2 for different scenarios in 2015, 2020, 2025 and 2030

Scenarios	*Worst case*	*Business as usual*	*Intermediate*	*Best case*
		CO_2 (Mtpa)		
2015	273	239	239	239
2020	314	300	300	300
2025	346	307	307	306
2030	367	308	306	306

4. Conclusions

South African coal is variable between regions and seams and has relatively high ash contents, low calorific values and characteristically low sulphur



*The worst case scenario is based on a higher energy demand forecast than other scenarios

Figure 6: Future projections of absolute CO_2 (in % change from a baseline) emissions for a worst case, and IRP baseline scenario during the period 2015 to 2030

contents. The difference between the maximum and minimum ash contents, calorific values and sulphur contents during the historical period 1999 to 2012 is 4%, 6 MJ/kg and 19%, respectively. The implication of this is that emissions from South African coal-fired power stations may vary only based on the variability of fuel coals. This is especially true for uncontrolled SO_2 emissions as sulphur contents showed large variability during the historical period.

An energy-restricted environment has an increasing effect on emissions. This is especially true for pollutants controlled by means of abatement as increased pressure on abatement technology and low maintenance opportunity reduce removal efficiencies. Absolute PM emissions doubled between 2007 and 2010, the height of the energy crisis, when energy output only increased by around 0.3% during the same period. There is a marked difference between projected best- and worst case PM emissions during the 2015 to 2030 projected period, but especially during 2030 when worst case PM emissions are expected to rise by 40% from a 2015 baseline value and best case PM emissions are projected to decline by 40% from the same value.

NO_x emissions increased by 10% during the 2006-2012 energy crisis period whereas energy output only increased by 6%. The reason for this increase was the reducing effect the energy crisis had on the overall thermal efficiency of the coal-fired power station fleet. Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030.

SO_2 emissions did not increase during the energy crisis because the sulphur content in fuel coals decreased. There is a marked difference between worst- and best case SO_2 emissions during 2030, where worst case emissions are predicted to increase by around 38% from a 2015 baseline in 2030 and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value. The best case SO_2 scenario (eight stations being retrofitted with FGD's) is highly improbable as FGD systems are major infrastructure investments with high complexity of operation and are associated with high capital and operational costs. At best Eskom undertakes to retrofit one FGD at Medupi power station (although some uncertainty exists on this). This means that the most probable SO_2 emissions trends are the business as usual scenario (which is projected to stay relatively constant between 2015 and 2030) or the worst case scenario (projected to increase by around 20% during the 2015 to 2030 period), if pressure on the energy system persists.

CO_2 emissions increased by 15% during the 2006-2012 period whereas energy output only increased by 6%, as a result of the decline of power station thermal efficiencies during the energy restricted period. Relative emissions used in the projection of future CO_2 emissions in this publication differs from that used in the energy demand and energy mix modelling done for the updated IRP baseline case. The reason for this is that the modelling for the updated IRP assumed a relative CO_2 emission for supercritical boilers whereas only Kusile and Medupi fall in this category. The relative CO_2 emissions for the rest of the South African coal-fired power station fleet are between 5% and 16% higher than that of supercritical boilers. From projections of future CO_2 emissions in this study it seems unlikely that the South African climate commitment target of 280 Mt in 2030 will be made, unless energy demand dramatically decreases in the future.

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Modelling energy supply options for electricity generations in Tanzania

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Abstract

The current study applies an energy-system model to explore energy supply options in meeting Tanzania's electricity demands projection from 2010 to 2040. Three economic scenarios namely; business as usual (BAU), low economic consumption scenario (LEC) and high economic growth scenario (HEC) were developed for modelling purposes. Moreover, the study develops a dry weather scenario to explore how the country's electricity system would behave under dry weather conditions. The model results suggests: If projected final electricity demand increases as anticipated in BAU, LEC and HEC scenarios, the total installed capacity will expand at 9.05%, 8.46% and 9.8% respectively from the base value of 804.2MW. Correspondingly, the model results depict dominance of hydro, coal, natural gas and geothermal as least-cost energy supply options for electricity generation in all scenarios. The alternative dry weather scenario formulated to study electricity system behaviour under uncertain weather conditions suggested a shift of energy supply option to coal and natural gas (NG) dominance replacing hydro energy. The least cost optimization results further depict an insignificant contribution of renewable energy technologies in terms of solar thermal, wind and solar PV into the total generation shares. With that regard, the renewable energy penetration policy option (REPP), as an alternative scenario suggests the importance of policy options that favour renewable energy technologies inclusion in electricity generation. Sensitivity analysis on the discount rate to approximate the influence of discount rate on the future pattern of electricity generation capacity demonstrated that lower values favour wind and coal fired power plants, while higher values favour the NG technologies. Finally, the modelling results conclude the self-sufficiency of the country in generating future electricity using its own energy resources.

Keywords: electricity generation, MESSAGE model, discount rate, renewable energy, supply options

1. Introduction

Energy is an important element in accomplishing the interrelated socio-economic development of any country. Tanzania's energy supply relies mainly on biomass, which accounts for nearly 90% of the total primary energy supply (Wawa, 2012, IEA, 2013). The remaining energy supply is accounted from petroleum products at approximately 8%, grid electricity 1% and renewable energy sources such solar and wind which account for nearly 1% (MEM, 2012, Kabaka and Gwang'ombe, 2007). Total electricity generation shares in 2012 were mainly from natural gas 50.7%, hydro 28.6%, oil products 20.1%, biofuels 0.3% and solar PV 0.2% (IEA, 2014). Projections are approximating electricity demand to reach 47.7 TWh in the year 2035 equivalent to an annual growth of approximately 8% (MEM, 2012). Energy resources are enormous and are available in various forms, including biomass, hydro, geothermal, biogas, wind, solar, natural gas and coal (Kihwele *et al.*, 2012, MEM, 2013a). There is an estimated coal proven reserve of 304 million tonnes. whereas that of natural gas is 45 billion cubic meters (Kusekwa, 2013, MEM, 2012). Geothermal has an estimated potential of 650 MW (Mnjokava, 2008, Kihwele *et al.*, 2012), while hydro estimated potential is 4700 MW (MEM, 2012). Biomass estimated sustainable potential is 12 million TOE from agriculture wastes, plantation forests and natural forests (Wilson, 2010). The country experiences annual sunshine hours of 2 800 to 3500 hours and solar irradiation ranging from 4-7 kWh/m^2 across the country (Casmiri, 2009, Kihwele *et al*., 2012). The renewable energy potential in the country is substantial but largely untapped for electricity and other thermal applications (Bauner *et al*., 2012, Kichonge *et al*., 2014b). The country's renewable energy potential from municipal solid wastes currently disposed in dump sites is considerable as shown in studies by Omari *et al.* (2014a) and Omari *et al*. (2014b).

Tanzanian energy demand, specifically electricity, has been growing over years because of socio-economic transformations that opened up the country's economy. Statistics on the country's GDP growth since the year 2000 show an annual average increase of 7% (BOT, 2012). However, substantial challenges faces the electricity sector owing to constrained generation capacity and distribution network (Kapinga, 2013, Wangwe *et al*., 2014) which previously resulted in outages and rationing (Loisulie, 2010, MEM, 2013b). Despite the electricity sector challenges, the demand is expected to grow as the country targets a middle income economy status as detailed in Development Vision 2025 (URT, 1999) and its implementation through Big Results Now (BRN) initiatives (Kahyoza, 2013). Realizing Tanzania Development Vision 2025 goals implies that the country needs adequate, reliable, affordable and environmentally friendly electricity supply options. Achieving these require optimal generation capacity additions, which consider diversifications of power plants systems. Finding optimal generation capacity addition based on least cost plan is important in formulating supply options considering the high investments costs associated with it. It is therefore the objective of this study to apply MESSAGE (Model for Alternative Energy Supply Strategies and their General Environmental Impacts) to find least-cost optimal energy supply options. MESSAGE is an appropriate framework for this study as it is capable of dealing with long-term planning horizons based on high-resolution short-term system dynamics. Using MESSAGE, optimization of electricity supply options in each scenario will help describes possible future final electricity supply options availability. Study results will benefit policy and decision makers to arrive at a relevant solution interactively in national electricity system expansion planning.

2. Methodology

2.1 MESSAGE Model

Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is an optimization modelling tool (Messner and Strubegger, 1995), which calculates the least-cost energy supply system. Connolly *et al.* (2010), describes MESSAGE as a bottom-up model capable of optimizing operation and investment of technologies in medium to long term energy systems. MESSAGE modelling approach allows the realistic evaluation of the long-term role of an energy supply option under competitive conditions (IAEA, 2008, Hainoun *et al.*, 2010). The least-cost determination in MESSAGE is through minimization of the total discounted energy system cost subject to the constraints representing demands, resource deficiency and capacity limits. Discounted energy system cost minimization includes investments, fixed and variable operation costs, maintenance costs, fuel and any additional penalty costs, which defines the limits and constraints relation. With MESSAGE, alternative energy supply strategies in agreement with user-defined constraints are assessed (IAEA, 2006, Tait *et al*., 2014).

Mathematical techniques tied up with MESSAGE comprises of linear and mixed-integer programming. The purpose for linear programming (LP) applications is that all the limits and the objective function (optimization target) are linear functions of the decision variables. Mixed-integer use in MESSAGE is due to integer values at the optimal solution requirements by some of the decision variables. Objective function in MESSAGE modelling approach is as shown in Equation 1. The variable $X_{i,j,t}$ denotes a flow variable (input) of fuel form *i* in technology *j* in the time step *t*. Flow variable describes amount produced in which technology and the type of fuel. The investment variable denoted by $Y_{i,t}$ represents new installation of technology *j* in time step *t*.

$$\mathrm{Min} \sum \mathrm{Cost} * \left(X_{i,j,t} + Y_{i,t}\right) \qquad (1)$$

The MESSAGE model computes the objective function to satisfy the condition to ensure demand-supply balance as illustrated in equation 2. The parameter *D* denotes energy demand, *j* represents energy demand of *j* while *t* represents time step. In addition, η represents technology efficiency, *X* denotes production decision of the technology, *i* is the number of technologies and *n* total number of technologies.

$$\sum_{i=1}^{i=n} \eta_{i,t} X_{it} \geq D_{j,t} \qquad (2)$$

MESSAGE has been used to model the power supply sector by means of the principle of reference energy system (RES), which allows representation of the entire energy network including possible development paths (Rečka, 2011, Selvakkumaran and Limmeechokchai, 2011). RES is composed of energy resources and sources, energy carriers (form) and technologies. RES captures network flow of energy carrier from one process to the other starting in the resource to the consumer delivery. The explanation of energy forms includes each level of energy chains, technologies using or producing these energy forms, and the energy resources. MESSAGE defines energy forms and technologies in all steps of energy chains. This includes identification of energy chain levels beginning from the demand to the resources, the energy forms to energy services. MESSAGE computes energy demand from the first level of each energy chain up to the energy resource level. Final demand level is distributed according to the types of consumption (Van Beeck, 1999, Pinthong and Wongsapai, 2009).

The MESSAGE modelling approach has previously applied to formulate an optimal energy supply strategy for Syria (Hainoun *et al.,* 2010); policy options study for power sector in Zambia (Tembo, 2012); strengthening of renewable energy applications (IAEA, 2007; IAEA, 2006); Optimal electricity system planning in a large hydro jurisdiction: Will British Columbia soon become a major importer of electricity? (Kiani *et al.,* 2013) alternate electricity supply model (Roque, 2014); climate change policy analysis (Nakicenovic *et al.*, 2000): nuclear energy in mitigating CO_2 emissions (AlFarra and Abu-Hijleh, 2012) among many others. Further information on MESSAGE as LP optimization tool is as found at the IAEA organization web site (www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html).

2.2 Electricity demand projections

The final electricity demand projections were done using Model for Analysis of Energy Demand (MAED) (Kichonge *et al.,* 2014a) and have been summarized in Figure 1. MAED is a bottom-up modelling approach (Bhattacharyya and Timilsina, 2009) chosen because of its suitability to model the final electricity demand projections based on time and data availability. Suitability of MAED to relate systematically the corresponding social, technological and economic factors which affect the demand was also considered in the selection of the model (IAEA, 2006, IAEA, 2009). Literatures such as *Hainoun et al.* (2006), IAEA (2006)), IAEA (2009), Nakarmi *et al*. (2013) and the IAEA organization website (www-pub.iaea.org/MTCD/publications/PDF/CMS-18_web.pdf) gives detailed account of MAED.

2.3 Modelling framework

2.3.1 Electricity conversion technologies

Conversion technologies considered includes coal fired power plant, solar PV, hydro, solar thermal, biomass, conventional gas turbine (GT), heavy fuel oil (HFO) and combined cycle gas turbine (CCGT) power plants.

2.2.2 Reference energy system (RES)

The proposed Tanzanian RES accommodates resources, primary, secondary and final demand energy levels. Simplified schematic flow of the energy chains, levels and conversion technologies in RES are as described in Figure 1. Rectangles in the RES represent the technologies, which contain the techno-economic data. A single technology as used in the proposed RES denotes all conversion technologies, which uses the same type of fuel. The energy resource level is characterized by coal and

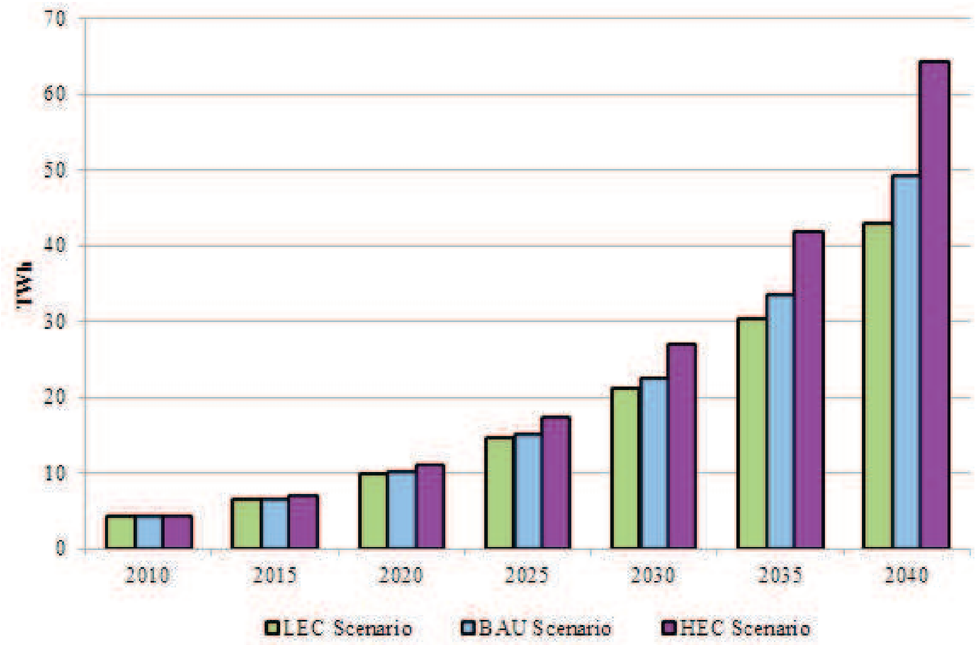


Figure 1: Electricity demands projections

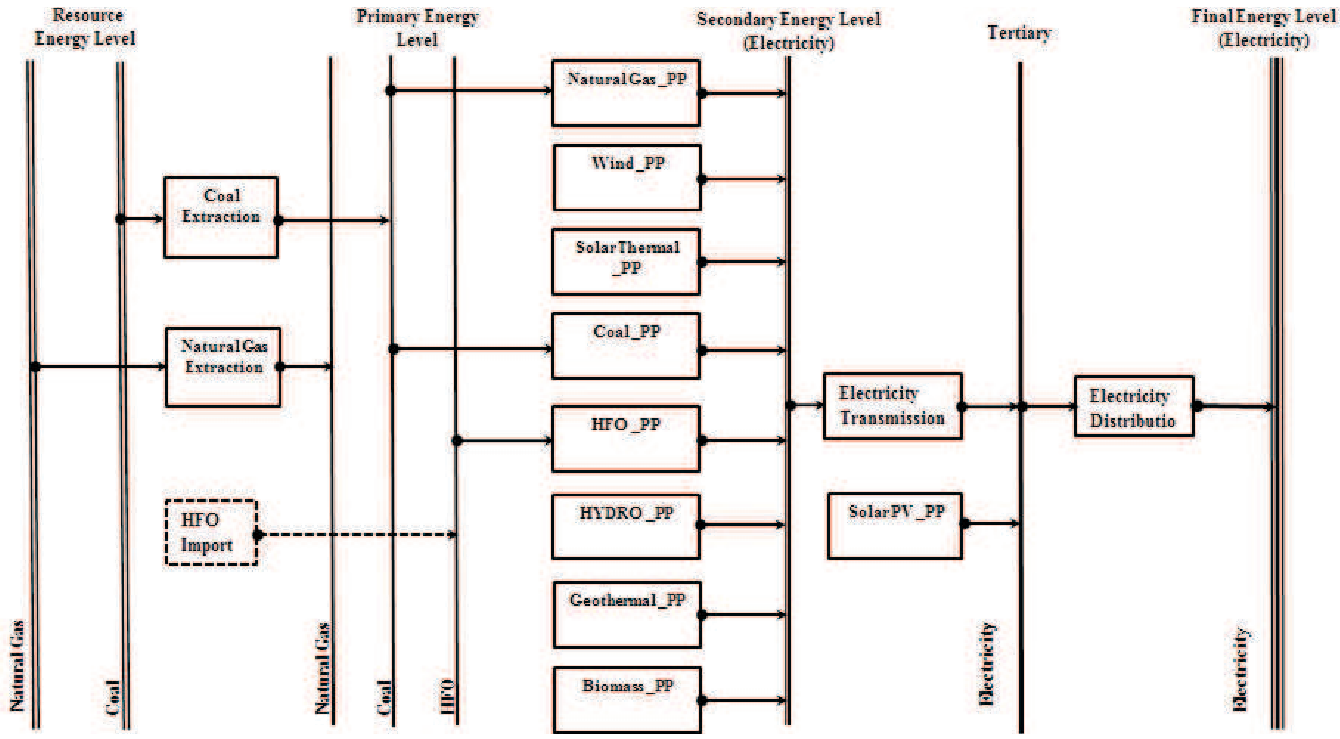


Figure 2: Energy chain levels and conversions technologies schematic flow diagram

natural gas, which are locally available resources. Energy carriers in the form of natural gas (NG), coal and HFO defines primary energy level in the energy chain. The secondary energy level is composed of electricity as the only form of energy echoed in this study. Intermediary of primary and secondary energy levels, there are electricity conversion technologies whose main inputs are energy carriers from the primary energy level. Electricity transmission and the distribution network connect secondary and final energy levels. The final electricity demand developed from the model's external factors (Kichonge *et al.,* 2014a) is given at the first level of each energy chain. The model calculates the equivalent productions of each of the technologies at the succeeding levels of the chain up to the energy resource level, which then gives the optimal technical choice by minimizing the total system cost, while meeting the given final electricity demand.

2.4 Modelling basic assumptions

The general assumptions considered in modelling energy supply options for electricity generation for Tanzania are as follows:

- All model scenarios span from 2010, which is the base year to 2040 as the last year. A time step of five years has been adopted throughout the study period as more steps slows down the solver and also for easy results reporting;
- Each model year in all scenarios is divided into four seasons to capture seasonal variations in reservoir inflows and load for hydro, solar PV and wind turbines. The seasons includes Season 1, which encompasses January to February (dry season); Season 2 – March to May (wet/rainy season); Season 3 – June to September (dry/sunny weather season) and Season 4 – October to December (short rainy season);
- The expected load profile for defining the mix in power generation plants follows an annual hourly and monthly load curve characteristics as shown in Figures 3 and 4. An annual hourly load curve with characteristics was produced from hourly generation data collected for the years 2009 to 2012. Generation of annual hourly load curves was done by taking average values in load demands for a particular hour throughout a year. Daily base load patterns together with energy resources variations are taken into account by describing two types of days which are workdays (Monday to Saturday) and weekends (Sunday and holidays). The daily base load patterns for a 24 hour day has been divided as nine parts for Season 1, ten parts for Season 2, eight parts for Season 3 and twelve parts for Season 4;
- Final electricity demand differences under business as usual (BAU), low economic consumption (LEC) and high economic growth (HEC) scenarios as projected in MAED are as depicted in Figure 1. Other parameters such as energy forms, seasonal and daily power demand variability, constraints, technologies and resources remained the same for BAU, LEC and HEC scenarios.
- Air emissions control measures have not been included in the model;
- The operation time thus electricity output for

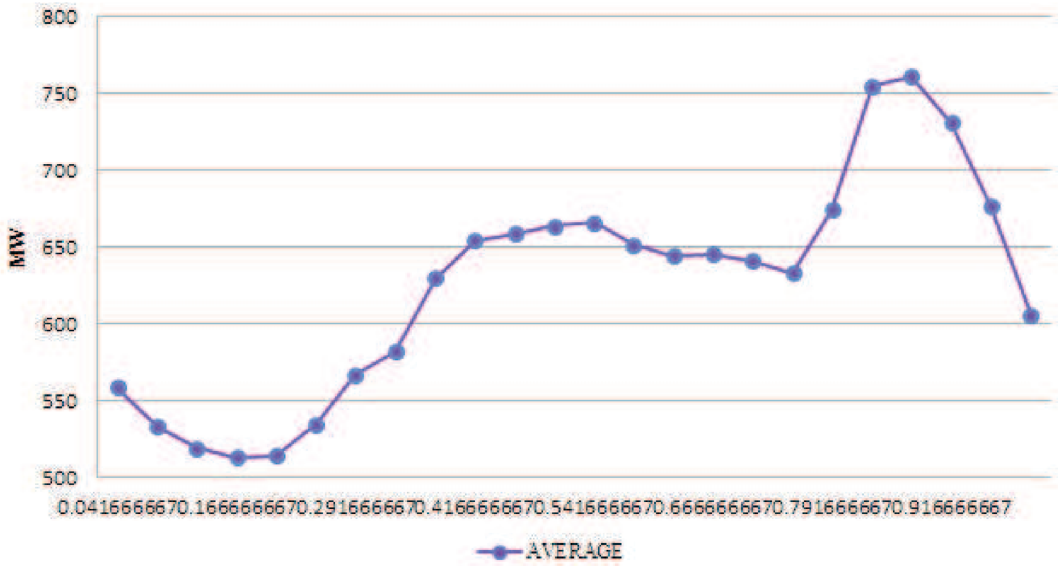


Figure 3: Annual hourly load curve characteristics

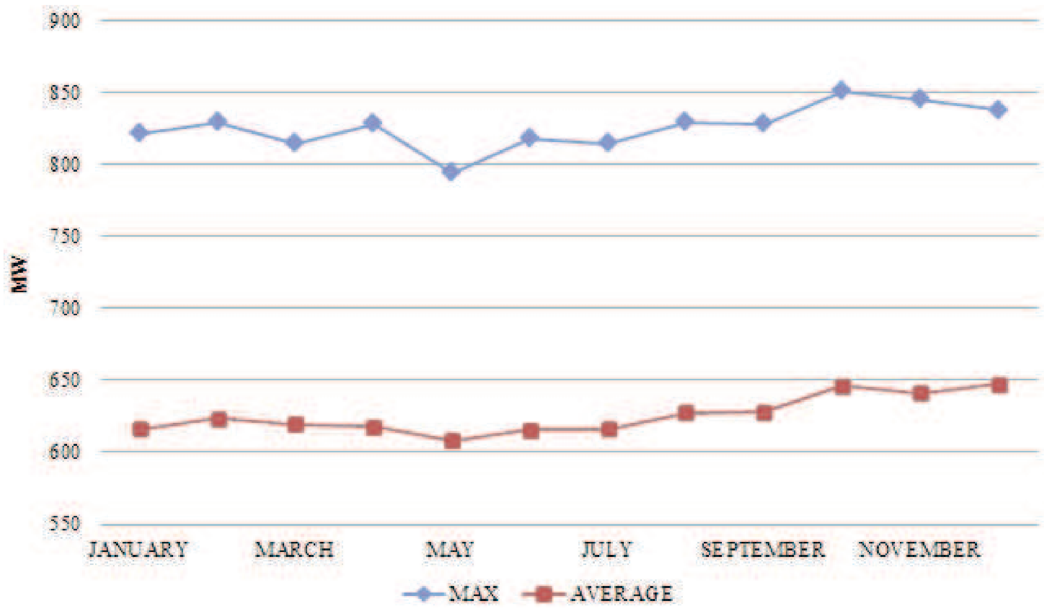


Figure 4: Annual monthly load curve characteristics

solar PV, solar thermal and wind power plants follows the proposed seasonal and daily sunshine/wind variation;

- Geothermal power plants begin operation in 2025, with an initial installed capacity of 100 MW and increasingly to 650 MW in 2040 (MEM, 2012, Mnzava and Mayo, 2010);
- The discount rate parameter for economic evaluation of the future investment project was set to 10% in each scenario;
- The entire national electricity system has been simplified and modelled as a single grid system;
- Existing and future expansion projects, transmission and distribution losses and reserve margins as specified in the power system master plan (MEM, 2012) has been adopted for optimization purposes;
- Summary of the crucial parameters for modelling electricity supply options in terms of specific technical and economic characteristics adopted for conversion technologies are as depicted in Table 1.
- The investment costs for renewable energy technologies (wind, solar PV and thermal) assumed a decreasing trend as the industry develops and thus becomes cost competitive in future (Philibert, 2014). The investment cost for wind technology in the base year as shown in Figure 5 was approximated at 2 438 US$/kW and then decreased steadily to 1 800 US$/kW in 2025 where it assumed this constant value to 2040. Solar PV technology investment costs assumed

Table 1: Summary of technical and economic characteristics of conversions technologies

	Conversion technology								
	CCGT_PP	*GT_PP*	*Hydro_PP*	*Solar PV_PP*	*Solar TH_PP*	*Biomass_PP*	*HFO_PP*	*Wind_PP*	*COAL_PP*
Investment Costs (US$'00/kW)	1808.5	1220	2227	4000	4500	3860	800	2438	1900
Variable O & M Costs (US$'00/kWyr)	26.5	39.5	4.5	0	40	26.5	105	4.5	52.56
Fixed Costs (US$'00/kW/yr)	9.5	9.5	8.5	40	149	40	20	40	50
Plant life (years)	25	25	50	30	30	30	40	25	30
Plant factor (share)	0.95	0.95	0.95	0	-	0.95	0.75	0.9	0.95
Efficiency (%)	0.52	33		-	-	28	30	-	40
Operation time (share)	0.94	0.75	0.85	0.26	0.26	0.9	0.7	0.35	0.85
Input	NG	NG	-	-	-	Biomass	HFO	-	Coal
Output	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity

a base year value of 4 000 US$/kW and decreased in steps to 3 500 US$/kW and 2 500 US$/kW in 2025 and 2030 respectively where it presumed a constant value of 2 500 US$/kW towards the year 2040. Similarly, the investment cost for solar thermal technology towards the end of the study period presumed a decreasing trend from the base year value of 4 500 US$/kW to 3 500 US$/kW.

3. Results and discussions

Final electricity demands have been optimized in order to determine the optimal energy supply options for Tanzanian electricity sector. This section presents MESSAGE modelling results calculated based on the least-cost energy supply options for electricity generation for the period 2010-2040. Based on the total system costs of the electricity system discounted over the study period 2010-2040, three different energy supply options have been optimized in lieu of BAU, LEC and HEC scenarios as detailed in Kichonge *et al*. (2014a).

3.1 Installed capacity

The total installed capacity increases gradually from 804.2 MW in the base year to 10 811.5 MW, 9 190.6 MW and 13 325.6 MW in 2040 for BAU, LEC and HEC scenarios respectively as illustrated in Figure 6. The least-cost optimal results show HEC scenario has the highest total capacity additions at 12 521.4 MW in 2040 as compared to the BAU scenario 10 007.3 MW and LEC scenario 8 386.65 MW. Annual increase of installed capacity in HEC scenario is equivalent to 9.81%, while BAU and LEC scenarios projection increases are 9.05% and 8.46% respectively. Hydro, NG, coal and geothermal power plants dominate the total installed capacity additions in all scenarios. Wind and bio-

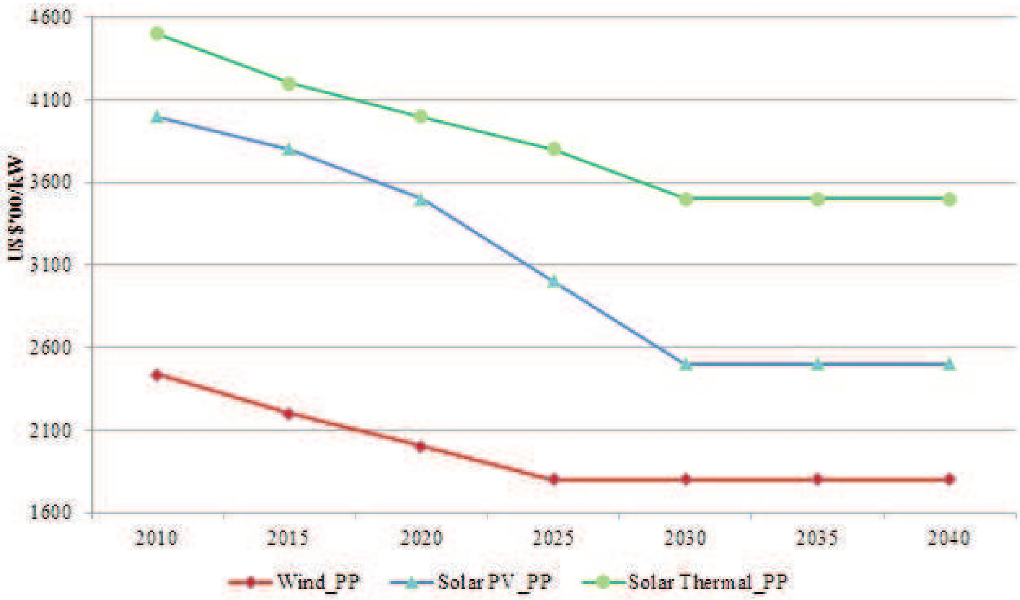


Figure 5: Evolution of the investment costs for wind, solar thermal and solar PV power plants

Table 2: Least cost installed capacity shares by technology (MW)

	2010	2015			2020			2025			2030			2035			2040		
	Base Year	BAU	LEC	HEC	BAU	LEC	HEC	BAU	LEC	HEC	BAU	LEC	HEC	BAU	LEC	HEC	BAU	LEC	HEC
Coal_PP	-	–	–	–	9.3	7.4	14.2	10.1	5.0	9.2	7.3	3.7	13.2	27.0	18.3	26.7	29.1	27.0	25.6
HFO_PP	5.1	10.8	10.9	10.5	6.4	6.6	6.1	4.34	4.48	3.95	3.16	3.31	2.75	2.37	2.61	1.92	0.96	1.13	0.78
CCGT_PP	–	30.6	30.2	33.2	36.8	37.6	34.8	24.8	27.9	31.6	9.8	11.1	12.9	2.4	5.2	15.9	18.4	16.7	31.8
GT_PP	25.1	21.9	22.0	21.1	13.8	13.8	12.8	9.1	9.4	8.3	6.8	5.6	7.7	7.8	7.3	6.5	5.2	6.1	4.2
Hydro_PP	69.8	35.4	35.6	34.1	25.4	25.9	24.0	43.3	44.6	39.3	56.4	59.1	49.0	51.0	56.0	41.3	35.8	42.1	29.0
Wind_PP	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.6	–	3.8
Biomass_PP	–	1.2	1.2	1.2	0.8	0.8	0.7	0.5	0.5	0.5	0.4	0.4	0.3	0.2	0.2	0.2	–	–	–
GeoTh_PP	–	–	–	–	–	–	–	2.6	2.7	2.4	12.4	12.9	10.7	9.3	10.2	7.5	6.0	7.1	4.9
Solar_PV	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Solar_Th	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Electricity Import	–	–	–	–	7.8	7.9	7.3	5.2	5.4	4.8	3.8	4.0	3.3	–	–	–	–	–	
Total(%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

mass represents a small proportion in the total installed capacity whereas solar PV and thermal were not able to compete.

There is a corresponding increase of thermal installed capacity addition (coal and NG power plants) in both scenarios. NG power plants (CCGT and GT) increase their shares in the total installed capacity from 202 MW in 2010 to 2 546.55 MW in 2040 for BAU scenario. LEC scenario observes a similar increasing trend to 2 090.67 MW in 2040, while HEC scenario is 4794.47 MW. The shares of hydro power plants witnesses an opposite decreasing trend in the period 2015-2030, where it picks-up the dominance to 2035. Hydro power plants shares decrease from 69.8% in 2010 to 35.8%, 42.1% and 29% in 2040 for BAU, LEC and HEC scenarios respectively. The main reason attributed to the decreasing trend is the potential constraints despite the fact that it is the cheapest in operating costs (MEM, 2013b).

3.2 Least cost electricity generation mix

Summarized least cost total electricity generation for each scenario are as shown in Figure 7 and the least-cost electricity generation supply options results by technology in Table 3. BAU scenario least cost electricity generation expanded from 5 632 GWh in 2010 to 62 770 GWh in 2040. The expansion is equivalent to an annual growth rate of 8.4% as compared to 7.9% and 9.3% for the LEC and

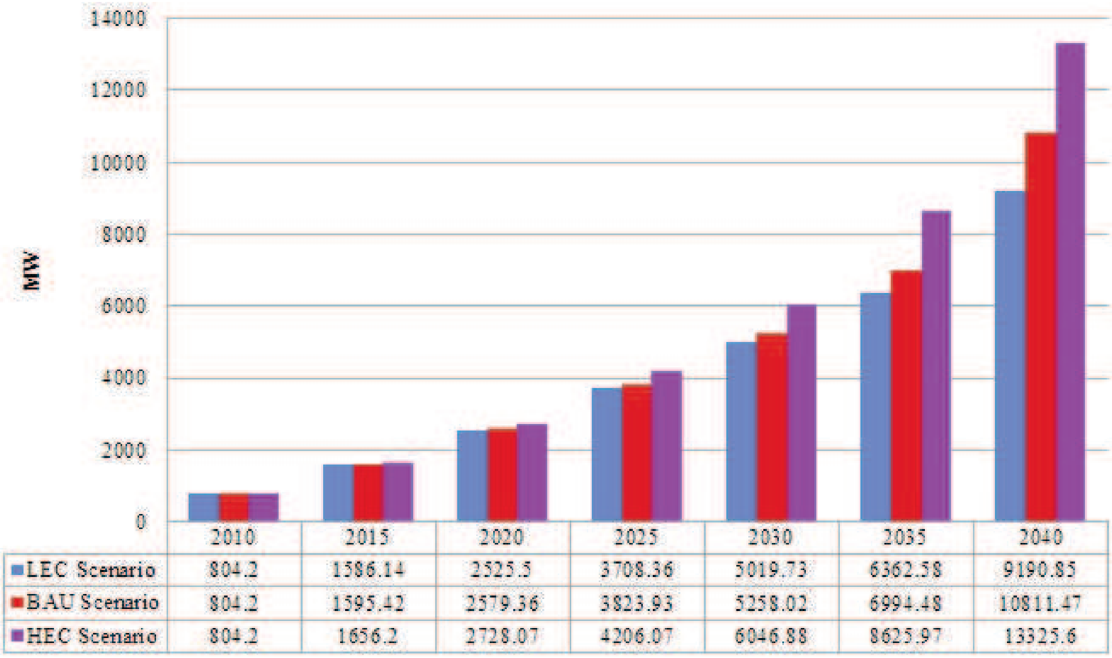


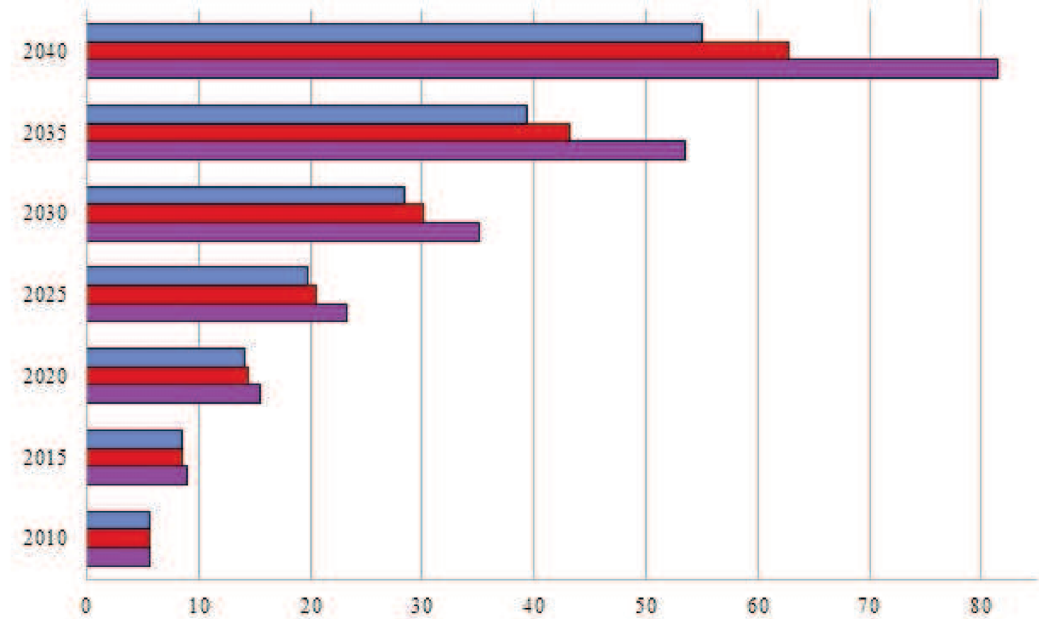
Figure 6: Least cost total installed capacity (2010-2040)

Table 3: Least cost electricity generation shares by technology

	2010	*2015*			*2020*			*2025*			*2030*			*2035*			*2040*		
	Base	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*
Coal_PP	–	–	–	–	11.8	9.3	17.7	13.3	6.7	11.9	6.6	3.3	15.0	25.9	17.2	30.4	38.1	33.5	3.0
HFO_PP	2.0	0.2	0.2	0.2	–	–	–	0.03	0.02	0.06	0.05	0.03	0.04	0.03	0.03	0.02	0.01	0.01	0.01
NGpower plants	28.9	54.3	53.8	56.5	57.1	58.8	53.4	28.9	33.1	36.9	11.8	11.8	14.5	7.5	9.8	15.8	10.7	10.6	27.6
CCGT_PP	–	76.5	76.2	78.8	86.9	86.6	86.8	88.6	89.4	92.6	88.3	92.2	90.5	88.3	91.2	96.3	96.9	95.7	99.3
GT_PP	100.0	23.5	23.8	21.2	13.1	13.4	13.2	11.4	10.6	7.4	11.7	7.8	9.5	11.7	8.8	3.7	3.1	4.3	0.7
Hydro_PP	66.7	44.3	44.7	42.2	30.4	31.2	28.2	53.9	56.1	47.8	66.0	69.8	56.5	55.2	60.5	44.6	41.2	47.1	31.7
Wind_PP	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	1.7
Biomass_PP	2.5	1.2	1.2	1.0	0.6	0.6	0.6	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
GeoTh_PP	–	–	–	–	–	–	–	3.6	3.8	3.2	15.2	14.8	13.8	11.2	12.3	9.1	7.7	8.8	5.9
Solar_PV	–	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–	–	–	–
Solar_Th	–	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–	–	–	–
Electricity Import	–	–	–	–	0.1	0.1	0.2	–	–	–	0.1	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.03
Total(%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

HEC scenarios respectively. The base year proportions in the generation mix include hydro (66.7%), NG (28.9%), biomass (2.5%) and HFO (2%). Results describe general dominance of hydro power plants in the generation mix with NG, biomass and HFO power plants compensating the balance. The optimized results show the proportion of hydropower plants generation increasing gradually to 41.2 %, 47.1 % and 31.7 % in 2040 for BAU, LEC and HEC scenarios respectively.

The proportion of coal power plants in the total generation rises gradually from 11.8 % in 2020 to 38.1% in 2040 for BAU scenario while for LEC scenario is 9.3% in 2020 and rises to 33.5% in 2040. HEC scenario witness higher proportion at 17.7% in 2020 and grows to 33% in 2040. The higher proportion of hydro, NG and coal power plants in the generation mix is imminent due to lower investment and fuel costs as compared to other candidates technologies considered. Unlike the increases in



	2010	2015	2020	2025	2030	2035	2040
LEC (TWh)	5.6315412	8.4541884	14.0708376	19.7202492	28.4188416	39.405984	54.9442968
BAU (TWh)	5.6315412	8.5338168	14.3978484	20.5393968	30.0662472	43.2119412	62.7696924
HEC (TWh)	5.6315412	8.9555232	15.5527668	23.1730032	35.1073644	53.4492276	81.4751832

Figure 7: Least cost electricity generation for study period (2010-2040)

hydro and coal power plants generation shares, the proportions of NG power plants increasingly dominate more than 50% of the generation from 2015-2020 and thereafter declines in 2040. The decline in NG power plants proportions after 2020 is due to presumed new investments in hydro power plants. NG power plants technologies proportion in 2040 for BAU scenario split into CCGT (96.9%) and GT (3.1%). However, a similar trend follows in LEC and HEC scenarios in which the share of CCGT will be as high as 95.7% and 99.3% respectively in 2040. The choice of CCGT in least-cost optimized results attributes to higher availability and efficiency up to 60% in comparison to that of GT 40% (Sharman, 2005, Sims *et al*., 2003). Combined thermal generation contributes 48.8% of the total in 2040 for BAU scenario whereas the contribution of thermal generation for LEC scenario is 44.1 % and that for HEC scenario is 60.6%. Higher final electricity demands in HEC scenario drives the increase in the use of thermal generations. Hydro and geothermal resource potential constraints attributes to the use of more thermal generations towards the end of the study period. On the contrary, renewable energy with the exclusion of hydro makes up small proportion in the contribution of the total electricity generation mix.

The contribution of renewables technologies into electricity generation for BAU, LEC and HEC scenarios extends to 6.2 TWh, 4.8 TWh and 6.2 GWh respectively in the year 2040. The share of renewable energy generation in BAU scenario accounted for an average of 2.1% in the period from 2010 to 2025 and, thereafter, grows to 15.4% in 2030 and then retreats to 9.9% in 2040. The rise of renewable energy in 2030 attributes to utilization of full geothermal energy potential presumed in the year. HEC scenario shares of renewable energy from 2025 – 2040 averaged at 1.9 % in the total electricity generation. Comparable trends are also as observed in LEC scenario. Moreover, within renewable energy technologies, geothermal dominates the generation mix followed by biomass and wind with insignificant shares from solar thermal and solar PV power plants. Geothermal and wind power plants by the end of the study period in 2040 generated 7.7 % and 2.2 % respectively of all electricity in the BAU scenario. Similarly, geothermal power plants generation for LEC and HEC scenarios was approximately 8.8 % and 5.9 % respectively. The constraints on geothermal energy resources potential and the rise in electricity demand reduced the share of geothermal technologies in 2040 for HEC scenario.

The least-cost electricity generation results in the BAU, LEC and HEC scenarios draws four most important conclusions. The first one is the key role played by hydro, coal and NG technologies in the final electricity generations. These technologies have shown least-cost competitiveness in electricity generation, which describes their importance in sustainable development of the electricity sector. The second is insignificant contribution from solar thermal and solar PV technologies in the entire study period. The high investment costs associated with the technologies discourages the penetration in generations mix despite their least operations and maintenance costs. The last conclusion is the country self-sufficiency in generating electricity using its own local energy resources thus ensuring security of supply for sustainable development.

3.3 Primary energy supply

Primary energy supply composition for electricity generation is as shown in Table 4. Coal, NG, HFO and biomass are the main primary energy supply for electricity generation. Conversion technologies for geothermal, hydro, wind, solar PV and solar thermal do not consume primary energy for electricity generation. Primary energy supply in the BAU scenario will grow from 6 203 GWh in 2010 to 73 083 GWh in 2040. Similarly, the growth in the LEC scenario amounts to 57 529 GWh against 110,700 GWh in the HEC scenario. Generally, all scenarios projects increased coal consumptions as compared to NG with small proportions from biomass and HFO towards 2040. The least-cost supply option, show electricity generation will depend on coal and NG to cover primary energy supply. It further depicts gradually decrease in HFO to less than

Table 4: Primary energy production (2010-2040)

	Coal			*Natural gas*			*HFO*			*Biomass*		
	BAU	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*	*BAU*	*LEC*	*HEC*
2010	–	–	–	5326.4	5326.4	5326.4	380.8	380.8	380.8	495.5	495.5	495.5
2015	–	–	–	10469.6	10310.4	11278.5	66.7	63.4	72.5	369.9	367.6	326.9
2020	4235.5	3283.0	6865.4	17314.4	17465.6	17524.9	0.0	–	0.0	313.0	315.7	312.7
2025	6809.8	3283.0	6865.4	12356.9	13519.5	17351.5	21.5	14.3	42.6	242.2	237.6	154.7
2030	4995.2	2366.6	13130.6	7430.1	6801.0	10467.1	52.6	25.4	48.0	126.4	117.4	123.8
2035	27982.2	16905.6	40673.7	6787.2	7933.7	16647.6	41.0	44.4	38.5	91.2	91.2	50.3
2040	59862.6	45949.3	67200.2	13196.3	11555.5	43475.7	24.2	24.2	24.2	–	–	–
Total	103,885	71,787	134,735	72,881	72,912	122,072	587	552	607	1,638	1,625	1,464

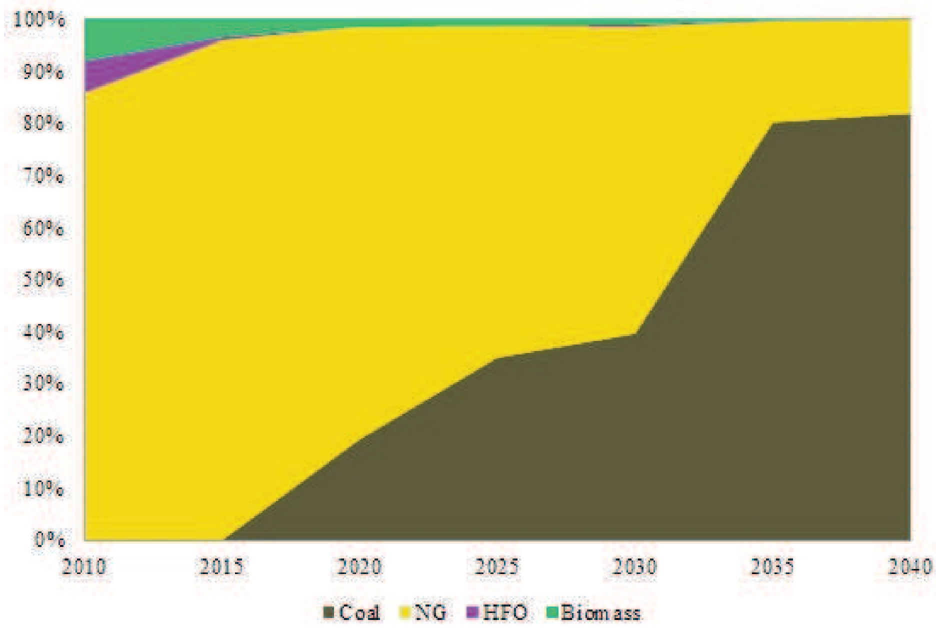


Figure 8: Primary energy supply – BAU scenario

0.1% in 2040. Figure 8 depicts primary energy supply in the BAU scenario that is the representative trend for other scenarios.

3.4 CO_2 emissions

The total CO_2 emission depicted in Figure 9 rises from 1182-kilo tonnes of CO_2 in 2010 to 23652.3-kilo tonnes of CO_2 in 2040 for the BAU scenario. The rise in CO_2 emission in the BAU scenario represents an annual growth of 10.5%. Similarly, the increases for LEC and HEC scenarios represent annual growth of 9.5% and 11.7 % respectively. The growth rate in CO_2 emissions in the LEC scenario is much lower than that of HEC and BAU scenarios due to slow economic growth presumed in the scenario representing less energy consumption. Similarly, the higher CO_2 emissions in the HEC scenario is highly influenced by higher electricity demands, which resulted in optimal capacity additions of coal and NG power plants. The emission of CO_2 in all scenarios is higher due to insignificant renewable energy conversion technologies applications.

3.5 Economics of scenarios

The capital investment cost required for the entire period of study is based on MESSAGE least cost modelling results. The sharing of capital invest-

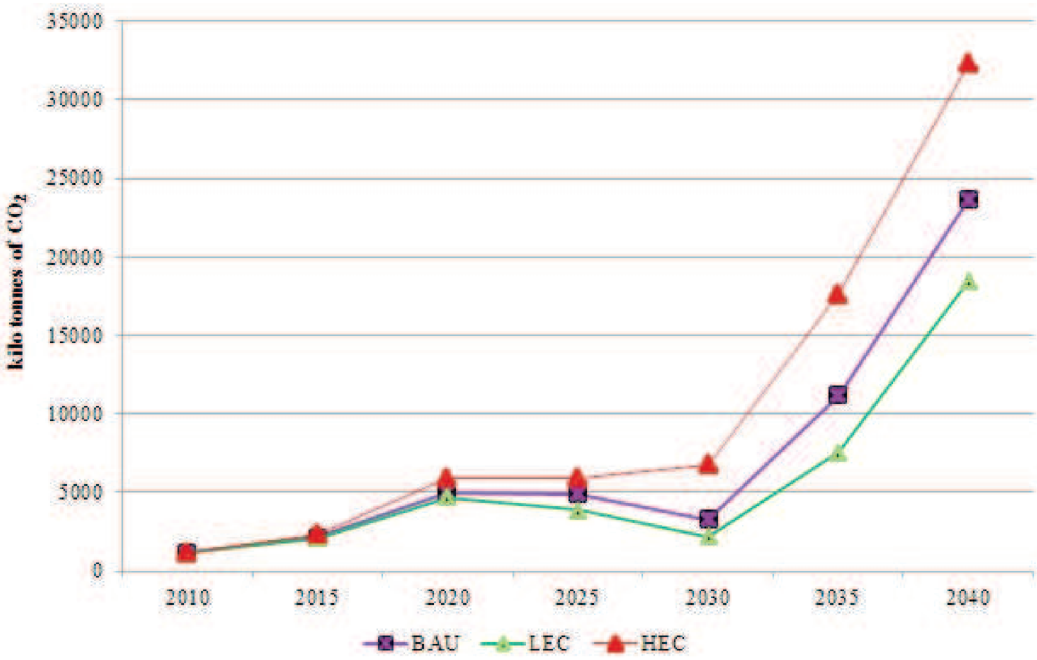


Figure 9: Least cost projected CO_2 emissions (2010-2040)

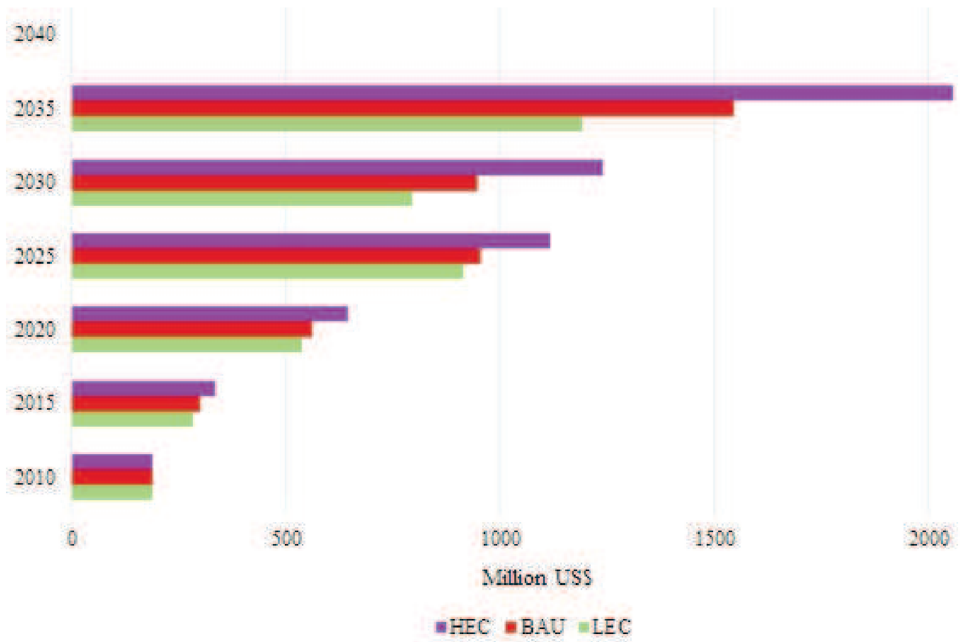


Figure 10: Capital investment costs for the entire study period (2010-2040)

Table 5: Total investment and O&M costs

Name of Scenario	O&M Variable Cost (Million US$)	O&M fixed cost (Million US$)	Investment cost (Million US$)	Total investment and O&M cost (Million US$)
BAU	999.7	1127.7	4487.6	6615.1
LEC	805.4	1013.4	3900.0	5718.8
HEC	1,334.8	1,222.2	5,595.3	8,152.4

ments for the period of 2010 – 2045 is as shown in Figure 10. In meeting final electricity demand under BAU, LEC and HEC scenarios, the total capital investment cost of 4 488 million US$, 3 903 million US$ and 5 573 million US$ respectively would be required. The main share of the capital investments for the entire period in BAU, LEC and HEC scenarios falls into the period of 2015 to 2035, in which most of the capacity addition is taking place. The capital investment needed to develop a BAU scenario final electricity demand in the entire study period would be about 584 million US$ more than LEC scenario, while 1 086 million US$ increase would be needed for a HEC scenario. The higher capital investment costs are observed in 2035 for HEC and BAU scenarios, while for LEC scenario is in 2030.

Least cost modelling results as presented in Table 5 shows the main differences among BAU, LEC and HEC scenarios in terms of the investment cost and variable and fixed O&M costs. Variable O&M costs for the HEC scenario are 335.1 and 529.4 million US$ higher than those for the BAU and LEC scenarios. Moreover, the LEC scenario entail lower fixed O&M costs at 1013.4 million US$ as compared with the BAU and HEC scenarios.

4. Sensitivity analysis

Sensitivity analyses carried out in this study, intended to explore the influence of techno-economic parameters, policy options and extreme dry weather conditions in the expansion of the final electricity generation mix.

4.1 Renewable energy penetration

Least-cost optimization results as distinguished in previous sections reveals in-significant penetration into electricity generation of renewable energy technologies due to the high investment costs. Among the reasons behind the insignificant penetration of renewable energy technologies in electricity generation is the absence of non-environmental friendly energy supply constraints. As a result, the market forces decide to choose the least-cost energy supply options for electricity generations, which in most cases, occurs as non-environmentally friendly sources (Bull, 2001; Lewis, 2007). Based on this fact, the study formulates a renewable energy penetration policy option (REPP) as an alternative scenario to study electricity system behaviour under energy supply constraints to promote renewable energy technologies in the generation of electricity. The policy option in REPP requires a compulsory penetration of renewable energy technologies (combined together) to contribute at least 10% of the total electricity generation in 2020 and increasingly to 30% in 2040. The REPP scenario assumes energy demands projections and all techno-eco-

Table 6: Renewable energy penetration between BAU and REPP scenarios

	Scenario	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*
Renewables shares in electricity generation (%)	BAU	2.5	1.2	0.6	4.0	15.4	11.3	9.9
	REPP	2.5	1.2	10.1	15.1	20.7	25.0	30.0
CO_2 emission level (kilo tonnes of CO_2)	BAU	1182.3	2134.0	4982.8	4889.3	3266.5	11189.3	23652.3
	REPP	1182.3	2134.0	3874.6	2927.7	1906.2	4380.7	12198.3
Primary energy supply (GWh)	BAU	6202.7	10906.2	21862.9	19430.5	12604.3	34901.5	73083.1
	REPP	6202.7	10906.2	18778.3	14069.0	8924.9	18971.2	41212.6
Renewables installed capacity shares (%)	BAU	0.0	1.2	0.8	3.1	12.7	9.5	10.6
	REPP	0.0	1.2	17.1	20.7	18.1	24.1	34.7

nomic parameters of the BAU scenario with the additions of the compulsory policy measures. All modelling inputs of REPP scenario remain the same as in the BAU scenario except for the imposed compulsory penetration of renewable energy technologies.

The results of REPP scenario implementations as compared to the BAU scenario in terms of the total installed capacity, electricity generation and CO_2 emissions are as illustrated in Table 6. The MESSAGE results depict a huge reduction of CO_2 emissions at approximately 48% in the REPP scenario as compared to the BAU scenario in 2040. The displacement of thermal power plants with renewable energy technologies has resulted in reduction of CO_2 emissions and primary energy supply. The total installed capacity shares of renewable energy technologies increases to 17.1% and 34.7% in 2020 and 2040 respectively. BAU scenario composition was 0.8% in 2020 and 10.6% in 2040. The shares of renewable energy technologies in the total generation mix for the REPP scenario has increased to 30% in 2040 as compared to 9.9% it had in the BAU scenario. Satisfactory inclusion of renewable energy technologies into the electricity generation mix, as shown in the REPP scenario, has demonstrated the importance of compulsory measures in policy formulation in favour of renewables.

Even though the compulsory policy measures resulted in the expansion of renewable energy technologies shares, REPP scenario depict additional investments costs as compared to the BAU scenario. The comparison in the investments costs between the BAU and REPP scenarios is as depicted in Figure 11. Meeting REPP scenario requirements will necessitate considerable investment cost of 7 665.8 million US$ as compared to 4 487.6 million US$ for the BAU scenario. Contrariwise, as shown in Figure 12, REPP scenario accommodation exhibits a decrease in the operation and maintenance variable costs (O&M). There is a decrease to 680.6 million US$ in the operation and maintenance variable costs for the REPP scenario, when compared to 999.7 million US$ for the BAU scenario in the entire study period. MESSAGE modelling results; show that the REPP scenario demands a more aggressive approach to investment in renewable energy technologies. For that reason, if the country chooses to implement the policy, additional policies such as renewable energy feed-in tariff and institutional frameworks that are essential for the growth of renewable energy technologies must be in place. The compulsory policy measures as revealed in MESSAGE modelling helps in tapping of the enor-

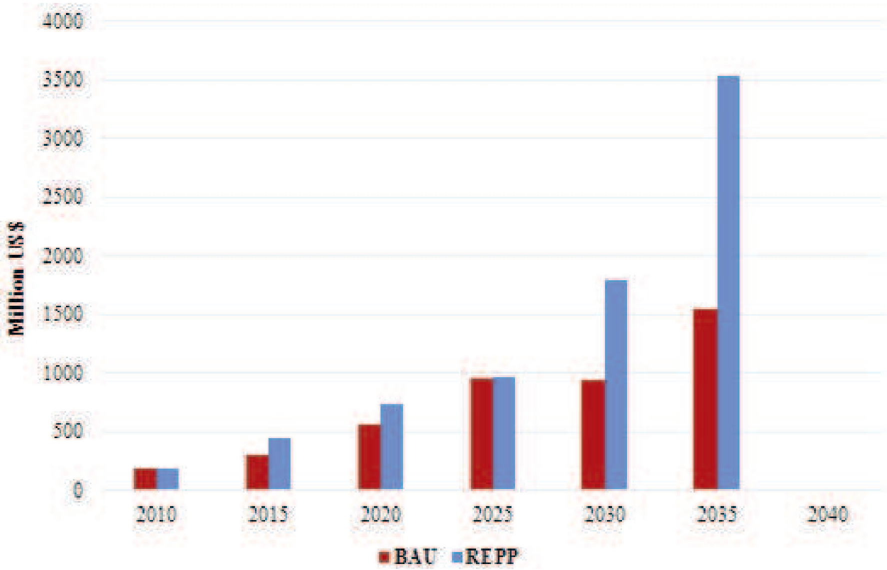


Figure 11: Investments costs comparison between BAU and REPP scenarios

mous potential of renewable energy resources into electricity generations for the benefit of the environment and security of supply.

for the fossil fuel scenarios. A decrease or increase of the discount rate has insignificant influence on capital investments of hydro, biomass and geothermal, which seems to be due mainly to the limited resources potential.

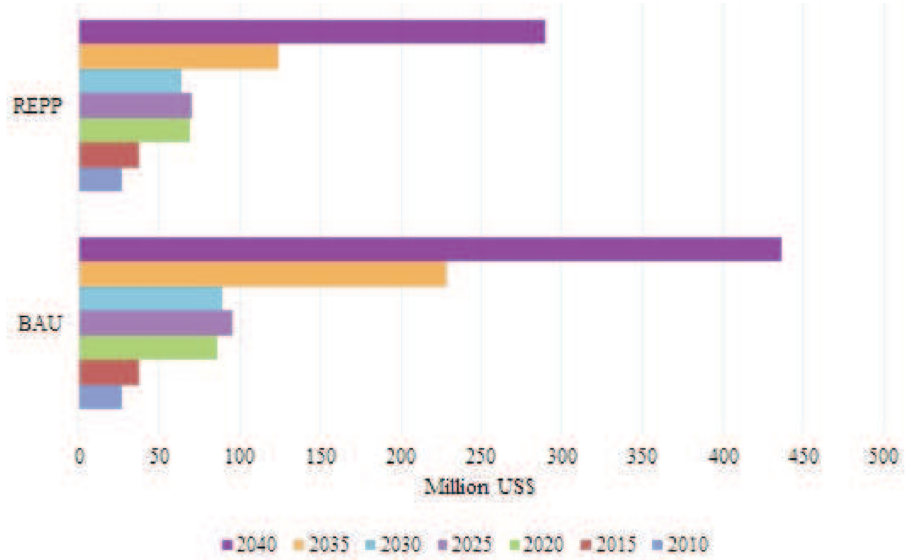


Figure 12: Variable O&M costs comparison between BAU and REPP scenarios

4.2 Discount rate adjustments

Adjustments were carried out on the BAU scenario to approximate the influence of the discount rate on the upcoming pattern of electricity generation capacity, electricity production or economic effectiveness of a number of electricity generation plants. The discount rate adjustments carried out were 6%, 8%, 12% and 14% in comparison to a study-adopted value of 10%. Adjustments of discount rate value to 6% preferred early capacity addition of 500 MW wind power plant into electricity generation in 2035, while 8%, 10% and 12% favours addition in 2040 with no addition for the 14% values. Solar PV and thermal failed to be competitive in all discount rates adjustments. These technologies require special policy option for their inclusion into electricity generation to be realistic. Adjustments of discount rate values to 12% and 14% were in favour of capacity addition of CCGT and GT power plants as opposed to lower values (6% and 8%), which preferred coal power plants. Higher efficiency coupled by a lower operating and maintenance costs, shorter construction time and fuel cost characterizes CCGT and GT power plants thus turn out to be more attractive for capacity addition in comparison to other technologies options. The discounts rates of 6%, 8%, 12% and 14% resulted in coal fired power plants total installed capacity of 6 652 MW, 6 108 MW, 5 385 MW and 4773 MW respectively. In other words, a higher value of discount rate leads to the postponement of large-scale investments. According to the minimum cost criterion, a discount rate of 10% gives greater preference

4.3 Dry weather scenario

Experience has shown weather conditions affect electricity generation capacity causing outages and rationing (Loisulie, 2010; MEM, 2013b). The alternative dry weather scenario was formulated to analyse electricity system behaviour under uncertain weather conditions. All modelling inputs of a dry weather scenario remain the same as in the BAU scenario except for the imposed generation's constraints of hydropower to 20% of the total generations in the period 2020-2040. The least-cost results as shown in Table 7 shows the generations will shift to coal and NG power plants at approximately 42.8% and 30.2% respectively. The capacity additions for coal power plants will expand to 9 772 MW as compared to 6 040 MW in the BAU scenario. Because of imposed hydropower constraints, the CO_2 emission will increase to 86938.67-kilo tonnes of CO_2 as compared to 51296.6-kilo tonnes of CO_2 in the BAU scenario. Based on MESSAGE modelling results, if the country chooses to implement measures because of dry weather conditions, more usage of coal and NG as primary energy supplies will be the least cost option. The additional capacity in terms of coal and NG power plants to replace hydropower plants would decrease both the risks of a dry weather condition and energy security uncertainties. However, the weaknesses of coal and NG development into a dry weather scenario are the higher CO_2 emissions as compared to the BAU scenario as depicted in Figure 13. The capital investment cost of the dry weather scenario will require less than 535.52 million US$ as compared

Table 7: Generation mix by technology dry weather scenario

	2010	2015	2020	2025	2030	2035	2040
Coal_PP	-	-	*25.11*	*34.92*	*41.15*	*52.93*	*42.85*
HFO_PP	2.03	0.23	-	-	0.004	0.03	0.01
NG_PP	28.86	54.56	54.41	41.00	22.06	15.60	30.20
CCGT_PP	0.00	76.62	89.11	87.23	92.20	90.55	97.88
GT_PP	100.00	23.38	10.89	12.77	7.80	9.45	2.12
Hydro_PP	66.65	43.98	19.90	20.04	20.23	20.03	16.98
Wind_PP	-	-	-	-	-	-	2.20
Biomass_PP	2.46	1.23	0.59	0.41	0.13	0.07	-
GeoTh_PP	-	-	-	3.63	16.29	11.22	7.71
Solar_PV	-	-	-	-	-	-	-
Solar_Th	-	-	-	-	-	-	-
Electricity Import	-	-	-	-	0.13	0.12	0.05
Total %	100	100	100	100	100	100	100

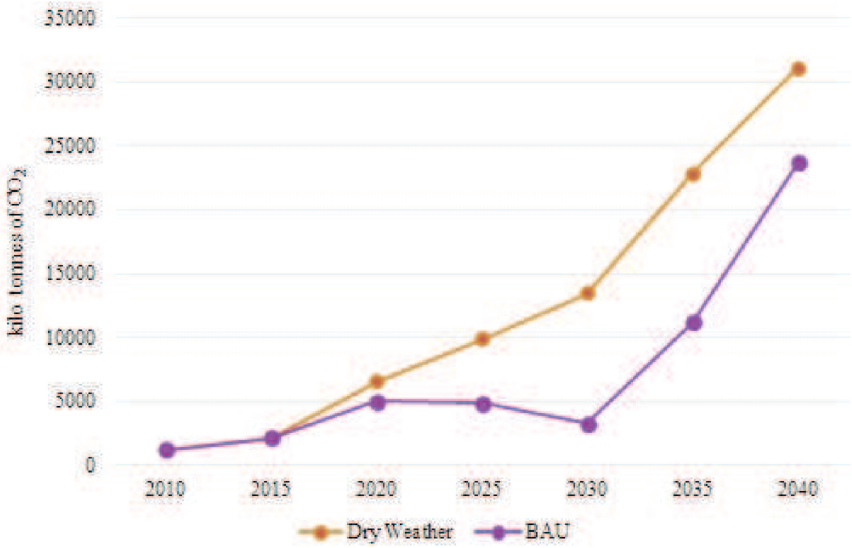


Figure 13: Comparison in CO_2 emissions between Dry weather and BAU scenarios

to capital investment in the BAU scenario. Less capital investment cost in the dry weather scenario is due to lower capital investment cost and shorter construction time of coal coal-fired and NG power plants. Despite hydro power plant lower operation and maintenance costs, coupled with zero fuel consumption for final electricity generation, they have higher capital investment costs and longer construction life (Sharma, 2010).

5. Conclusion

The study presented a modelling approach on the energy supply options for electricity generation in Tanzania. The modelling approach emphasized optimal results based on the least-cost as assumed in MESSAGE. Based on the results presented, MESSAGE turned out to be a useful tool to address energy supply options for electricity generation in Tanzania. The projected total installed capacity increases gradually from 804.2 MW in the base year to 10811 MW, 9190.9 MW and 13325.6 MW in 2040 for the BAU, LEC and HEC scenarios respectively. The increase in the total installed capacity would call for capital investment cost of 4 488 million US$, 3 903 million US$ and 5 573 million US$ respectively for the BAU, LEC and HEC scenarios.

Hydropower plants dominate the capacity additions followed by coal, CCGT, geothermal and GT power plants to meet the electricity generation expansion in both scenarios. Total primary energy supply dominated by coal and NG rises to 73 083 GWh, 57 529 GWh and 110 700 GWh in 2040 for the BAU, LEC and HEC scenarios respectively, as compared to base year amount of 6 203 GWh. In meeting final electricity demands, CO_2 emissions will expand from 1182-kilo tonnes of CO_2 to 10.5%, 9.5% and 11.7% respectively for BAU, LEC and HEC scenarios with decreases of CO_2 in the REPP scenario.

Renewable energy sources as concluded in the REPP scenario were identified as promising for meeting the future electricity demand in Tanzania.

Potential contribution of renewable energy sources to the savings of coal and NG reserves would be a great contribution to the economy and the environment. However, the dry weather scenario has shown a shift to coal and NG power plants generations at approximately 42.8% and 30.2% respectively resulting into higher CO_2. The sensitivity analysis tests results have shown lower discount rates to favour investments on wind and coal power plants, while higher discount rates favour NG power plants. The least-cost results have shown implications concerning capital investment costs versus environmental impacts concerns. Least cost modelling results have concluded that meeting final electricity demands without considerations of environmental impacts concerns is cheaper. Policy makers should balance the capital investment costs and environmental concerns in the energy planning of the country.

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Options for the supply of electricity to rural homes in South Africa

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Abstract
The residential sector in South Africa is being electrified by the South African government on a priority basis. For this purpose, both grid and off-grid electrification options are being used. As off-grid option, 50 Watt Solar Home Systems (SHS) is being provided to consumers in remote rural areas where grid connection is inaccessible. But the SHS of the mentioned size can hardly produce 0.3 to 0.4 kilowatt-hour (kWh) of electricity per day, even under the best solar conditions. This electric energy is substantially lesser than the Basic Electric Energy (BEE = 50 kWh per month), being utilized in the country free of cost by grid connected low income households. In this research work, efforts have been made to determine the most economical options in South Africa's rural areas with off-grid capacity equivalent to BEE. For analysis, off-grid/micro grid options have been compared not only with one another but also with grid connection. To incorporate renewable resources spatial variations, the work has been carried out at provincial level with the period 2014 to 2050. From analysis, it has been found that currently grid-connection is marginally better than off-grid options. But due to increasing grid connection cost and development in the off-grid technologies, the later with generation equivalent to BEE will be a more attractive option to electrify South African rural areas.

Keywords: South Africa, rural electrification, renewable energy

Introduction

South Africa is a developing country, with a population of about 52.89 million people living in around 13.2 million households. In the early 1990s, the electrified households' percentage was around 35% which grew up to around 75% (including both formal and informal[1] while 87% in the case of formal only). From this, it is clear that the South African government electrified the residential sector on a priority basis, but still a reasonable backlog, of around 3.4 million households, is to be electrified (Republic of South Africa, 2013), (Department of Energy, 2013).

In the latest approval, the South African government planned to electrify the sector to the maximum limit (up to 97% in case of formal households) by 2025. From the Department of Energy's statement, it is clear that they are not only considering the above mentioned backlog but also future growth in the sector. Additionally, it is mentioned that 90% of the households will be connected to the national grid, while the remaining 7% will use quality off-grid options (Bongwe, 2013).

The Department of Energy, South Africa, considered off-grid options due to the grid system infrastructure limitations, mainly transmission and distribution system availability to remote rural areas. To electrify the sector through grid, many challenges are being faced by the Electricity Supply Commission (Eskom)[2] including:

1. More than 95% of all non-electrified households are from a low income group (i.e. annual income around ZAR[3] 50,000.00). For them, payment of connection charges is obviously difficult (Department of Energy, 2013), (University of South Africa, 2012).
2. About 31% of the South African population lives in rural areas of the country. In these areas, more than 60% of households have no access to electricity. This means that the share of the rural communities, in the non-electrified households, is more than 50%. From these facts, it can be

deduced that the system cost will increase further if Eskom expands its transmission network in those areas (White and Kooperman, 2011; Municipal Institute of Learning, 2013; Madzhie, 2013; Noah, 2012).

3. According to Eskom, 'the consumption levels of rural customers are so low that it is impossible to recover capital and operations costs from the tariffs alone. In most instances, it is not possible to recover operation cost' (Barnard, 2011).
4. In the Integrated Energy Plan, the Department of Energy perceived further increase in the generation and operational costs of the system in future, which will result in further financial burden for the government if opted only for the grid option (Department of Energy, 2011).

From these facts and figures, the urgency of off-grid electrification options in South Africa can be understood. The government is currently providing 50 Watt Solar Home Systems (SHS) per household at a highly subsidized rate, to the remote rural consumers. Since 2002, a total 65 929 households have been electrified using SHS (Bongwe, 2013). According to Madzhie (2013), only in the fiscal year 2012-13, Eskom supplied 9 343 SHSs in different parts of the country with a total cost of 86 400 million rand. The figure of SHS supplied is impressive but the size of a 50 Watt solar system can hardly produce 12-15 kWh of electric energy per month under optimal weather conditions. This quantity of electric energy is hardly 20 - 30 % of BEE.[4] Therefore, to make renewables based supply sufficient and reliable, increase in both generation and storage capacity is mandatory.

In this study, work has been carried out to analyse different off-grid options with enough reliability to determine the optimal choice using MESSAGE (Model for Energy Supply Systems And their General Environmental Impact). For analysis, the provinces are considered separately to incorporate the spatial variations in renewable resources availability. For example, the Cape region has better wind resources, therefore, the role of wind based generation would be more effective than other parts of South Africa.

Additionally for investment, two options have been considered. The first option is the case, in which investment cost is relatively lower, while O&M cost is high. The second option is opposite of the first one i.e. high investment with low O&M cost. For example a user installs a photovoltaic system using both solar panels and batteries of low cost. This will need frequent replacement of system components which will increase its O&M cost. Here in this case, the Investment cost is low, while O&M is high. To differential between the two options, numeric '1' has been added at the end of name for the first option, while '2' for the second one.

Analysis method

For analysis, the International Institute of Applied Systems Analysis' (IIASA) developed a modelling framework MESSAGE that has been used. The framework is also used by well-known organizations including the International Atomic Energy Agency (IAEA) and International Renewable Energy Agency (IRENA) for energy system analysis.

The user defines the energy system under consideration providing input data to the MESSAGE using a graphical user interface. On the basis of input data, MESSAGE produces an optimal solution using economics as the only criteria. The other criterion can also be incorporate by applying constraint or penalty e.g. CO_2 emissions can be incorporated in the decision criteria through applying a limit on its emission quantity or applying a cost for its production. In this research work, no limit or emission costs have been considered. Therefore, the results are solely investment and O&M costs dependent. To find the solution, MESSAGE uses linear and mixed integer (operation research) techniques. In general, the layout of MESSAGE and its working environment can be outlined as shown in Figure 1.

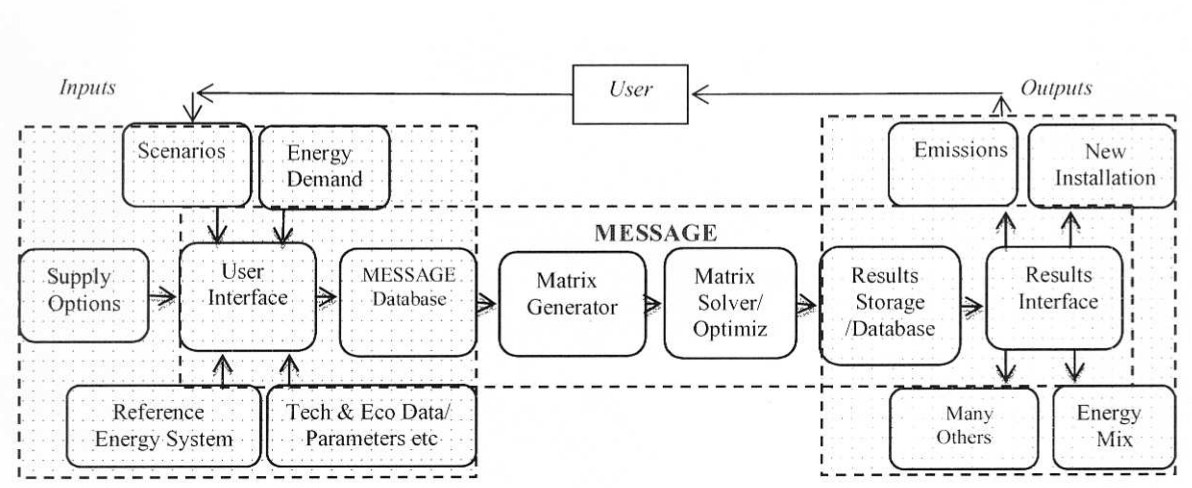

Figure 1: MESSAGE layout and its working environment

Assumption and data

Demand projection

The South African Government is providing 50 units (i.e. kWh) of electricity per household per month to low income consumers, free of cost, to fulfil their basic electricity needs (Adam, 2010). In this study, the total demand has been projected using the same electric demand per month per household in rural areas. To determine the total demand, it is therefore necessary to know about the number of households that are; I) located in rural areas; II) un-electrified; and III) belong to a low income group. For this purpose, the following information has been considered.

1. According to the University of South Africa (2012), around 48% (6.7 million) households in South Africa belonged to a poor group with annual income between 0-50 000 Rand per annum by 2010.
2. The Department of Energy found that 95% (3.2 million) of total un-electrified households, including both formal and informal, are from a lower income class (Department of Energy, 2013).
3. South Africa's 31% of population live in rural areas. In these areas, more than 61% are un-electrified. This means that:

Rural unelectrified population
$= \text{Total population} \times 0.31 \times 0.61$
$= 52.89 \text{ million} \times 0.31 \times 0.61$
$= 10.0 \text{ million}$

With these facts in mind, it can be deduced that most of the un-electrified households are from a lower income class and are locating in rural areas of South Africa. For a future number of such households, the Department of Energy (2013) household's projection has been taken into account with assumption that the low income class will decrease from 48% to 35% by 2050. This change could be for many reasons including socio-economic development, urbanization etc. Using these facts and figures, the projection would look like as shown in Figure 1. In this figure, the demand of BEE qualified households has been considered for further analysis

It is important to mention here that the Department of Energy numbers are average values at country level and may not represent specifically the rural communities. But adjustment in the number for rural community does not affect the main objective of the research work, which is targeted to determine the optimal option. Therefore, changes in the demand will affect the scale of required installed capacity, while the sequence of optimal choice would remain the same. Using Figure 2 households' projection with demand equal to BEE per household, the projected demand looks like as shown in Figure 3.

Supply options

The supply options are different type of standalone or hybrid generation facilities that could fulfil the rural consumers electric energy needs with reasonable reliability. For this purpose, the options considered are given in Table 1.

Except grid connection, all the above mentioned options have been analysed with battery storage, even in the case of a diesel generator. To fulfil the demand, the supply system charges the batteries to store electric energy. The stored energy is supposed to be used by consumers as per demand. Due to difference in supply options reliability, the storage capacity considered for each technology option is different. The additional feedback is considered only with a solar and wind standalone supply system due to their relatively low reliability.

Techno-economic data

Technologies basic prices

The basic prices of technologies are the market prices including services, installation and infrastructure cost (only if needed). For investment, WT and DG based standalone or their hybrid systems have been considered as micro grid. Due to this, additional cost of 30 - 50% of total investment cost for distribution within community has been considered. These basic prices of the technologies are the same

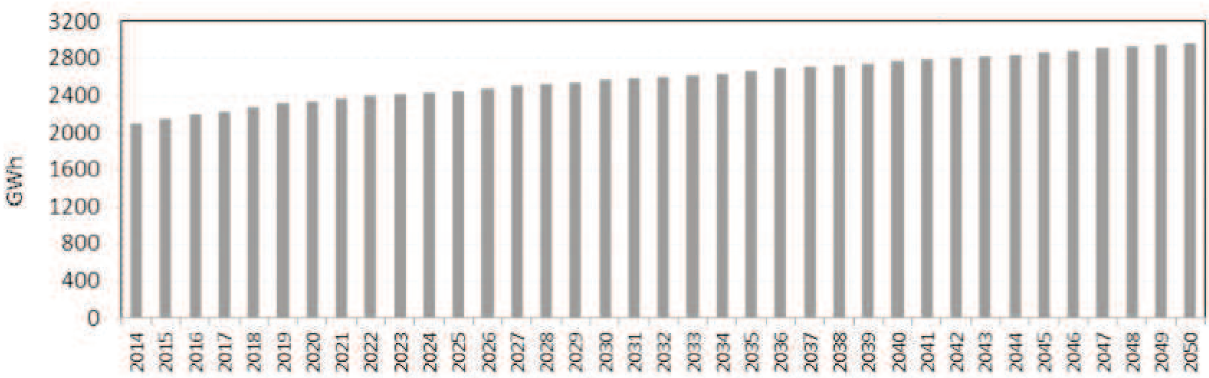

Figure 2: Projected electricity demand of un-electrified households in remote rural areas of South Africa

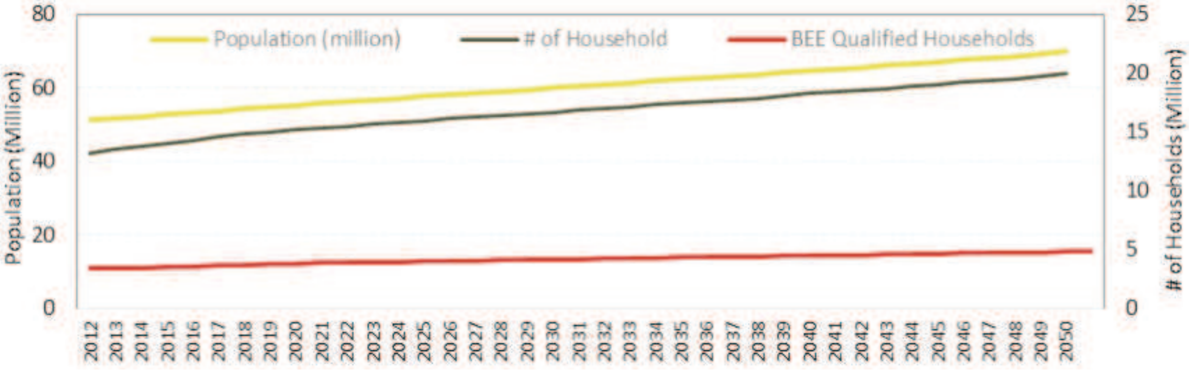

Figure 3: South Africa's population, households and BEE qualified households projection

Table 1: Electric energy supply options in remote rural areas

Supply options	*Installed capacity expected generation (% of BEE)**	*Expected share in demand fulfilment (%)*	*Feedback period through storage*
(days)			
PV Standalone	200	100	1
PV-Diesel Generator Share	NA	80 - 20	Nil
Diesel Generator Standalone	NA	100	Nil
Wind Turbine Standalone	120	100	0.2
Wind Turbine-PV Hybrid	130	60 - 40	Nil
Grid System	NA	100	Nil

* The expected generation of installed renewable capacity is based upon the resources availability under optimal weather conditions per day

irrespective of its installation location and are shown in Table 1. Later on for analysis, they are adjusted as per installation requirement. The need of adjustment and its concept are discussed below.

Technologies adjusted prices

To model the system, the investment and fixed cost should be in 'cost per unit of installed capacity', while variable cost in 'cost per unit of generation'. But here in this particular case, market costs data cannot be used directly in the modelling framework due to the following reasons:

1. The size of installed wind and solar change from place to place to provide the same energy to the consumer. For example, wind speed and its availability are better in the Western Cape than Gauteng. Therefore, a 1 000 Watt wind turbine will produce more energy in the Western Cape than Gauteng. To produce the same energy in Gauteng as in Western Cape, more WT capacity will be required there. This additional installation will make wind energy more expensive in Gauteng than Western Cape for the same demand.
2. The required installed capacity (Watt) of different technologies within a region will also be different from one another. For example anywhere, the required PV installed capacity will be significantly higher than DG to produce energy equivalent of BEE for the consumer.
3. In general, the household grid connection cannot be exactly defined in term of wattage due to

Table 2: Supply technologies market prices

Sustainable (2014) Workstation Solutions (2014); Alternagy (2014); Uprice (2014): Department of Energy (2014); Madzhie (2013); IRENA (2012)

Off-grid technology options	Technology types	Investment cost (Rand/Watt)*	Infrastructure (Rand/Watt)	Fuel (Rand/Litre)
PV System (Including all accessories and battery)	Type 1 Type 2	85.359 141.121	- -	- -
Wind Turbine (Including all accessories and battery)	Type 1 Type 2	94.153 153.930	5.878 8.095	- -
Diesel Generator	-	6.143	3.072	12.600

* Investment cost including all accessories (i.e. inverter, converter) and storage costs

variation in the demand. But the case becomes more complicated when the consumption level is so low i.e. up to 50 kWh. The daily load in such households could change between zero and maximum (most probably at the evening).

To overcome these issues and incorporate the required size and effect for comparison purposes, a hypothetical source of 95 watt has been considered. Such source can produce BEE with a utilization factor of 72%. For adjustment, the total investment of each supply option and their fixed costs in each province have been divided with this capacity. For variable costs, these have been divided with BEE i.e. 50 kWh to represent them in cost per unit generation. Since only wind and solar change from region to region, adjusted costs will change for the options where any of them is involved i.e. standalone or as hybrid. Additionally, the technologies development with time i.e. learning curve impacts, have also been considered in the work, with the corresponding rate mentioned in Table 3. For reference, the adjusted costs found for the Western Cape and Kwazulu-Natal have been shown in Table 3.

To have idea about the wind and solar resources availability and their impact on the adjusted investment cost, values found in all nine provinces have been shown in Figure 4.

Discount rate

For analysis, a discount rate (DR) of 11% has been used. This value is close enough to the DR (i.e. 11.3%) used by the Department of Energy, South Africa in the recent study i.e. Integrated Energy Plan-2012 (Department of Energy, 2013).

Renewable resources in South Africa

For wind and solar, the Atmospheric Science Data Center, NASA, USA data has been used (Atmospheric Science Data Center, 2014). To get the data from the Atmospheric Science Data Center

Table 3: Adjusted techno-economic data of supply technologies

Technology Options	*Western Cape*			*Kwazulu-Natal*			*Growth Rate*
	Inv. (000 ZAR/kW)	*Fix Cost (000 ZAR/kW)*	*Var. Cost (000 ZAR/kWyr)*	*Inv. (000 ZAR/kW)*	*Fix Cost (000 ZAR/kW)*	*Var. Cost (000 ZAR/kWyr)*	
Type 1: Low Investment High O&M Cost Technologies Option							
PV Standalone 1	231.17	9.19	0.006	220.02	9.06	0.006	0.982
PV + DG Hybrid 1	140.81	20.62	0.048	134.59	20.56	0.048	0.993
PV + WT Hybrid 1	233.45	3.51	0.008	432.23	3.64	0.008	0.988
DG Standalone 1	127.24	44.49	0.277	127.25	44.49	0.277	-
WT+DG Hybrid 1	274.61	12.49	0.078	582.04	12.49	0.078	0.996
WT Standalone 1	325.78	8.01	0.029	685.10	8.01	0.029	0.993
Grid Connection	163.98	2.01	0.099	163.98	2.01	0.099	1.076
Type 2: High Investment Low O&M Cost Technologies Option							
PV Standalone 2	331.34	6.03	0.004	328.167	6.02	0.004	0.982
PV + DG Hybrid 2	195.79	18.76	0.044	193.960	18.76	0.044	0.993
PV + WT Hybrid 2	328.72	1.57	0.004	380.498	1.57	0.004	0.988
DG Standalone 2	166.77	43.05	0.268	166.766	43.05	0.268	-
WT+DG Hybrid 2	385.82	11.02	0.069	469.558	11.02	0.069	0.996
WT Standalone 2	460.08	6.37	0.023	553.024	6.37	0.023	0.993

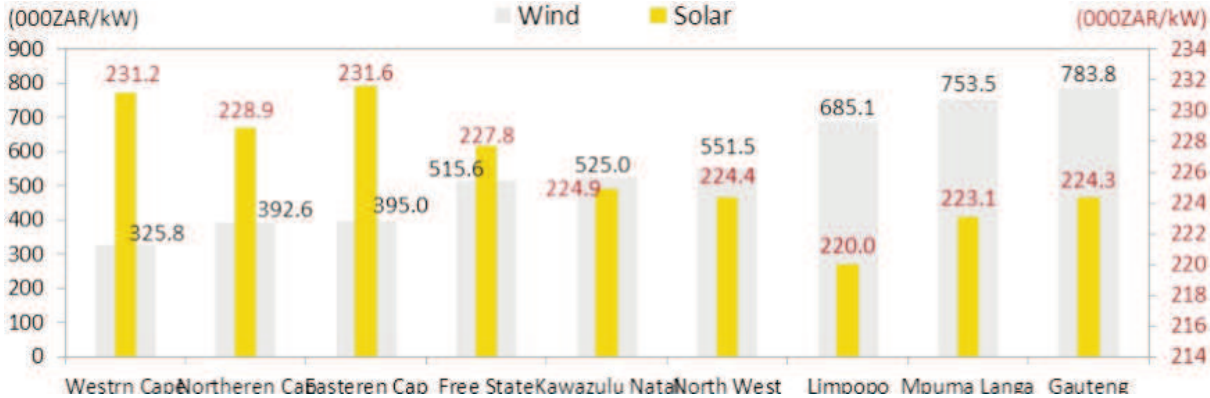

Figure 4: Adjusted solar and wind investment cost (000ZAR/kW)

(2014), one needs to provide colocation ordinates. For South Africa's provinces coordinates, a Google map online service has been used with South African solar and wind resource maps (Wind Atlas for South Africa, 2014; Google Map, 2014). Special attention was paid not to consider the location for data where resources availability are extraordinary different than remaining part of the province e.g. Wind resources availability in coastal regions of Western Cap and Eastern Cap are quite higher than remaining part of the province. The high resources availability in such areas make them attractive options for a grid connected large scale wind farm than just small size community based generation. Therefore, coordinates of such a location have not been used to extract data.

Results and findings

From an analysis of the system at provincial level, grid connection is generally found as an attractive option at the mentioned costs, but for a limited period of time. The probability of connection costs increase with expansion of the grid system is high. Therefore, everywhere around the country, renewables replaced the grid option to electrify rural areas. But the time taken by renewables based generation to replace grid connection varies. In general, with respect to time span and type of renewable choice, two to three different trends have been found to electrify the rural areas in South Africa. In the following three cases as representative of similar type findings are discussed, while remaining figures can be found in Appendix A of the work.

In general, the wind conditions in the Cape region of South Africa are good enough to be exploited. Therefore, in the Eastern Cape, Western Cape and Northern Cape, the WT-PV hybrid system is found to be the most attractive solution to replace grid connection and supply BEE to the consumer with enough high reliability. Moreover, the region also took a relatively short period to use renewables in place of grid option, which means that the renewable programme can be started now in rural areas of these provinces. For reference, the optimum installed capacity mix and its generation found in the Eastern Cape, are shown in Figure 5.

The country with those provinces where wind potentially is significantly low while solar high, the grid connection is found for a relatively longer period of time. In general, the regions are also found with a choice of a PV-DG hybrid system. But the role of PV-DG is found critical in the Free State only while in others, it could be ignored. The main candidate to electrify the rural areas in these provinces is therefore a PV based standalone system. Besides the Free State, the other provinces with this type of findings are Gauteng, KwaZulu-Natal, and Mpumalanga. For information, the installed capacity and energy balance found from simulation in the Free State Province are given in Figure 6.

In Limpopo Province, the overall installation and energy generation trend is quite resemble as

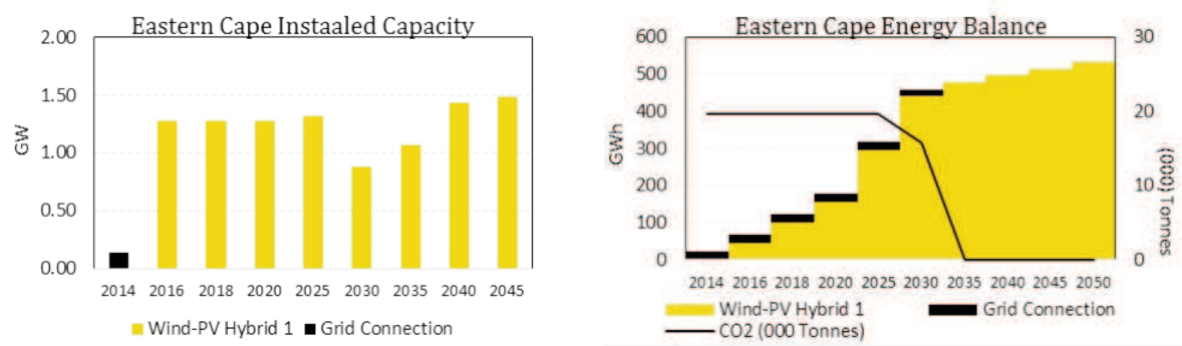

Figure 5: South Africa's Eastern Cape Province rural areas installed capacity and energy balance

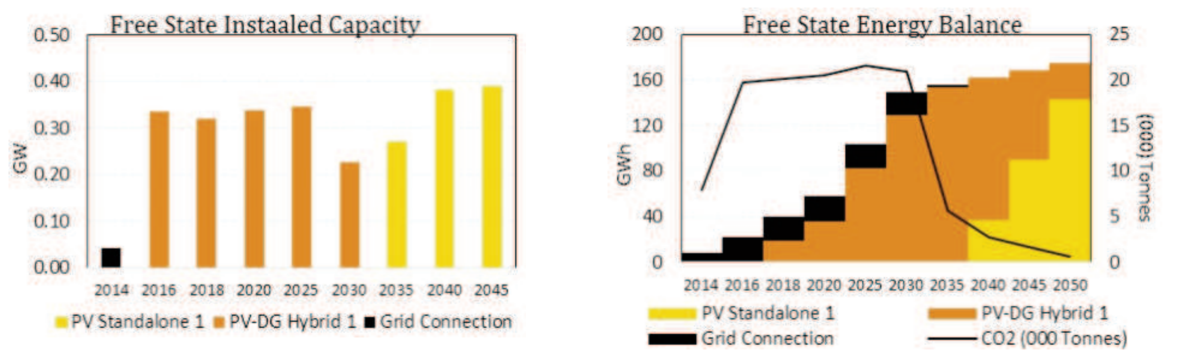

Figure 6: South Africa's Free State Province rural areas installed capacity and energy balance

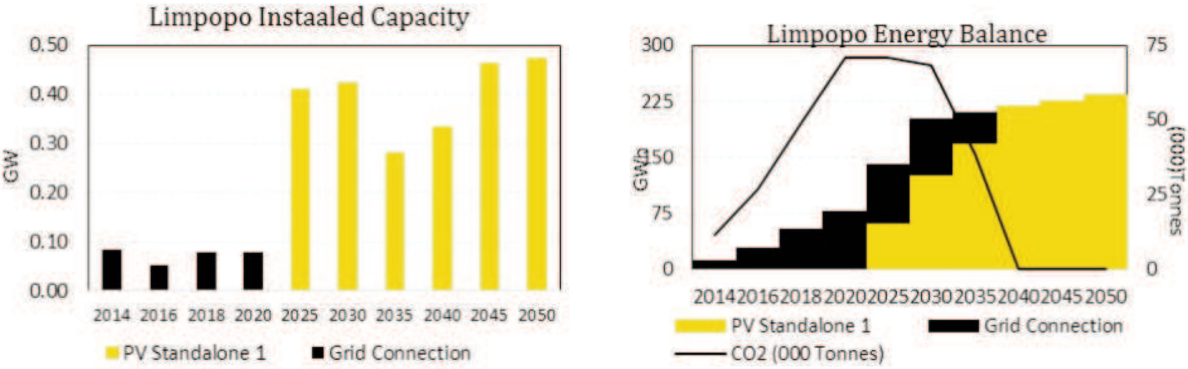

Figure 7: South Africa's Limpopo Province rural areas installed capacity and energy balance

the previous one i.e. provinces with high solar insolation. But its extremely good solar resources make it a stronger candidate for a PV based standalone system. Therefore, the PV based standalone system followed the grid option soon after and no support of DG was found at all, as shown in Figure 7.

Discussion and conclusion

The results found in this study show that grid connection is the marginally preferred option with cost of ZAR 15 450 per connection. But this cost is growing continuously. According to Eskom, the growth rate recorded in the connection cost is around 1.10 for the period 1995 to 2009. Similarly, the growth rate recorded from 2008 to 2012, in the subsidy given by government per connection is found to be 1.19 (Madzhie, 2013). For these reason, the benchmark grid connection cost considered by the DoE in the Electrification Master Plan is ZAR 17 000 per connection for the rural consumer (Bongwe, 2013). If this increase in the connection cost continues due to system expansion for electrification, and the consumption level of the consumer remains relatively lower, the grid connection will be no more as an economical choice in South African rural areas.

In that case, a PV-WT based hybrid system in the Cape region would be a better choice. Despite the fact that wind is localized in nature, the region still has high potential for a small scale community or home based PV-WT (e.g. SolAir system) hybrid system with storage that can be exploited for remote areas of electrification. As the findings of the simulation showed that renewables replaced the grid option very soon, the implementation efforts for the choice can be started even now across the region.

In other parts of South Africa, PV standalone or its hybrid with DG is a more reliable choice. Compare to PV standalone, PV-DG hybrid is a more reliable and economical choice for a brief period but still the option attributes maintenance concerns. Due to motive parts and a relatively complicated structure of the diesel generator, the choice required more technical skills than others. Therefore, additional efforts will be required to provide highly skilled services in the areas. Moreover, the choice may not be a good one if CO_2 emissions is considered in the decision making process. Keeping these in minds, a PV based standalone looks like good choice than its hybrid. For optimization of the investment, the electrification programme should be initiated in those remote areas where grid connection availability in the coming five to ten years is difficult.

At the end, it can be easily concluded that the targeted 7% off-grid electrification option in South Africa's long term plan is a reasonable choice but could not be achieved only through a PV based system, particularly in the Cape region. Moreover, the size of off-grid installed capacity per household should also be increased to a level where the rural consumer could fulfil its basic energy consumption including lighting, entertainment and communication. Finally, the greenhouse gases emission intensity of the South African electric sector is quite high due to the high coal share, therefore implementation of off-grid technologies will contribute in the reduction of CO_2 emissions in the country.

Notes

1. Informal Household is a kind of housing structure usually constructed by using unconventional building materials e.g. a shack, used by poor urban residents.
2. The "C" is replaced by "K" for word Kommissie means Commission in Afrikaans (one of the national languages in South Africa)
3. ZAR stand for Zuid-Afrikanse Rand, which is South African's currency name
4. BEE is 50 kWh electric energy being provided by South African Government to the grid connected to an extremely low income class without charges

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Determinants of energy poverty in South Africa[1]

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Abstract

This paper provides empirical evidence on the determinants of energy poverty in South African households using the National Income Dynamics Survey (NIDS, 2012), while controlling for individual, household and demographic characteristics. This is formulated within a logistic regression framework, while defining energy poverty using the expenditure approach consistent with the definition by the Department of Energy (DoE) of South Africa. The model reveals that household expenditure patterns, race, education level, household and dwelling size, location of the household and access to electricity are important factors in explaining the state of energy in South African households. This paper also discusses limitations in defining energy poverty using the expenditure approach. Finally, some recommendations are made for regulators and policy makers.

Keywords: energy, energy poverty, Logit, South Africa

1. Introduction

South African policies echo the sentiment for energy access through the White Energy Paper (RSA, 1998) where it is stated that, "energy security for low-income households can help reduce poverty, increase livelihoods and improve living standards" (RSA, 1998). Access to energy is important as it leads to an eradication of poverty through improved education, health services and may eliminate structural unemployment (Department of Energy, 2009).

The South African government believes that energy poverty deepens general poverty and contributes to an erosion of health and education outcomes (RSA, 1998). As a result of it being a policy focus, the country has made strides in addressing energy poverty. This is evidenced in the Medium Term Strategic Framework (MTSF, 2009), which states that the government aims to, "include, amongst others, diversification of the energy mix in pursuit of renewable energy alternatives and the promotion of energy efficiency".

According to the Integrated Energy Plan (IEP) (2013), South Africa has an urban electrification rate that is around 80% and rural electrification rates that is around 50%. Eskom is South Africa's electricity public utility provider and in terms of electrical supply is the dominant player; supplying 92.8% of the country's electricity demands. The remaining 7.2% is supplied by Independent Power Producers (IPP) from renewable energy sources.

Even though South Africa possesses large electrification rates, Ferriel (2010) states that in total there are approximately 2.5 million rural and urban households in the country not connected to the national electricity grid, in addition to the millions that are connected to the grid but are not able to pay for electricity. As a result, even with a high electrification rate, households earning low incomes cannot afford sufficient electricity to improve their welfare (Mapako and Pasad, 2005). Many South

African households predominantly use traditional and unclean energy resources for many activities such as cooking, lighting and drying of farm produce (*Statistics SA*, 2008). The attainment of the Millennium Development Goals (MDGs) rests on the availability and access of affordable energy to all people (Kohler, Rhodes and Vermaak, 2009). Kohler, Rhodes and Vermaak, (2009) believe that in order to achieve the MDGs, policy needs to be developed to encourage the use of efficient energy at the household level, so that the use of unclean energy such as biomass and charcoal is minimised.

The following section provides a literature review, which explains the meaning of energy access and energy poverty. It ends with an overview of some of the policy initiatives the South African government has implemented in order to combat energy access and energy poverty issues.

2. Literature review

2.1 Energy access

There is a lack of consensus in the literature on what the term "energy access" means. One of the reasons is that there have been problems in the techniques and concepts used to define it (Kohler *et al.*, 2009). For example, definitions that have been based on minimum physical levels of cooking or heating are often location specific due to the difference in climatic conditions between different parts of the world (Barnes *et al.,* 2011).

The IEA, in its World Energy Outlook (2009), identified three levels of access to energy services depending on household energy needs and the benefits energy services provide. These include:

1. The minimum level of energy access required by households to satisfy basic human needs (electricity for lighting, health, education and community services).
2. The energy access required by households to improve productivity (electricity and modern fuels to improve productivity)
3. The level of energy access required by households to satisfy modern society needs (modern services for domestic appliances, increased requirements for cooking and heating and private transportation)

Kohler, Rhodes and Vermaak, (2009) describe a theory of transition in which households gradually ascend an "energy ladder. The ladder, beginning with traditional biomass fuels (firewood and charcoal), moves through to transition fuels (kerosene, coal and charcoal) and then on to modern commercial fuels (Liquefied Petroleum Gas (LPG), natural gas, or electricity) as incomes rise and urbanisation grows (Kohler *et al*., 2009). According to Leach (1992), during periods of economic growth it is expected that people living within a community will switch from using traditional fuels to more modern fuels such as electricity, due to the industrialization and urbanisation that takes place. This is the energy transition prevalent in the model and states that as a country develops economically, households will convert to more efficient sources of energy.

Hosier and Dowd (1987) conducted empirical research in order to determine which factors have a significant effect on the energy ladder and factors which cause movements up the ladder focusing on people's choice of household cooking fuels in Zimbabwe. They found that the choice of fuels was determined by household income, regional ecological potential, relative fuel prices, household size, and the perceived fuel wood accessibility. The results showed that a larger household size would cause a transition from wood to kerosene, but decreases the chances that electricity will be used over kerosene or wood. Hosier and Dowd (1987) also found that households located in urban areas were significantly more likely to use kerosene than wood. When relative per unit price of kerosene was high compared to the per unit price of electricity, this increased the probability of a household choosing electricity over kerosene. Furthermore, households that did not perceive wood as being difficult to collect, preferred wood. The results also showed that substitutions to more sophisticated energy sources, was likely to occur when household income rises.

Leach (1992) also investigated the energy transition model. At the time, it was found that in the poorest developing countries biomass accounted for 60-95% of total energy consumption. In urban areas of these countries energy transitions progressed slowly and even slower in rural areas. For example in India, urban transitions were quicker when there was a rise in relative firewood prices and an increase in household income. As a result, the use of biomass for cooking and heating fell from 42% to 27% (Leach, 1992). These energy transitions were driven by the social economic changes that give households the opportunity to use modern fuels.

Leach (1992) also found that the price of these fuels is a major barrier in the transition to more modern fuel sources especially in developing countries where the price variations are greater. A household's ability in obtaining modern fuels is another significant constraint on the energy transition model. This was observed from the patterns of household energy use in comparison to the settlement size and the distance from major trading centres and roads in rural areas located in India (Leach, 1992). In these locations, even the highest income households only used biofuel, with maybe kerosene for lighting. This was the case because more efficient fuels could not easily be accessed in small and remote settlements due to the insufficient supply of modern fuels in their settlements, as a result of poor distribution (Leach, 1992).

The same sentiments are echoed in the South African context. Even though an increase in income dictates a higher demand for energy, the transition to more modern energy is not easy for many South African households. This is evidenced in empirical work done by the Energy Sector Management Assistance Programme (ESMAP, 2000), the International Economic Agency (IEA, 2002) and Heltberg (2004), including research on energy use patterns in South Africa by Aitken (2007), who all reveal that many South African households rely on multiple energy sources for their energy needs and this applies to both electrified and non-electrified households.

Kohler, Rhodes and Vermaak, (2009) highlight that access to efficient and affordable cooking and heating fuels, like LPG or kerosene, are vital to alleviating the effects of energy poverty. This finding provides a strong empirical challenge to prevailing energy transition theories and the "energy ladder" model. Kohler *et al*., (2009) explain several possible explanations for this. One is that unreliable supplies require households to rely on diverse sources of energy. Another is that different energy sources are more cost-effective in some uses than in others. For instance, it may make economic sense to use electricity for lighting but LPG for cooking. Therefore, the focus on income is only one part of the problem.

2.2 Energy poverty: Measurement

Broadly defined, energy poverty is viewed as the *lack of access to modern energy services,* be it electricity, heating or cooking fuels, necessary for human development (Kohler, Rhodes and Vermaak, 2009). Several authors have been able to theoretically provide a definition for energy poverty but practically fail to agree on a threshold poverty line. There are numerous approaches that are used to measure energy poverty. Each will be discussed in turn:

- *The income approach:* is defined based on the share of a household's income that is spent acquiring basic energy sources (Fahmy, 2011). This approach shows that for the lowest income households, the share of income spent acquiring fuels is usually higher than those of higher income households.
- *The self-reported approach:* is based on a household's perception of adequate amount of household fuels and their expenditures (Fahmy, 2011).
- *The objective approach:* Objective approach is usually operated by the government, it is measured by calculating the proportion of household's income that needs to be spent on energy. The government can deem a household energy poor if more than 10% of its income is sent on energy (Waddams *et al.,* 2007) or the government can rely on expert assessments that link people's thermal needs and physical characteristics such as weather temperature and climate (Fahmy, 2011).
- *The access-adjusted approaches:* The access-adjusted measure looks at the accessibility of an energy source by households in specific areas Kohler *et al*., (2009).
- *The expenditure approach:* The expenditure approach is considered to be the universal measure of energy poverty and has been adopted by a number of countries because of its attractiveness. The approach doesn't require governments to identify the amount of energy that is being used by households, and the average energy source used by households can be easily be determined at the expenditure poverty line that can be based on household energy surveys (Barnes, Shahidur and Hussain, 2010). Households with energy expenditures above this threshold are considered energy poor and are likely to be confronted with difficult choices between meeting energy requirements and spending on competing goods. This poverty expenditure line is generally estimated to be 10-15% of income.

The expenditure approach has been adopted as the measure of energy poverty in South Africa (DoE, 2013). This is the equivalent of a middle income household earning R10 000 a month and spending up to R1 000-R1 500 a month on acquiring energy services (Aitken, 2007).

Kohler *et al*., (2009) compared the results of an expenditure approach and access-adjusted approach based on South African households. Using a 2008/2009 DoE survey amongst LSM1-LSM3 in all nine provinces for electrified and non-electrified households, indices of energy poverty were created. The energy burden of households was calculated using energy expenditure as a percentage of total income. The access-adjusted measure was calculated using the percentages of households below different poverty lines (667kWh, 1200kWh and 2000kWh) by province (Kohler *et al*., 2009).

The results showed that access-adjusted data was more robust and informative (Kohler *et al.*, 2009). For example, the expenditure approach showed that Northern Cape's energy burden was 11.8% for electrified households, and 11.6% for non-electrified households. For Limpopo, the energy burden was 11.7% for the electrified and 16% for non-electrified households. On the other hand, the access-adjusted approach showed that more than 60% of non-electrified households in the Northern Cape and Limpopo were below the

667kWh energy poverty line, meaning they had access to 667kWh or less per person per year. Using the expenditure approach these provinces were considerably not energy poor, but when the type of fuels used is considered using access-adjusted approach these areas were considerably energy poor.

The United Kingdom government defines energy poverty using the objective method and a study by Fahmy (2011) provides a summary of benefits relating to the objective approach. Households that are defined as being energy poor must spend more than 10% of their income on all fuel that is used to warm their homes to a decent level. The energy poverty measure focuses on warmth because 25 000 people die every winter as a result of cold homes (Hope, 2013). Fahmy (2011) iterates that the advantage of using the objective approach as opposed to the expenditure approach is that it has the ability to identify households that are spending below the energy poverty line due to under-consumption. As well as being able to estimate the proportion of households that will need to spend disproportionately in order to maintain the adequate temperatures in their homes, these households may be supported by the government (Fahmy, 2011). Compared to the self-reported approach, the objective approach is not subjected to the measurement error that may result due to changes in wording (Fahmy, 2011). This is because changing the wording when conducting subjective surveys is known to change people's answers (Tietenberg and Lewis, 2012).

The approaches mentioned above each have advantages and disadvantages when measuring energy poverty. It is unlikely that one approach is able address all the concerns. The measure chosen should be based on the policy objectives that are trying to be achieved (Fahmy, 2011).

2.3 Policy initiatives in South Africa

Currently, Eskom and the Department of Energy (DoE) are embarking upon endeavours to increase the electricity supply by commissioning renewable energy from IPPs. The policy implemented to achieve the commissioning of renewable energy from IPPs is the Renewable Energy Independent Power Producer Procurement Programme (REI4P). The South African government has made massive strides to ensure that there is sufficient supply to meet the growing demand of electricity. This will see the price of electricity increase for South African households connected to the national grid. Furthermore, policy benefits will accrue only to households connected to the national grid who can afford to pay for the energy supply. This does very little for households which are not connected to the grid.

In July 2003, the government endorsed the Free Basic Electricity (FBE) policy as a possible solution the country's electrification challenges. According to Mvondo (2010), The FBE policy was derived from the government decision that was made two years prior to provide basic services to poor households, with a priority put on water, energy and sanitation services (DoE, 2013). The policy compels municipalities and state owned firms that are in the electricity sector, to supply a certain amount of electricity to poor households in the country for free. Households that are already connected to the grid qualify for 50 kWh every month, as this is considered sufficient to satisfy basic energy needs. Off-grid households are given a R40 subsidy per month that is paid towards a R58 monthly service fee which makes for up to an 80% subsidy, such that these households only have to make payments of R18 a month (DoE, 2013).

Based on a study that was done in Buffalo City in the Eastern Cape using a Quality of Life (QoL) survey, Mvondo (2010) found that the FBE policy had a major social impact on its population. It was found that the FBE policy was very limited in the productive use of electricity as only 34% of the households were able to run at least one electricity dependent business (Mvondo, 2010). Regarding the health benefits, it was found that 92% of the households indicated that they had not experienced any illness cases in the last 9 months, the study also indicated that the electricity usage patterns were related to better health practices (Mvondo, 2010). For example, fires that were caused by using candles were reduced with better access to electricity. Regarding education, it was found that electricity access had a positive effect on the time children spent studying in most households, despite this positive impact some households complained that children would spend more time watching television (Mvondo, 2010).

Ferriel (2010) conducted a qualitative study based on 30 households to see if the 50kWh on the FBE was sufficient. Households were asked the following two questions: 1) is the 50kWh of FBE sufficient? And 2) what amount of free electricity is reasonable? The results showed that only 25% felt that the 50kWh was sufficient but this had to be used with other energy sources. It also illustrated that on average households used up to 750kWk per month. This means that the free allocation was only 6.6% of monthly electricity use.

Ferriel (2010) concluded that the objective of the policy marginally improves the lives of the poor, removing the health risks of using wood for cooking. However, given that the 50kWh amount still requires many households to use other energy sources, it cannot improve people's lives especially for those living in urban areas. The FBE policy also states that homes applying for FBE need to be fitted with a pre-paid meter, and then vouchers have to be used in order to access the free based allowance (Mvondo, 2010). This further creates inequality as the poor are often unable to buy vouchers due to the uncertainty of incomes in poor households. The policy also states that electricity demand for poor households could be met by restricting the current supply to 20 amps (Ferriel, 2010). This limited 20 Amp restriction creates an inconvenience to low income as it limits the number of domestic tasks they are to perform. Mvondo (2010) also recommended that social education programmes should be implemented together with FBE in order to restrict the negative social effects of having electricity.

In 2008, the DoE implemented an Incline Block Tariff (IBT). IBTs divide the electricity price into several steps or blocks. The first block of electricity is at the lowest price. As the customer purchases more electricity during the month, the electricity bought will eventually fall in block two, which is a bit more expensive. This process repeats automatically as the customer purchases further electricity to move into block 2. At the end of the month, the history is reset and the customer will again start the next month from block 1. The process to move from the one block to the next is automatic and depends only on the amount of electricity that is acquired by the customer. The movement to the next block is not at all affected whether the purchases are spread over many transactions or if all the electricity is part of one transaction. Because the blocks increase in the price, customers can save money by not buying more electricity than what they will use during the month. It is much better to wait until the next month and start to buy again at the low price (DoE, 2013).

This paper seeks to add to the energy poverty literature and build and extend on the work by Ismail (2015) by empirically measuring energy poverty as defined by the DoE. More importantly, this paper empirically tests for determinants associated with energy poverty amongst households. This is discussed in detail in the sections that follow. Therefore, the main goals of the paper are as follows (Ismail, 2015):

1. Estimating energy poverty of households using the expenditure approach as defined by the Department of Energy of South Africa (DoE).
2. Constructing a logistic (logit) regression model of the determinants of energy poverty using the measure of energy poverty developed in 1) as a dependent variable.

The data is drawn from the National Income Dynamics Survey (2012) since it provides detailed information of income and expenditures of households, as well as individual, household and demographic characteristics of South African households.

The paper is organised as follows: Section 3 describes the data used, including a description of variables used in estimation. Section 4 presents the measurement of energy poverty and the methodology for logistic regression analysis. Section 5 presents the results of the estimation and tests to ensure the predictive power of the model. Section 6 talks about the limitations of the energy poverty measurement in estimation. Section 7 provides policy recommendations for regulators and policy makers. Lastly, section 8 concludes.

3. Data

The National Income Dynamic Survey (NIDS, wave 3, 2012) is used for estimation in the logit regression analysis. The NIDS dataset is by nature an individual dataset and each individual is tracked with a unique identification number across each of the three waves. There are various questionnaires that consist of the NIDS data: including an individual, child, proxy and household questionnaire. Each household is tracked with a household identification number. This is unique within a wave, but not unique across the three waves. For this reason, household transitions in and out of energy poverty can be tracked at a particular point in time. However, it is difficult to track over time. Therefore, analysis of individuals is done at the household level using only wave 3. Each questionnaire is structured and given to the individual in the household to be used for the collection of information. The household questionnaire is typically answered by the oldest female in the household. The questionnaire has a set of questions on variables such as gender, marital status, household size, dwelling size, location of the household, education, and energy use, and income and expenditure patterns of the household, amongst others (NIDS, 2012).

This paper only focuses on relevant information from individuals in households needed to conduct this study. It follows the empirical work done by Dunga, Grobler and Tchereni, (2013) and builds and extends on the work by Ismail (2015) to estimate energy poverty and its determinants among South African households. First, energy poverty is calculated for each of the individuals in the households using the expenditure approach. This allows us to determine the number of individuals in households below the expenditure energy poverty line within the sample (households spending more than 10% of their income on energy sources). Second, a discrete choice analysis using a logistic model is adopted to analyse determinants of energy poverty. Below are some statistics which describe the dataset used in the analysis.

3.1 Descriptive statistics

The sample used for estimation is comprised 6 961 households and 29 918 individuals. Table 1 shows that of the individuals in the sample, close to 25% live in energy poverty as defined by the expenditure approach. Figure 1 shows the relationship between Energy poverty and income. Where income represents imputed household income after tax split into deciles. It is clear to see that the poorest 20% of individuals are also the most energy poor in the sample. Therefore, as income increases, individuals face lower energy poverty.

Table 1: Individuals in sample
Source: NIDS, 2012

Energy poverty dummy variable	*Frequency*	*Percentage*
Energy well-off	22,349	74.7
Energy poor	7,569	25.3
Total	29,918	100

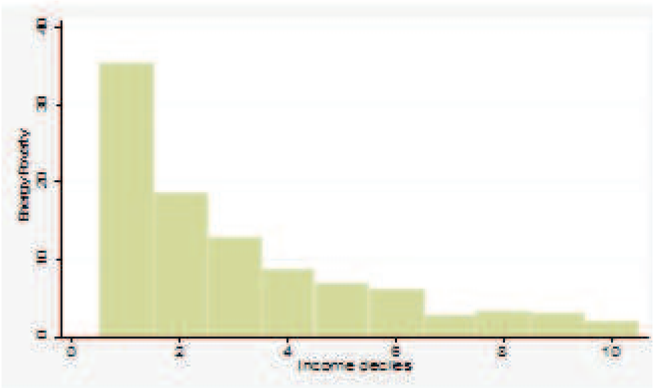

Figure 1: The relationship between energy poverty and income

Table 2 gives a list of all the variables used in the logistic regression analysis.

Table 2: Variables used in the logistic regression analysis
Source: NIDS (201)2

Variable	*Frequency*	*%*
Individual characteristics		
Gender		
Male	13,453	44.97
Female	16,465	55.03
Race		
African*	25,014	83.61
Coloured	3,855	12.89
Asian/Indian	326	1.09
White	723	2.42
Educational attainment		
Tertiary education	1,957	6.54
Completed Matric	2,949	9.68
Incomplete schooling	24,737	82.68
Household characteristics		
Electrified	24957	83
Location		
Rural	16,529	55.25
Urban	13,389	44.75
Married	5,273	17.62
Household size		
1	945	3.16
2	2162	7.23
3	3390	11.33
4	4096	13.69
5	4475	14.96
6	3828	12.79
7	3122	10.44
8	2256	7.54
9	1827	6.11
10	1150	3.84
>10	2667	8.92
Number of people in the household		
1	1771	5.92
2	3987	13.33
3	5126	17.13
4	6386	21.35
5	4040	13.5
6	3201	10.7
7	2127	7.11
8	1508	5.04
9	778	2.6
10	442	1.48
>10	514	3.19
Demographic characteristics		
Province of the household		
Gauteng	2537	8.48
Limpopo	3099	10.36
KwaZulu Natal	9175	30.67
Eastern Cape	3773	12.61
Northern Cape	2133	7.13
North West	1933	6.46
Western Cape	3212	10.74
Mpumalanga	2310	7.72
Free State	1746	5.84
Sample size	29918	

* African refers to Black South Africans

4. Methodology

Logistic regression

The logistic regression model is used in estimation. This model makes use of predictors to estimate probabilities that an event does or does not occur relying on similar inferential statistical methods as in Ordinary Least Squares (OLS) (Gujarati, 2004). Theoretically, a decision maker *n* faces *J* alternatives. The utility that the household obtains from alternative *j* can be represented as:

$$U_{nj} = V_{nj} + \varepsilon_{nj} \quad (1)$$

Where, U_{nj} is total utility; V_{nj} and ε_{nj} represents unknown variables classified as stochastic utility (Gujarati, 2004). The logistic function is obtained by assuming that each ε_{nj} is an independently, identically distributed extreme value. The density for each unobserved component of utility is (Gujarati, 2004):

$$f(\varepsilon_{nj}) = e^{-\varepsilon_{nj}} e^{-e^{-\varepsilon_{nj}}} \quad (2)$$

And the cumulative distribution is given by (Gujarati, 2004):

$$F(\varepsilon_{nj}) = e^{-e^{-\varepsilon_{nj}}} \quad (3)$$

From the above, this represents the probability that decision maker chooses. Therefore, the empirical model is formulated as follows:

f(Energy poverty) =
(exptpt, expfood, expsch, gender, race, educ, location, electrification, hhsize, dwelsize, marital, ε) (4)

Dependent variable

In expenditure terms, a household is considered to be energy poor if 10 percent or more of its income is on energy (Fahmy, 2011; Department of Energy, 2009). This definition therefore requires data on energy expenditure at the household level and total income.

The NIDS (2012) data set provides information of monthly expenditure patterns of electricity as well as other energy sources. It also provides information of a household's monthly income. Therefore, a summation of all energy expenditure was taken as a proportion of household after tax imputed income as follows:

$$\textit{Energy budget share of total household budget} = \frac{\textit{expenditure on all energy sources}}{\textit{After tax income}} \times 100 \quad (5)$$

Households whose energy expenditure budget exceeded 10 percent were regarded as being energy poor and therefore they were coded 1 and those who were spending less than 10 percent on energy received a code of 0 (zero). This allows for the creation of a dummy variable for energy poverty in this manner as shown in Table 1.

5. Results

Expenditure patterns

In general, a household will consume goods and services which will maximise its utility of consumption, thereby making the most of limited resources to maximise utility. As consumers are insatiable and utility functions grow with quantity, the only thing that limits a household's consumption of a good is its budget. Furthermore, consumers cannot obtain an additional unit of one good without giving up some other goods. Following this logic:

The results in Table 3 show that there is a positive and statistically significant relationship between energy poverty and transport expenditure as well as energy poverty. The results suggest that the odds ratio of 0.105 is in favour of transport expenditure to increase the energy poverty level. In terms of elasticity as reported in Table 3, the relationship between transport expenditure and energy poverty is inelastic. This means that if the price of energy increases, the household cannot forgo transport expenditure and must cushion the price increase of energy from elsewhere in its budget. More specifically, a 1 percentage increase in transport expenditure could increase energy poverty by 0.13 percent.

There is also a positive and statistically significant relationship between energy poverty and schooling expenditure at the 1% level. The odds ratio of 0.009 was in favour of schooling expenditure to increase the energy poverty level. Like transport expenditure, the relationship between schooling expenditure and energy poverty is inelastic. A 1 percentage increase in electricity expenditure could increase energy poverty by 0.015 percent.

There is a statistically negative relationship between food expenditure and energy poverty. At the 1 percent level of significance, the odds ratio predicts that households who spend more on food are likely to have better energy access. As Table 3 shows, for every 1 percentage point increase in the food budget, there is likely to be a 0.034 percentage decrease in energy poverty. Said differently, low energy poverty levels are likely to be associated with higher expenditures in food for members of a household as funds are released from spending on energy and the gains are moved towards improved consumption of food.

Gender

There is a positive relationship between gender and energy poverty although the association was statistically insignificant to reject the null hypothesis. The odds ratio however, shows that one is more likely to be energy poor if they are female than male. This finding opposes Dunga, Grobler and Tchereni, (2013), who find that males are more likely to be

Table 3:
Source: NIDS (2012)

Energy poverty variable	*Odds Ratio*	*Elasticity*	*Std. Error*
Socio-economic characteristics			
Expenditure on transport	0.105‡	0.130	(0.006)
Expenditure on schooling	0.009‡	0.015	(0.003)
Expenditure on food	-0.003‡	-0.034	(0.001)
Individual characteristics			
Gender	0.030	0.065	(0.036)
Race			
Coloured	-0.138†	-0.908	(0.081)
Asian/Indian	2.390‡	0.007	(0.155)
White	1.642‡	0.209	(0.134)
Educational attainment			
Tertiary education	-0.254*	-0.034	(0.530)
Completed Matric	-0.300	-0.038	(0.596)
Incomplete schooling	0.153	0.179	(0.224)
Household characteristics			
Electrified	0.296†	0.224	(0.117)
Location	-0.409†	-0.096	(0.179)
Married	-0.140	-0.029	(0.191)
Dwelling size	-0.141‡	-0.783	(0.058)
Household size	0.277‡	1.289	(0.058)
Demographic characteristics			
Province of the household			
Gauteng	-0.197	-0.032	(0.094)
Limpopo	-0.679	-0.085	(0.365)
KwaZulu Natal	0.437	0.064	(0.308)
Eastern Cape	0.676‡	0.044	(0.090)
Northern Cape	1.269‡	0.082	(0.304)
North West	0.592	0.036	(0.349)
Western Cape	(Omitted)	(Omitted)	(Omitted)
Mpumalanga	0.827	0.056	(0.369)
Free State	0.600	0.048	(0.104)
Constant	0.615†	0.096	(0.670)
N	29918		
Log-Likelihood	-10246.265		
Significance: * 10%, † 5%, ‡ 1%			

energy poor in rural Malawian households. The reason is that men culturally do not go to the forest to fetch firewood the way women do in parts of Africa.

However, with regards to the South African context, this result is consistent with authors such as Annecke (2002). She explains that the positions which women hold along the energy chain reveal a clustering around the biomass sector and women are seldom in control of resources. Therefore, they have greater access to inefficient sources which lead to them being energy poor.

Race

In 2008, nearly 80 percent of the population was of African descent, while the Coloured and White population accounted for 9 percent each. The remaining 2 percent of the population were of Asian or Indian origins. Even though Africans make up the highest percentage of the population, the distribution of resources is extremely unequal across these groups. For example, white people report about 8 times the average per capita income and expenditure levels of Africans (Gradin, 2011). This indicates a stark inequality between the races.

The results in Table 3 highlight this, as African people are more energy poor than white and Asian/Indian people. These results are significant at the 1% level. It was also found that Coloured people are more likely to be in energy poverty compared to African people. This was found to be significant at the 5% level. Differences of poverty between races can be explained by unequal access to education, family planning, or the labour market, or by the fact that they live in more deprived areas (Gradin, 2011). Each of these factors is likely to affect the income of an individual and contribute towards higher energy poverty.

Educational attainment

At the 10% level, education of the members of the household was statistically significant if they had a tertiary level education. It was also found that possession of a matric certificate also reduced energy poverty. However, this finding is statistically insignificant. There is a negative relationship between level of education and energy poverty. This is expected, since higher education levels are associated with higher income levels and therefore the energy share in the expenditure budget should be smaller. The odds ratio obtained in the regression output, supports this finding. Furthermore, it shows that an individual's completion of tertiary education reduces energy poverty by 0.034 percent. The findings also indicate that having incomplete schooling increases energy poverty. Even though this finding is not significant, it highlights the importance of a complete education for increased income and acts as a strong determinant of energy poverty.

Based on a study in a rural area in Assam, India, Kanagawa and Nakata (2008) investigated the relationship between energy access and the improving socio-economic conditions affecting rural areas in developing countries. They found education to be the most essential component for poverty reduction. Kanagawa and Nakata (2008) explain that poor households are not able to complete their secondary schooling because financial constraints do not allow them to pay the needed educational expenditures. Education therefore affects energy poverty as low education rates hamper people's household incomes as a result aren't able to afford modern energy services causing energy poverty.

Marital status

On marital status, the relationship was negative suggesting that homes with married couples or committed partners were less likely to be energy poor than those who were not. The reason for this could be that married couples combine their income and share the expenses of the household, including energy expenditure. However, this relationship is not significant.

Household and dwelling size

The higher the number of people residing in the household, the higher the incidence of energy poverty. The odds were that it was more likely for a household with more members to be energy poor than those with less members. This could be because as the number of household members increase, a fixed household budget must be distributed amongst more people – thus, increasing energy poverty. This relationship is statistically significant at the 1% level.

There was a negative relationship between the size of the dwelling unit and energy poverty. This relationship is statistically significant at the 1% level. The negative relationship suggests that individuals dwelling in larger houses were less likely to be energy poor compared to those living in smaller units. One reason to explain this, is that the larger your income, the larger your household, therefore one has more access to more modern energy sources Ismail (2015).

Demographic characteristics

In terms of the demographic characteristics, the Western Cape was dropped in the regression due to collinearity with the other variables in the regression. All provinces exhibited a positive relationship with energy poverty, except for Gauteng and Limpopo. This means that households situated in these provinces are more likely to be energy poor. However, of these four provinces, only the Eastern Cape and the Northern Cape displayed statistical significance at the 1% level. Kohler, Rhodes and Vermaak, (2009) found that the Eastern Cape is one of the provinces with the lowest electrification rates in South Africa. Furthermore, this could also signal structural issues inherent within these provinces with regard to energy access.

Gauteng and Limpopo exhibit a negative relationship with energy poverty. This means that households situated in these provinces are less likely to be energy poor. However, only Gauteng province is statistically significant at the 5% level. Of all the provinces, Gauteng is the most urbanized and this could mean that inhabitants have more access to cleaner and cheaper energy sources.

The results also show that households who are electrified are more likely to be energy poor than households who are not. This is significant at the 5% level. This is an interesting result, as access to electricity does not necessarily mean one will be less energy poor. This reflects the unaffordability of electricity as lower income households cannot necessarily afford electricity provided by the national grid, even though they might have access to it.

Lastly, there is a location dummy, which indicates that households situated in rural areas in South Africa are more likely to be energy poor than houses situated in urban areas. This could mean firstly that, households in urban areas have access to better jobs and therefore higher incomes, such that they can afford energy. Second, rural households are slower in transitioning up the energy ladder and have access to less efficient energy sources that cost more than cleaner energy.

5.1 Evaluation of the energy poverty regression model

Logistic analysis relies on other statistics to analyse the reliability of any model (Gujarati, 2004). The Log-Likelihood Ratio test is distributed as a Chi-Square and is computed to test the overall performance of the model (Gujarati, 2004). The Chi-Square statistic was 2332.84 and it was statistically significant. Thus, the null hypothesis that the overall explanatory power of the model could not be relied upon was rejected. The predictors in the logistic regression were collectively important in explaining the behaviour of energy poverty in South African households.

The Pseudo R-squared was 62 percent implying that the model explained about 62 percent of the deviations in the probability of energy poverty.

A further goodness of fit test that is recommended for logistic regressions in the literature is the Hosmer-Lomeshow (HL) Chi-square statistic (Ping, Lee & Ingersoll, 2002; Gujarati, 2004). The statistic is distributed as a Pearson Chi-square and is evaluated through a log-likelihood estimation calculated from a 2 x g table of observed and expected frequencies, where g is the number of groups formed from expected probabilities of each one of the observations (Gujarati, 2004). This test was conducted based on the results in Table 3 and the null hypothesis that the model was a good fit to explain the deviations in the behaviour of energy poverty is accepted even at the 10 percent level of significance. The value of the HL statistic was 32.1 with the probability to accept the null hypothesis of about 91 percent.

6. Limitations when defining energy poverty

The measure of energy poverty based solely on household expenditures can be problematic because poor households in countries such as South Africa typically rely on cheap but inferior biomass for their energy needs. As a result, estimating energy poverty in the way above can underestimate the extent of energy poverty in households (Kohler, Rhodes and Vermaak, 2009).

Kohler, Rhodes and Vermaak, (2009) put forward the following example: If households X and Y both spend 15% of their income on energy, then the way in which the expenditure approach is defined above will classify both households as being equally poor. However, they explain that if the type of energy used is taken into account: If it was found that X uses paraffin and candles, while Y uses electricity, then Y obtains a better use of quantity which is more useful since electricity is a more efficient energy source. Therefore, X must be classified as poorer than Y, by taking into account the quantity of energy used by the household, rather than just its cost. Furthermore, if household X now gains access to free basic electricity (FBE), it should be classified as less poor than it was before but its poverty status would not change if energy poverty is defined according to the expenditure approach.

The reader should note that even though this study is consistent with the DoE's interpretation of energy poverty, more efficient results can be achieved if quantity of electricity is taken into account in household expenditure/income data as well as information on FBE at the household level. Neither the General Household Survey (GHS) nor the NIDS data as used in this study allow for this information to be incorporated. This then leads to recommendations in the following section.

7. Recommendations

The policy recommendations are based on the results found in section 5. Households can be made less poor by simply making all energy cheaper if one solely looks at the expenditure approach. However, more rigorous analysis must be done by dissecting energy sources that South Africans rely on. With regard to the analysis done in this paper, this could not be done across each of the waves in the NIDS dataset as households do not have unique identification numbers across the three waves. Therefore, the expenditure approach becomes more attractive as it allows measurability of energy poverty.

With regards to electrified households, the National Energy Regulator of South Africa (NERSA) and the DoE can play an important role in the determination of prices that individuals face, for the following reason:

As highlighted by Ismail, Mabuza, Xolo and Pillay (2014): Allowable Revenue (AR) of a state owned enterprise such as such as Eskom hugely influences the amount of revenue the entity is entitled to receive as determined by the regulator (NERSA). The tariff decision of NERSA is normally based on the amount of revenue that would reasonably be required to recover a set of costs included in the regulated asset base (RAB) amongst others (AER, 2011).

$$\text{Allowable revenue (AR)} = (\text{RAB} \times \text{WACC}) + D + E + +C + F \quad (6)$$

$$\text{Tariff} = \text{Allowable revenue/ Quantity of output sold by the regulated entity} \quad (7)$$

Where: The RAB is the cumulative historical investment made by the utility. The weighted average cost of capital (WACC) reflects the opportunity cost of the investments made by the investor. D = depreciation of the RAB over time. E = operational expenses incurred by companies. C = claw back and F= F-Factor, which is additional revenue to meet debt obligations that may be granted by a Regulator. If the allowable revenue excluding the F-factor does not enable the applicant's regulated activity to operate with a debt service cover ratio acceptable to its financiers, then additional revenue may be allowed (Ismail *et al*., 2014).

The RAB is typically the largest component of AR and it grows by the amount of the net capital expenditure outlays made by Eskom (Meaney and Hope, 2012). One reason why companies increase capital outlays is to expand infrastructure capacity as the demand for services increase (AER, 2011). Therefore if capital expenditure increases, RAB increases; so does the AR and subsequently the tariff. Regulators must ensure that capital outlays allowed into the RAB must be prudently acquired. If they are not acquired prudently, it will unnecessarily inflate the RAB. Ismail *et al*., (2014) highlight that if there are any imprudent costs in the RAB, this will be passed through to consumers. Therefore, NERSA plays a crucial role in evaluating prudent pricing of Eskom and therefore, the protection of consumers. As such, any increase in tariff increase applications by Eskom must be scrutinised so that consumers face the most efficient prices.

Also related to pricing is a study done by Thopil and Pouris (2013) showed 'actual sales and revenue' figures of Eskom over the 2012/13 period. The study indicated that two sectors - industrial and mining (the largest two sectors in South Africa) - contributed 77% of the sales but generate only 67% of the revenue, with the industrial sector showing the largest disparity. This trend can be better observed in the revenue to sales ratio of the percentage contribution, shown in Table 4.

Table 4: Revenue-to-sales ratio of electricity in South Africa, per sector
Source: Thopil and Pouris (2013)

Sector	*Revenue: Sales ratio*
Residential	1.56
Commercial	1.13
Industrial	0.82
Mining	0.96
Agriculture	1.75
Traction	1.5

The largest reverse parity (where revenue is greater than sales) occurs in the agricultural sector, which is a vital sector of the South African social make-up. More importantly for this study, is that the residential sector also shows a degree of reverse parity. This finding suggests that the industrial sector, in spite of being the largest sector in terms of sales, is under-priced[1] (Thopil and Pouris, 2013).

This leads to the question, why does Eskom increase prices equally in the residential and industrial sectors, when the benefits that these sectors receive are not proportional? Is it the best approach to equally increase the prices among all sectors or is a discriminatory pricing approach across sectors more beneficial for both the economy and Eskom (Thopil and Pouris, 2013)? Therefore, a primary recommendation is for the DoE in collaboration with NERSA, to look into differential pricing across sectors. This might alleviate energy poverty amongst households (Ismail, 2015).

Given many of the poorest households are located in remote rural areas, expansion of the electricity grid may be prohibitively expensive. As shown in Table 3, accessibility to the grid will not solve energy poverty. The FBE policy must be relooked at, as Feriel (2010) showed that the policy only marginally improves the lives of the poor, given that the 50kWh amount still requires many households to use other energy sources and it cannot improve people's lives.

Kohler, Rhodes and Vermaak (2009) also suggest that further research should be done into the cost-effectiveness of small-scale renewable energy projects and that any type of renewable energy expansion be accompanied by an education programme, so that households do not view alternative energy sources as being inferior to electricity (Ismail, 2015).

The final recommendation regards the problems associated with estimating energy poverty using the expenditures approach. The DoE should use a more efficient approach in defining energy poverty, as there are many limitations defining energy poverty in this way. It is recommended that future rounds of the household expenditure surveys such as the GHS and NIDS data sets should collect information on the prices per kWh that households pay for their individual energy sources, in addition to the total cost (Ismail, 2015). This will enable researchers to calculate more accurately the quantity of energy used, and thus to identify more precisely the degree of energy poverty experienced by households (Ismail, 2015).

8. Conclusion

This paper used the NIDS wave 3 (2012) dataset to achieve two main objectives. First, it estimated the energy poverty line using the expenditure approach for South African Households. Second, it estimated the determinants of energy poverty of these households by means of a logistic regression model. It was found that when these households increase their expenditure on transport and schooling, it significantly increases energy poverty since more of a household's budget is allocated away from energy spending. Food expenditure has the opposite effect. If individuals within the household possessed education at the tertiary level, it significantly decreases energy poverty since education increases income. African people are more likely to be energy poor than White and Asian/ Indian people, but not significantly more than Coloured people. This highlights stark inequality between the different races. This paper also finds that larger households were significantly less likely to be energy poor but households with more inhabitants within it are more likely to be energy poor.

Households who were connected to the national electrical grid were found to be more energy poor. This is an interesting finding as it highlights the fact that connectivity is only one part of the problem. Affordability of basic services is an issue that needs to be addressed. Households situated in rural areas were found to be more energy poor than households in urban areas. Lastly, it seems that the provinces with the highest significant energy poverty rates are the Northern Cape and the Eastern Cape.

This paper acknowledges the limitations of estimating energy poverty using the expenditure approach as it does not incorporate energy efficiency or FBE. This paper was unable to incorporate these elements because of unavailability of data at the household level within the NIDS (2012) data set. Therefore, this paper ends with recommendations to government as well as regulators. Regulators and government agencies should ensure electricity is efficiently priced and also look into differential pricing across sectors. Current policies such as the FBE policy must be revised, such that it contributes towards more intensive energy poverty eradication. Furthermore, accessibility and affordability of efficient energy sources such as electricity should be made available to all South Africans. This is an expensive notion – therefore, this paper suggests that education campaigns around renewable energy options must be made available to poorer households. Further, the DoE should use a more efficient approach in defining energy poverty. Lastly, in order for a more accurate estimation of energy poverty using household data sets should incorporate data on pricing and quantity of different energy sources and information on free basic electricity, so that more accurate results can be obtained in the future.

Notes

1. This paper builds and extends on the work done by Ismail, Z. (2015). An Empirical Estimation of Energy Poverty in Poor South African Households. *Journal of Economics and Sustainable Development,* Vol. 6 No. 13, 2015.
2. One of the primary reasons for standing contractual agreements between Eskom and large industrial users such as mines. These contracts are equally beneficial for both entities: large industrial users contribute to the largest section of revenue for the utility while being able to keep their utility costs low

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An overview of refrigeration and its impact on the development in the Democratic Republic of Congo

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Abstract
The development of refrigeration is a priority in all countries, given the multidimensional roles that it plays in the sustainable development of society. In developing countries, efforts are being made to catch up with the delayed experienced in the use of refrigeration. To achieve this goal, several countries are allowed to trace the history of refrigeration in their countries in order to understand the main causes of non-expansion, and then set up a new strategy of sustainable development for this technology. The Democratic Republic of Congo (DRC) is a developing country that has experienced a very interesting history of refrigeration, but is still less known by the Congolese themselves as well as by scientists. This paper has traced out the outline in the history of refrigeration in the DRC. Surveys were conducted in the industrial, health, residential, commercial, and tourism sectors during the colonial and post-colonial period. Results showed that the use of refrigeration in the DRC has been remarkably observed in the industrial sector, especially in breweries, with a cooling capacity ranging from 50.1 thousand to 2.88 million kWh, about 5 659 % between 1929 and 1957; from 3 million to 26.5 million kWh, about 783.3 % between 1958 and 1980, and then dropped to 6.5 million kWh in 2004 before resuming its growth up to 11 million kWh in 2009. The variations in the use of refrigeration during the above periods significantly influenced the economy, in the sense that the economic and social indicators of the country grew from 0.415 to 0.430 between 1975 and 1985, and then declined to 0.375 in 2000, due to political instability, before rising up to 0.410 in 2005.

Keywords: sustainable development, refrigeration, cooling capacity, energy, food industry

1. Introduction

In prehistoric times, man found that the game killed in the hunt would last longer if it was stored in the coolness of a cave or packed in snow. Later, ice was harvested from lakes and rivers and stored to be used in summer. As man became more industrialized and mechanized, cooling requirements in industrial processes and other sectors became more and more important. This led to a technological revolution in refrigeration. However, the evolution of refrigeration technology was slow and difficult until the invention and development of electricity in the 19th century, which boosted the development of technology based on vapour compression (Arora, 2000) that subsequently became more competitive worldwide. The growth of refrigeration technology and its applications has enabled many countries around the world to achieve sustainable development. Its impact may be appreciated through social, economic and environmental dimensions.

In society, the refrigeration sector generates jobs. According to the International Institute of Refrigeration report (IIR, 2002), the refrigeration sector employs more than 2 million people worldwide, particularly in industrial and commercial areas. Refrigeration is essential to human life. In the food sector, refrigeration contributes to reducing post-harvest losses by allowing perishable foods to be preserved at all stages from production to consumption (Laguerre et al., 2013; Tassou et al., 2010; Wang and Wang, 2005). In the health sector, refrigeration is used for vaccine storage (McCarney et al., 2013), and new medical equipment and tools (Langenhuijsen et al., 2009; Polascik et al., 2007). Apart from its primary function of producing cold, refrigeration is used for air conditioning by creating comfortable living and working environments (Fanger, 2001; Ji et al., 2003).

In the economy, refrigeration plays an important role in national and international businesses. It enables the storage of perishable commercial products and facilitates their sale to distant markets (Tassou et al., 2010; Wu et al., 2013). Refrigeration is necessary to the development of energy sources (Trivedi et al., 2013; Yang et al., 2013). Many industries (chemical, pharmaceutical, agri-food, manufacturing, etc.) require refrigeration for their operation (Sanzida and Nagy, 2013; Sun and Zheng, 2006).

Refrigeration has some environmental benefits worth mentioning. It helps to maintain biodiversity by allowing the cryopreservation of genetic resources: cells, tissues, organs of plants, animals, micro-organisms (Benelli et al., 2013; Wang et al., 2012).

The impact of refrigeration throughout the world is more meaningful than is generally believed. There are about 1 300 million household refrigerators (more than 80 million are produced annually), 340 million air-conditioning units, and 350 million m3 of cold-storage facilities operating worldwide. The investment gap in this technology between developed and developing countries remains wide, for example, in the total annual production of household refrigerators, only about a third is traded in developing country markets (IIR, 2002). The fundamental reason for this imbalance is the underdevelopment of electricity (Meincken, 2012; Udochukwu and Ogbonnaya, 2014; Lloyd, 2014), which is the main energy source for the majority of refrigeration technology.

According to the World Energy Outlook (IEA, 2014), 1.3 million people continue to live without access to electricity. This is equivalent to 18% of the global population and 22% of those living in developing countries. Nearly 97% of those without access to electricity live in sub-Saharan Africa and developing Asian countries. In sub-Saharan Africa, the most affected countries are: South Sudan (99%), Liberia (98%), Central African Republic (97%), Chad (96 %), Sierra Leone (95%), Malawi (91%), and the Democratic Republic of Congo (91%).

Apart from the lack of electricity, poverty caused by economic and political instability must also be added to the problem since it does not allow the population living in electrified cities to acquire household refrigerators. According to the Millennium Development Goals Report (2013), 1.2 billion people in the world still live in extreme poverty. In the Sub-Saharan region, 48.4% of people live on less than 1.25 USD a day, in comparison with Latin America where only 4.5% of the population lives with less than 1.25 USD daily.

The underdevelopment of refrigeration technology in developing countries has resulted in an increase of the mortality rate, due to the lack of vaccine storage (McCarney et al., 2013), diseases caused by the consumption of spoiled food (Yu and Nagurney, 2013), the difficulty of cryotherapy (Mohammed et al., 2014), etc. According to the Millennium Development Goals Report (2013), in Sub-Saharan Africa, one in nine children die under the age of five, more than 16 times the average for developed countries. In addition, in 2011, an estimated 6.9 million children, 19 thousand a day died from mostly preventable diseases.

From the nutritional point of view, perishable foodstuffs represent 31% of the total volume of foods consumed in developing countries. But, only 1/5th of perishable foodstuffs is refrigerated (IIR, 2002). This means that high losses are incurred following harvest, slaughter, fishing, milking, then during transportation and finally during sale.

The details provided above sufficiently demonstrate the role that refrigeration has to play in the sustainable development of developing countries. Today, several developing countries are mobilized to find lasting solutions to the problem of electricity and refrigeration. In sub-Saharan Africa, considerable efforts are noticed in some countries such as South Africa, Ghana, Capo Verde, Botswana, etc. (IEA, 2014). In the DRC, despite the precarious situation of electrification in rural and urban areas, which today hampers the development of refrigeration, it should be noted that this past was dominated by a growth in refrigeration in some sectors, but history is not so much known to the public. This paper presents an overview on the use of refrigeration in the DRC from colonial times to the current period by demonstrating the role it has played in the socio-economic development of the Congolese people.

2. Presentation of the DRC

The DRC, a former Belgian colony, is the second largest country in Africa after Algeria and the largest one in the Sub-Saharan region with 2 345 000 square kilometres. It is bordered by the Central African Republic and South Sudan to the north; to the east by Uganda, Rwanda, Burundi, and Tanzania; to the southeast by Zambia; and to the southwest by Angola. To the west are the country's short Atlantic coastline, the Angolan exclave of Cabinda, and the Republic of Congo (see Figure 1a). Its population is about 70 million (Census Bureau-US, 2013). The country is divided into ten provinces and one city-province (see Figure 1b). The provinces are subdivided into districts, which are divided into territories.

3. Overview on the refrigeration use and its impact

This section traces the history of refrigeration applications in the DRC by demonstrating the role it has played in the country's economic recovery. The

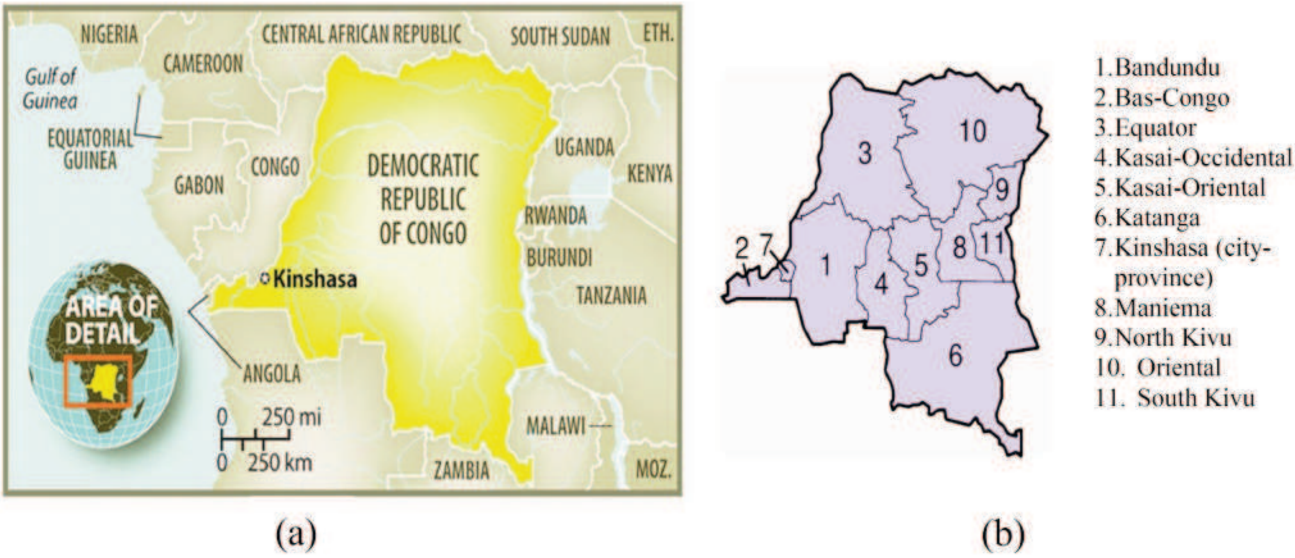

Figure 1: Political maps of the DRC: (a) Neighbouring countries; (b) Administrative divisions

facts are divided into two stages, namely: the colonial and post-colonial period.

3.1 The colonial period (1908-1960)

The use of refrigeration technology in the Democratic Republic of Congo dates back to the late 1920s, particularly in the health and food industry sectors. The refrigerants belonging to the family of chlorofluorocarbons (CFCs) and specially CFC-12 were the first to be used during this period (ODM, 2013).

In the health sector, refrigeration was used for preserving vaccines against smallpox (Schneider, 2009). Figure 2a shows the evolution of smallpox immunization in the DRC during the colonial era. As can be seen, the vaccination program against smallpox began in the DRC in 1925. During this campaign, 400 000 infected people were vaccinated, which represents a total of about 40 litters of vaccines (0.1 ml of vaccine per person). However, considering the storage temperature of vaccines against smallpox, which ranges between 2 °C and 8 °C (Lee, 2006), the estimated cooling capacity of the vaccine storage equipment is evaluated through a thermodynamic analysis of a compression refrigeration cycle working with CFC-12.

The results are presented in Figure 2b. The tendency of the curve leads us to believe that the use of refrigeration in the vaccination program has enabled a significant reduction in infection rates of smallpox in the 1950s.

Apart from the application in the immunization program, refrigeration has played an important role in the brewing industry during the colonial era. Refrigeration is the main process in the fermentation, maturation and packaging of beer (Sturm et al., 2013; Muster-Slawitsch et al., 2011; Braeken et al., 2004). In the DRC, breweries were among the first industries established by the colonial power. The first two Congolese brewing companies of Leopoldville (now Bralima) and Brasimba (Brasseries Simba) were created 15 years after the country was occupied by Belgian colonists. The brewery of Leopoldville was founded on October 23, 1923 by a Belgian industrial group under Brussels Bank financing (Luboya-Kasongo, 2007). While for Brasimba, its creation took place on December 08, 1923 in Elisabethville (currently Lubumbashi), on request of the Belgian workers at the Upper Katanga Mining Union (Union Minière du Haut-Katanga), addressed to a Belgian industrial group (Mukenga, 2010). After the growing consumer demand patterns of these two breweries, they quickly extended their actions creating several other plants in the provinces.

During the 1950s, other independent breweries (Kisangani, Kasaï, Bas-Congo and Isiro) were established. The increase in the number of brewery companies led to a significant growth rate of beer production, and consequently an increase in the capacity of refrigeration in brewing processes. As it can be seen in Figure 3, beer production, cooling capacity and energy consumption experienced a high increase in 1957, about a 5 659% growth rate, in comparison with production in 1929. The decline registered in 1934 was due to the difficulty experienced in the management of the brewery of Leopoldville (Lutete, 2005).

In the previous figure, the cooling capacity was evaluated considering the thermodynamic conditions recommended for fermentation, maturation and packaging of beer (Sturm, 2013), and the refrigerant taken into account is the CFC-12; while for the consumption of energy, Felgentraeger and Ricketts (2003) correlation is used as described in Equation (1).

$$E_{beer} = 118.4 * V_b^{0.910} \quad (1)$$

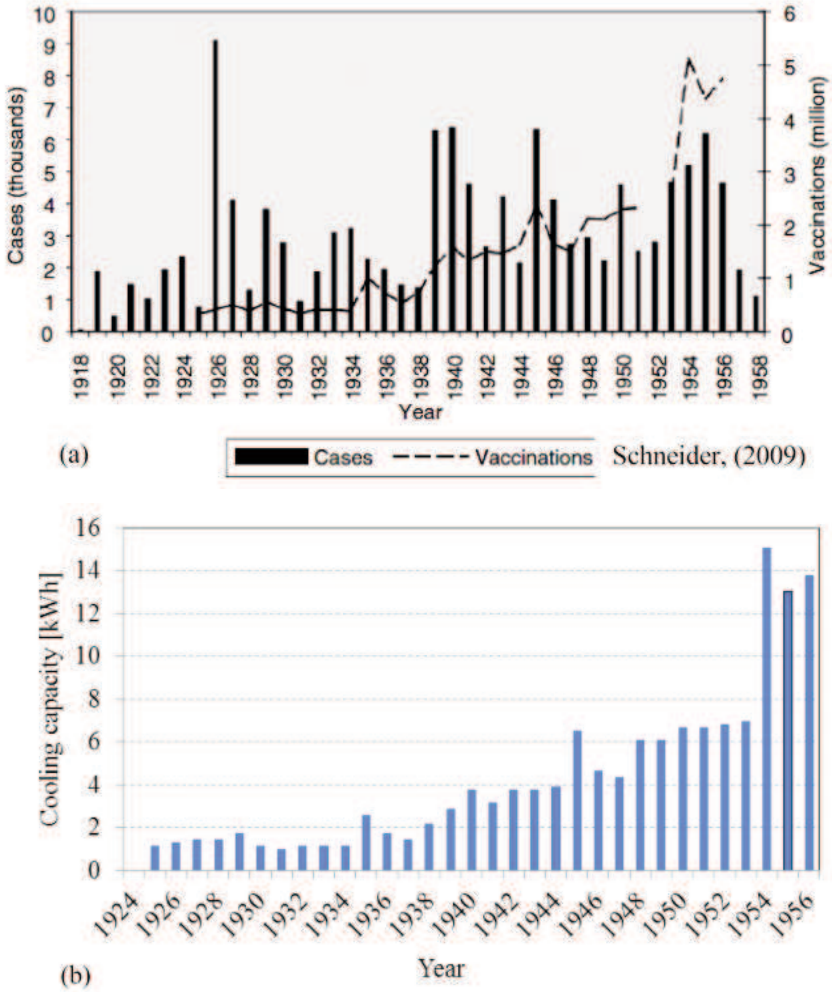

Figure 2: Application of refrigeration in the immunization program between 1924 and 1956 in the DRC: (a) Smallpox cases and vaccinations; (b) Cooling capacity of the vaccine storage equipment

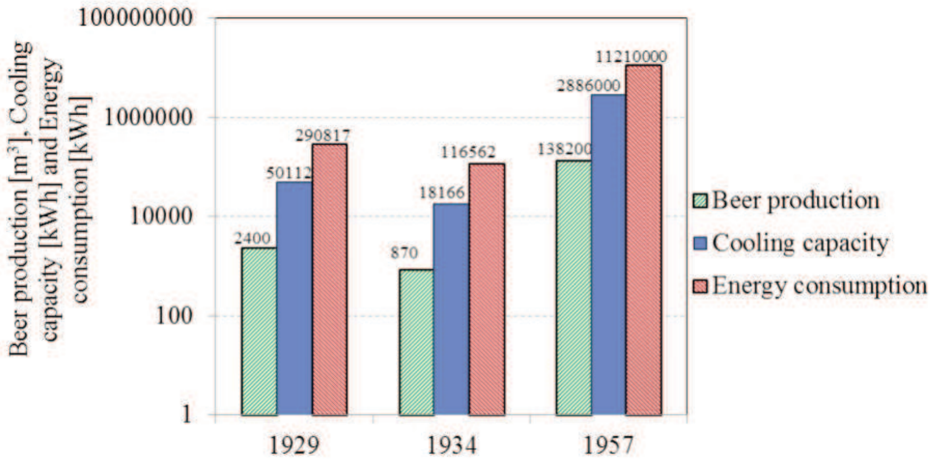

Figure 3: Beer production, cooling capacity and energy consumption in the DRC brewery process between 1929 and 1957

where Ebeer is the energy consumption in the brewery industry (in MJ) and Vb is the beer volume (in hl).

Besides the brewing industries, refrigeration is also used in beverage factories. The results of the study conducted by Buelens and Cassimon (2013) show that in 1957, the industrial production of lemonade and water in the Belgian Congo was about 32 000 m^3. This represents approximately 668 161 kWh of cooling capacity and 3 million kWh of energy consumption. However, the total cooling capacity of refrigeration equipment in the food industry can be estimated at 3 558 161 kWh in 1957 and the corresponding energy consumption approximately 14.2 million kWh. Achievements made in the food sector were not sufficient since refrigeration was not developed in other food areas such as the greengrocer, fishery and meat industries. This was due to the agro-industrial policy applied by settlers which was focused on the production of cash crops for export instead of food production (Jensen, 2012).

Apart from the food and health sectors that experienced refrigeration shortly after the takeover of the Congo by the colonial power, other sectors such as residential and commercial did not experience the same situation. The use of refrigeration in the residential sector began in the DRC in the 1950s. The use of this equipment was essentially reserved for settlers and expatriate officials. This restriction was an obstacle to the development of refrigeration during the colonial period. Similarly, the Congolese commercial sector had not experienced significant development in refrigeration during the colonial period, due to the type of trade applied by settlers, which was centred on the export of mineral resources and cash crops (Buelens and Cassimon, 2013).

The development of refrigeration was intimately linked to electricity. Provinces that have experienced the development of refrigeration (especially in the brewing industry) were those in which electricity has been developed. Table 1 shows the different hydropower plants built during the colonial era and some plants whose construction was started before independence. The total installed capacity of these hydropower plants is about 630 160 kW.

Despite this important access to electricity, Congolese rural areas had remained without electricity during the entire period of colonization. Some Congolese living in slums did not have access to electricity (Kaplan, 2007; SNEL, 2013). This situation was a major constraint to the development of refrigeration.

3.2 The post-colonial period (1960 -)

The inventory of refrigeration in the post-colonial period is characterized by a widening of its scope in almost all sectors of activity, despite the slow start-up that the country had experienced shortly after independence due to the unpreparedness of Congolese administrators during the colonial time to ensure the continuity of public affairs (Kaplan, 2007). The technology of refrigeration used in the early post-colonial years was dominated by mechanical compression machines working with refrigerants belonging to both hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (ODM, 2013; WMO, 2011).

The development of refrigeration during the post-colonial period was far more influenced by the country's political stability. Several socio-political events (war, political crisis, looting, etc.) occurred throughout the post-colonial period were the basis of instability in the refrigeration use. Indeed, after the political instability experienced by the country in the first five years of independence (1960-1965), the political recovery realized by President Mobutu Sese Seko (from 1965 to 1980) has led to socio-economic development of the country (FMI, 2010).

In the industrial sector, food industries experienced significant growth in production compared to the colonial period. In brewery industries (see Figure 4a), the growth rate of beer production between 1964 and 1980 was about 63.80%. While in beverage, despite the decrease of production in 1967, the growth rate between 1964 and 1980 still remains important (about 80%) (Mukenga, 2010). Increasing beer and beverage production involves a growth in the cooling capacity of refrigeration equipment used in fermentation, maturation and packaging processes. Figure 4b shows the cooling capacity of refrigeration equipment used in the brewing and beverage process between 1958 and 1980 and the corresponding energy consumption.

Table 1: Hydropower plants built during the colonial era in the RDC
(SNEL, 2013; Buelens and Cassimon, 2013)

Location	*Plant*	*Building date*	*Capacity [kW]*
Bas-Congo	Mpozo	1934	2 200
	Sanga	1932-1949	11 500
	Zongo	1956-1965	75 000
Kasai-Occidental	Lungudi	1949	1 560
Katanga	Mwadingusha	1929	68 000
	Koni	1950	42 000
	Nzilo	1953-1954	108 000
	Kilubi	1954	9900
	Kyimbi	1959	17000
	Nseke	1956-1957	248 000
Oriental	Thsopo	1959-1974	18 000
South Kivu	Ruzizi I	1958-1972	29 000

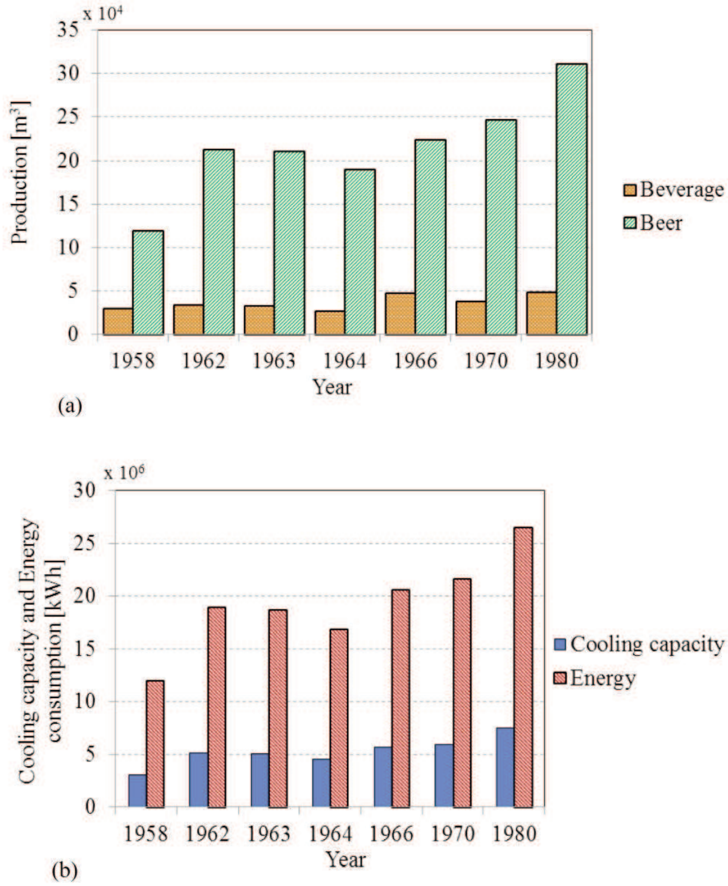

Figure 4: Application of refrigeration in the brewery and beverage industries between 1958 and 1980 in the DRC: (a) Beer and beverage production; (b) Cooling capacity and energy consumption

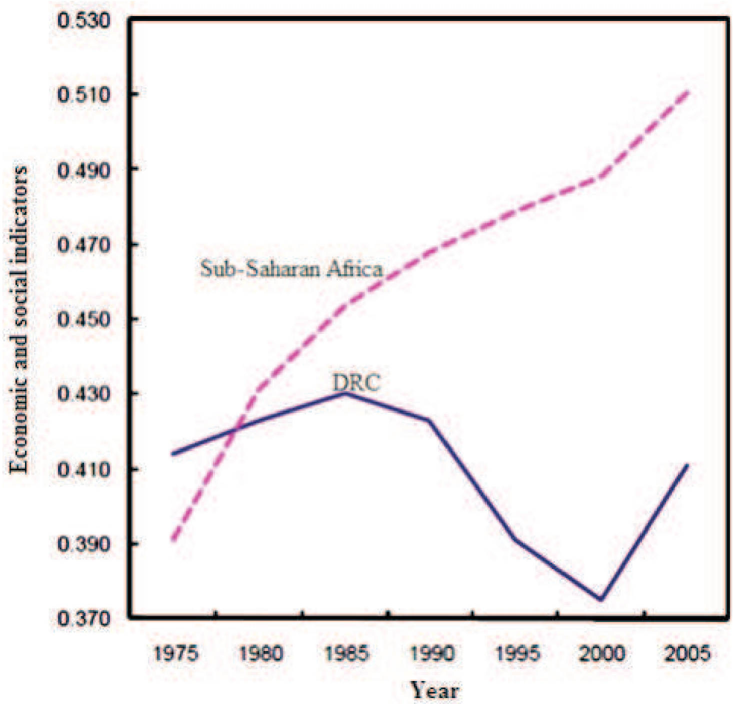

Figure 5: Economic and social indicators in the DRC and Sub-Saharan region from1975 to 2005
Source: FMI, (2010)

It can be seen in this figure that cooling capacity and energy consumption in the brewery and beverage industries experienced an important growth between 1958 and 1980, despite the decline recorded in 1964 (CES, 1969).

Refrigeration took active part in the consolidation of purchasing power of the population in the DRC after independence. This is evidenced by its significant applications in the manufacturing processes of beverages and beers. The contribution of brewery and beverage industries in the economy of the DRC was considerable in the early years of independence. In 1964 added value of breweries was up for 8 million USD, which represented 39% of the total value added by industries supplying the Congolese interior market (CES, 1969). The achievement realized in breweries as well as in mining and other sectors has allowed the government of President Mobutu to increase the country's economy. But, this growth was not sustainable; in the 1980s the country fell back in the economic crisis. The main cause of this collapse was the 'zaïrianisation' decision taken in November 1973 to redistribute economic assets (businesses, plantations, etc.) held by expatriate to the politico-commercial elite close to the regime (PNUD, 2004). The poor management of companies attributed to Congolese business men and the decline of public investment led to the fall of the purchasing power of the population. In 1990, economic and social indicators fell to 0.40, and continued to decline until the early 2000s (see Figure 5).

The decline in the purchasing power of the Congolese population has had an impact on the development of refrigeration in a number of sectors. Cooling capacity had significantly been reduced in the 2000s. In 2004 (see Figure 6), beer and beverage production experienced a fall of around 20% compared to 1980 (see Figure 4). In addition, the growth rate is low, with only 70% between 2004 and 2009.

The decline in the purchasing power of the Congolese has had an impact on the development of refrigeration in a number of sectors. Cooling capacity has significantly reduced in the 2000s. In 2004 (Figure 6), beer and beverage production experienced a fall of around 20% compared to 1980 (Figure 4). In addition, the growth rate is low with only 70% between 2004 and 2009.

Apart from the brewery and beverage industries after the crisis period, the Congolese food industry was also expanded into fishery and food processing thanks to the development of refrigeration as it can be observed in Figure 7a. Between 2006 and 2009, the cooling capacity in fishery and food processing experienced an increase of about 221.3% and 133.3%, respectively (WMO, 2011).

The economic reorganization performed after the crisis has also enabled the development of refrigeration in the residential and commercial sectors. Figure 8a shows the estimated cooling capacity in the residential and commercial sectors between 2006 and 2013. The data used in this analysis comes from an inventory realized by the Congolese government on the use of refrigerants belonging to the family of HCFCs in the residential and commercial sectors between 2006 and 2008, with a projection from 2009 to 2013 (WMO, 2011). This inventory was part of the proposal of HCFC phase-out in the DRC as recommended by the Montreal Protocol. According to this report, the residential sector in the DRC holds 35% of the refrigeration technology working with the HCFC-22.

Besides the residential and commercial sectors, tourism in the DRC is an area in which refrigeration plays an important role (MECNT, 2012). The inventory realized in this sector between 2006 and 2013 (see Figure 8b) reported a growth rate in the use of refrigeration of about 436 % (WMO, 2011).

The period from 2006 to 2013 was marked by a special event in the field of refrigeration in the DRC. In 2010, refrigerants belonging to the family of CFCs were completely eliminated in Congolese sectors. However, hydrochlorofluorocarbons have remained the main refrigerants in the DRC (WMO, 2011). In residential and commercial sectors, HCFC -22 is the most widely used refrigerant (about 93%). It is used in several types of refrigeration technology as can be seen in Figure 9, which presents the results of an inventory realized in 2006, 2007 and 2008. It follows from this inventory that more than 2 million units operate with HCFC-22. A total of 1 893 849 units were identified in 2006, 2 104 277 in 2007 and 2 630 346 in 2008 representing a growth of about 25%. As result of the inventory, air conditioning and commercial refrigeration are the most used in the DRC.

Another sector that requires particular attention is health care. It is well known that refrigeration plays an important role in the health field. Unfortunately, in the DRC refrigeration is not at all developed in the health sector. Its applications are limited in hospitals and health centres located in urban areas, and in the Enlarged Program of Immunization (Programme Elargi de Vaccination: PEV). The PEV remains the only area of health care where refrigeration is developing (PEV, 2012). This is due to the requirement of the World Health Organization (WHO), which demands the government of each country to be equipped with a program to fight against preventable diseases (WHO, 2012).

The refrigeration technology applied in the immunization program in the DRC is vapour compression. Three different energy sources are used to power these machines: electrical energy from network, solar energy and Kerosene. Figure 10a shows the distribution of refrigerators by energy source in each province. It becomes clear that Kinshasa is the only province where electrical energy from the network is more used for vaccine storage, because of its political position as the DRC capital. In all the other provinces, more than 50% of cold chains are powered by Kerosene, which poses problems for its

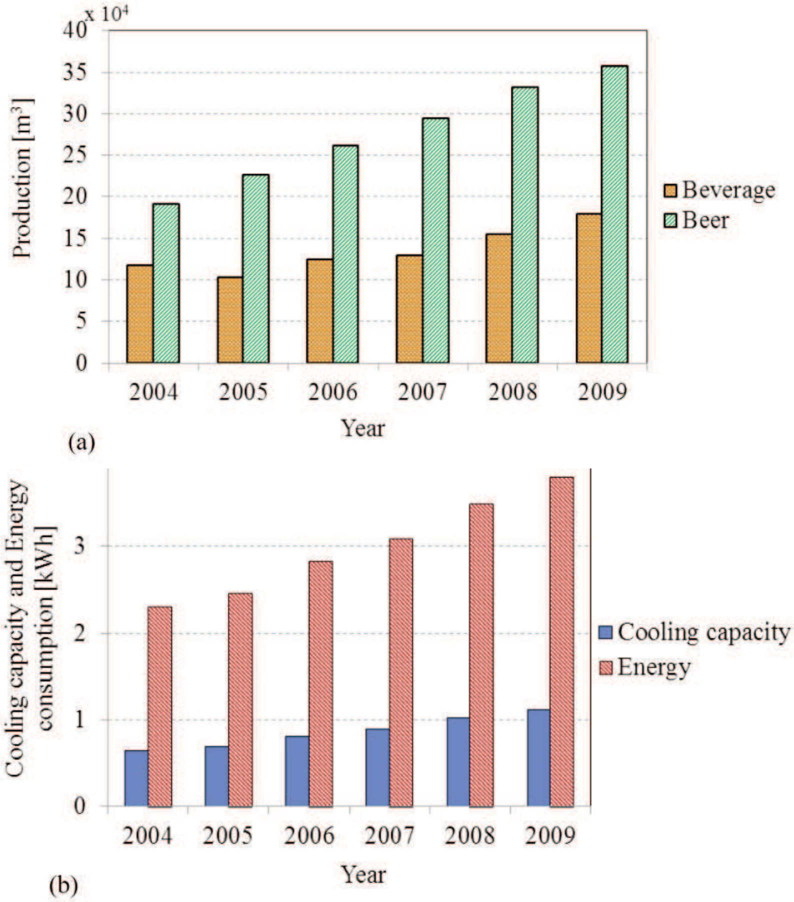

Figure 6: Application of refrigeration in the brewery and beverage industries between 2004 and 2009 in the DRC: (a) Beer and beverage production; (b) Cooling capacity and energy consumption

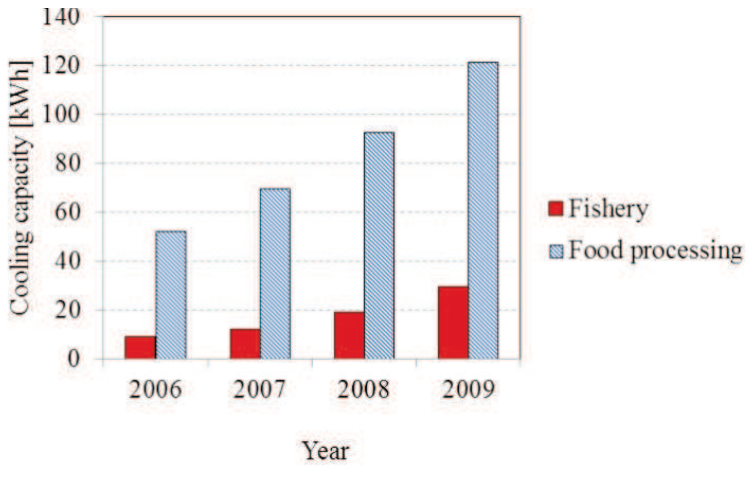

Figure 7: Application of refrigeration in fishery and food processing between 2004 and 2009 in the DRC

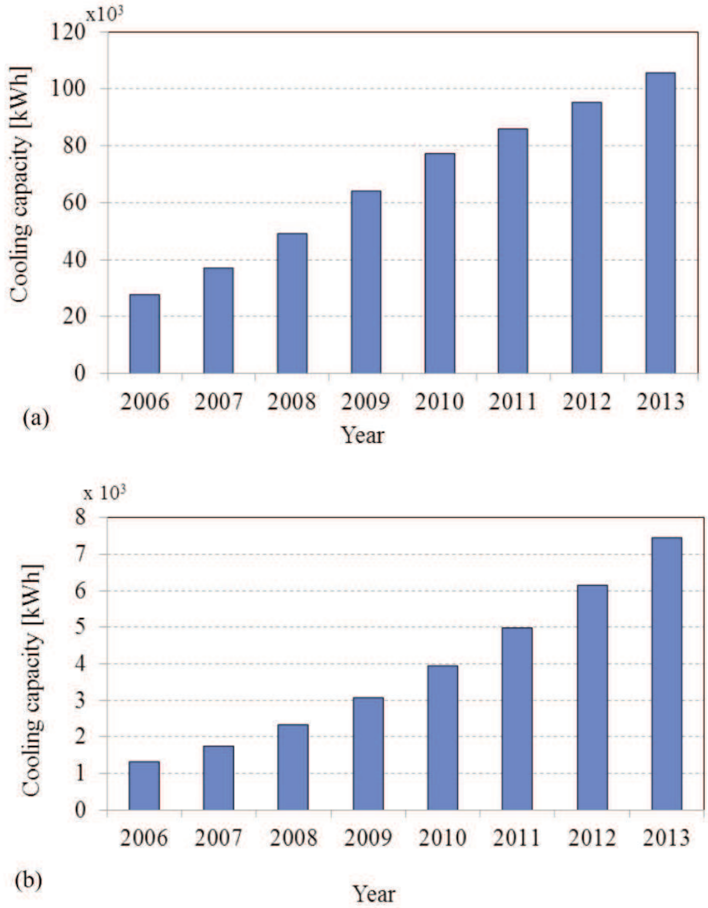

Figure 8: Application of refrigeration in the residential, commercial and tourism sectors between 2006 and 2013 in the DRC: (a) Residential and commercial sector; (b) Tourism sector

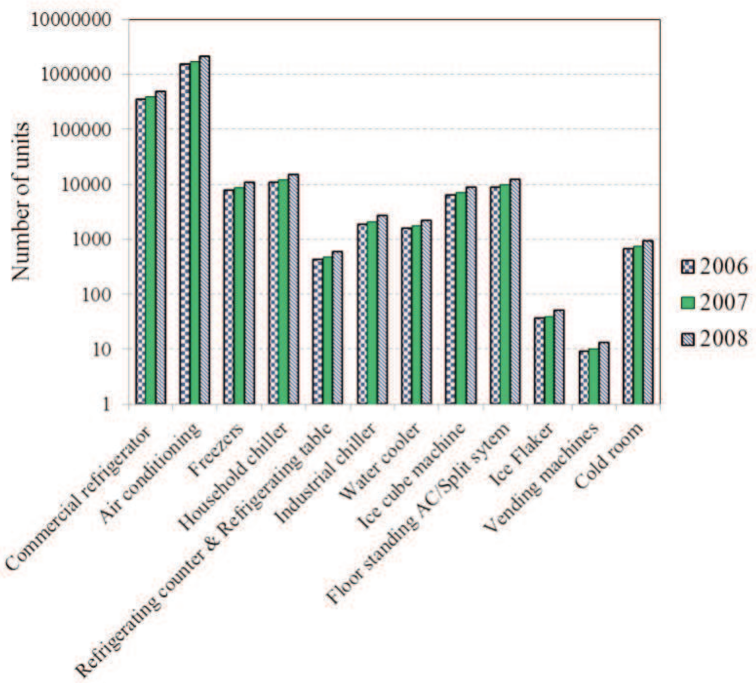

Figure 9: Refrigeration systems operating with HCFC-22 in the DRC between 2006 and 2008

supply in rural centres. Solar energy is only about 10% of feed rate, despite the high availability of solar radiation that the country abounds. Moreover, the cooling capacity of cold chains installed in each centre throughout the country is shown in Figure 10b. The results are presented according to the subdivision of PEV activities (namely in Kinshasa, provinces, PEV antennas and Central Offices of the Health Zone and health centers (BCZS)) and depending on the application. The data used in this analysis comes from an inventory realized in 2011 by PEV (PEV, 2012). The overall cooling capacity of vaccine cold chain equipment in 2011 is approximately 274 337 kWh.

4. Conclusions

The outline in the history of refrigeration and its impact on the sustainable development in the DRC was set out in this paper. Surveys were conducted in two periods in the colonial and post-colonial period. The results sufficiently demonstrated that refrigeration had played an important role in the socio-economic development of the Congolese people before the period of crisis.

In the colonial era, refrigeration had played an important role in the brewing industry and the health sector. The growth rate of the cooling capacity in the beer production process has positively affected the socio-economic level of the population by increasing their purchasing power. In the health sector, the use of cold chain in the smallpox immunization program has led to saving human lives. But, its impact was not significant in the residential and commercial sectors due to the political and agricultural systems imposed by the settlers.

In the post-colonial period, refrigeration took an active role in rebuilding the Congolese state. Its impact was highly significant on the purchasing power of the population before the period of crisis. The increase in the refrigeration capacity in the brewery, fishery, tourism, food processing, residences, and health care industries, are examples which demonstrate how refrigeration has contributed to the sustainable development of the DRC after independence.

Today, after heavy destruction of the economy due to looting and different wars that the country experienced in the early 2000s, a significant reduction in refrigeration applications is recorded in all sectors. In the health sector, children are dying due to the lack of vaccines since there is no equipment to keep vaccines cold in rural areas. These few examples show that efforts should be made in the DRC in the field of refrigeration to save human lives.

To solve this problem, the government of the DRC must establish in a short term a sustainable development program of refrigeration in all sectors. This program must be accompanied by a develop-

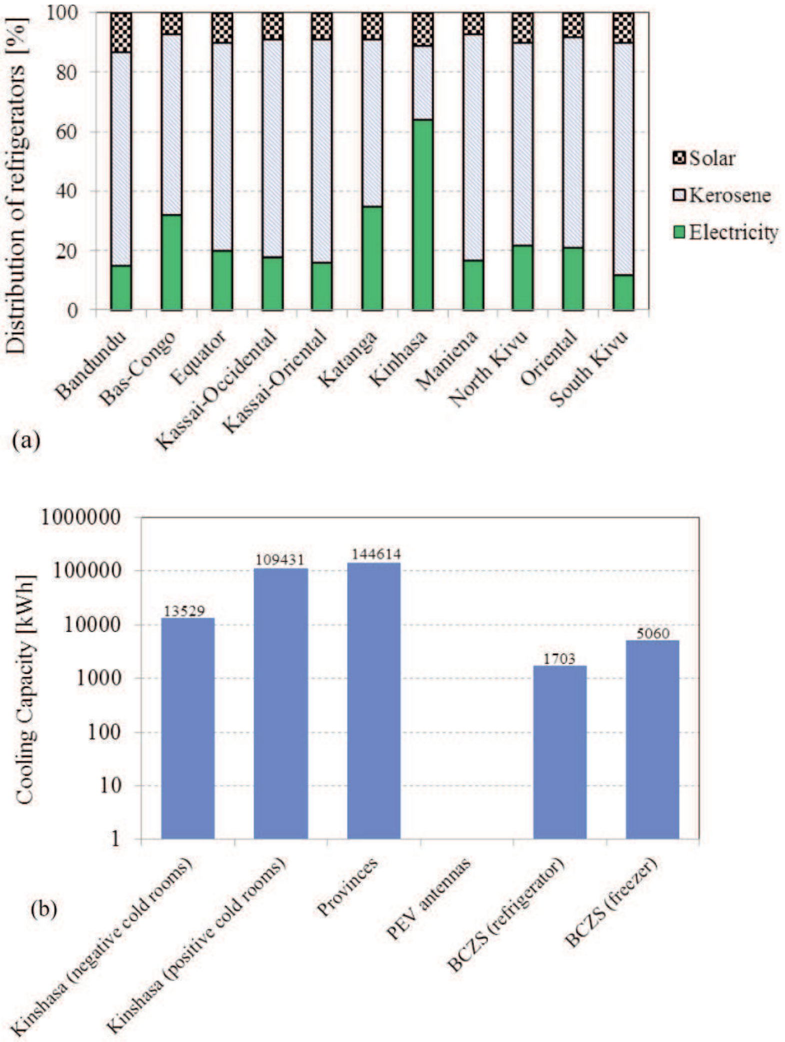

Figure 10: Current status of the refrigeration equipment in the immunization program in the DRC: (a) Distribution of refrigerators by energy source; (b) Vaccine cold chain equipment
Source: PEV, (2012)

ment plan for renewable energy such as solar energy in rural areas. Health centres should be re-equipped with refrigerators powered by solar photovoltaic panels for vaccine storage. On the other hand, the private sector must also contribute to the development of the refrigeration by building cold rooms in urban and rural areas to promote food preservation.

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Comparative bioelectricity generation from waste citrus fruit using a galvanic cell, fuel cell and microbial fuel cell

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Abstract

This article demonstrates the new approaches for the generation of bioelectricity from waste citrus fruit using direct a galvanic cell (DGC), an indirect galvanic cell (IDGC), a conventional fuel cell (CFC) and a microbial fuel cell (MFC). The citrus fruit was used as whole for the preparation of DGC and their juices for the preparation of IDGC, CFC and MFC. The performance and bioelectrical parameters obtained were compared. The voltage found to be increased by increasing the number of cells in a series while, the current remains constant. Whereas the voltage remains constant and the current found to be increased with increasing the number of cells in parallel sequence. The power output of three units of citrus fruit connected together in a series found to be sufficient to turn on the LED light bulb in all cases. The result showed that lemons have the maximum power output by the DGC and MFC method, whereas grapefruit showed the maximum power output by IDGC, and thus considered as the best citrus fruit. Addition of NaCl solution in DGC and IDGC slightly increased the values of power output. The power output of citrus fruit was also determined by CFC and MFC before and after the inoculation of Escherichia coli. The detailed microscopic analysis of all the samples was carried out. It is found that all MFCs have higher power output as compared to their counterpart CFCs. However, maximum power output was displayed by DGCs. Moreover, a lemon fuel cell has the higher power output as compared to the fuel cells of other citrus fruit. This approach can be used to overcome the disadvantages of many non-renewable and conventional sources of energy including burning of fossil fuels to mitigate the major source of global warming and pollution by using such biodegradable and renewable sources.

Keywords: citrus fruit, bioelectricity, direct method, indirect method, galvanic cell, microbial fuel cell, E. coli

1. Introduction

Energy is the prime requirement of all sectors including industry, transportation, agriculture and domestic use without which advancement of technology and survival of life is not possible (Carvalho *et al*., 2011). Most of the energy around the world comes from non-renewable sources including: petroleum, coal, oil and natural gas which are being depleting at a high rate (Larhum, 2010). Fossil fuels are the major source of global warming and pollution due to increase in greenhouse gases, volatile matter and particles in the atmosphere (Khan *et al.,* 2011). However, technologies of renewable energy are growing worldwide that can overcome these drawbacks (Christi, 2007; Goff *et al.,* 2004; Ha *et al.,* 2010). Biomass, which includes agricultural crops, seeds, algae and biowastes are major sources of renewable energy that replenish themselves through natural processes (Hossain and Mekhled, 2010; Mata *et al.,* 2010; Dincer, 2000). Bioelectricity generation is reported from wastewater using a microbial fuel cell (Khan 2009, Khan *et al.,* 2010, Khan *et al*., 2011, Khan and Naz, 2014). Lemon, orange and grapefruit are examples of biomass and commonly known as citrus fruit (Randhawa *et al.,* 2014). They contain citric acid, sugar and other ingredients with sufficient chemical energy that can be converted into electrical energy by means of redox reaction with a specific condition and thus be utilized as batteries to light up LEDs and power up a clock or a calculator etc. (Kelter and Morgan, 1996; Goodisman, 2001; Swartling *et al*., 1998). Under certain conditions, the citric acid contained in citrus fruit may act as an electrolyte, which enables the generation of electricity just the same way as a galvanic battery (Oon, 2007).

The population around the globe is continuously increasing, which is demanding not only more food but also the energy to fulfil the requirement of the latest needs and technology. Some crops may be produced and consumed for both purposes like corn, sugarcane, fruit and vegetable oils. Therefore, there is an urgent need to develop the food vs. energy priority for a sustainable future. However, the increase in crop yield with the passage of time is not as per the desired level, which may increase the price of food grain but on the other hand, hectors of arable land is available for additional harvesting of crops for both food and fuel (energy). This manuscript demonstrates the conversion of waste to energy using waste citrus fruit as a source of biofeedstock. Large quantities of waste citrus fruit are generated from agricultural processes and in the retail markets worldwide. This waste is often simply dumped into landfills or the ocean. Therefore, there is no doubt in easy availability and cheap prices of such waste biofeedstock. Waste citrus fruit has sufficient content of acid and sugar that can be used for the production of bioelectricity using a galvanic cell and microbial fuel cell technology at a laboratory scale. This will not only reduce the disposal cost of waste but also increase a total of the production of bioenergy with nominal investment. Moreover, the production of citrus fruit is increasing gradually and there is no evidence that the supply of citrus fruit will face a shortage in the near future. Therefore, there is no significant impact of food vs energy due to the generation of bioelectricity from waste citrus fruit.

2. Experimental

2.1. Materials and instruments

The materials and instruments applied during this research included analytical weighing balance TE 3135-DS (Sartoris, Germany), digital multimeter, CD771 (Sanawa, Japan), pH meter, Hi-9810 (Hanna, Rhode Island), TDS/ conductivity meter, LF12 (Schott, Germany), Karl Fisher (Mettler, USA), Binocular Microscope, 107BN (Jinhua Huiyou Equipment and Instrument Co. Ltd.), incubator (MMM Medcenter Einrich-tungen, Germany), autoclave YX 280B (China), Cumber test kit (Roche), copper electrode, zinc electrode, LED (light bulb), copper electrical wire, connector, alligator clip, fruit (lemons, oranges, grapefruit), sodium chloride solution (1%), distilled water, potassium chloride (KCl), volumetric flask, beaker, glass vessel, container, PVC pipe and microorganism (*E. coli*), glass slide, crystal violet, Gram's stain, safranin, ethanol, and a wire loop.

2.2. Direct galvanic cell (DGC)

In this experiment, four series of fruit were studied for the generation of bioelectricity. The three series contain a single type of either of the waste fruit (lemon, orange and grapefruit) and the fourth series contain mixed fruit arranged in alternate arrangement in a successive manner. A zinc electrode of dimension 5 cm x 1 cm was inserted into one side of the fruit and a copper electrode of the same dimension was inserted into another side of the fruit. A copper wire was connected to the zinc electrode on one end and the other end was connected to one end of the electric socket. Similarly, a copper wire was connected to the copper electrode on one end and the other end was connected to another end of the electric socket to complete the circuit.

The voltage, current and other parameters of this electric circuit were determined with a digital multimeter with a positive terminal connected to the zinc electrode and a negative terminal connected with copper electrode. The LED was connected to the circuit with zinc electrode to its short leg and copper electrode to its long leg. Then the numbers of citrus fruit were increased in series by connecting the zinc electrode of one fruit to the copper electrode of the next fruit via copper wire using alligator clips. In addition to the above series combination, the cells were also connected in parallel sequence by connecting the anode electrodes (zinc) of all cells together and the cathode electrodes (copper) of all cells together. The electrical parameters were determined using the same multimeter. Afterwards, 1% solution (1 ml) of NaCl was injected into each fruit and the electrical parameters were measured (see Figure 1).

2.3. Indirect galvanic cell (IDGC)

During this experiment, the juice of waste citrus fruit (lemon, orange, grapefruit and mixed fruit), were collected into a separate glass vessel. The parameters of the fruit juices including pH, total dissolved solids (TDS), water content (Karl Fisher), acid content, salinity were determined and compared. The juices of citrus fruit were transferred into 1 to 4 glass vessels. One electrode of each metal (zinc and copper) of dimension 5 cm x 1 cm was inserted into the fruit juice distant (2 to 4 cm) to each other. A copper wire was connected to the zinc electrode on one end and the other end was connected to an electric socket. Similarly, a copper wire was connected to the copper electrode on one end and the other end was connected to the electric socket to complete the circuit. The voltage and current were noted by connecting a digital multimeter. The positive terminal was connected to the zinc electrode and negative terminal to the copper electrode. The LED was connected to the zinc electrode to its short leg and the copper electrode to the long leg of the LED bulb. The cell units were also connected in a series and parallel combination and the electrical parameters were determined using the same multimeter. Afterwards, 1% solution (1 ml) of NaCl was injected into each fruit juice and the electrical parameters were measured.

2.4. Conventional fuel cell

The construction of a conventional fuel cell (CFC) consists of two chambers. One is the Anodic chamber containing either of the fruit juice of waste

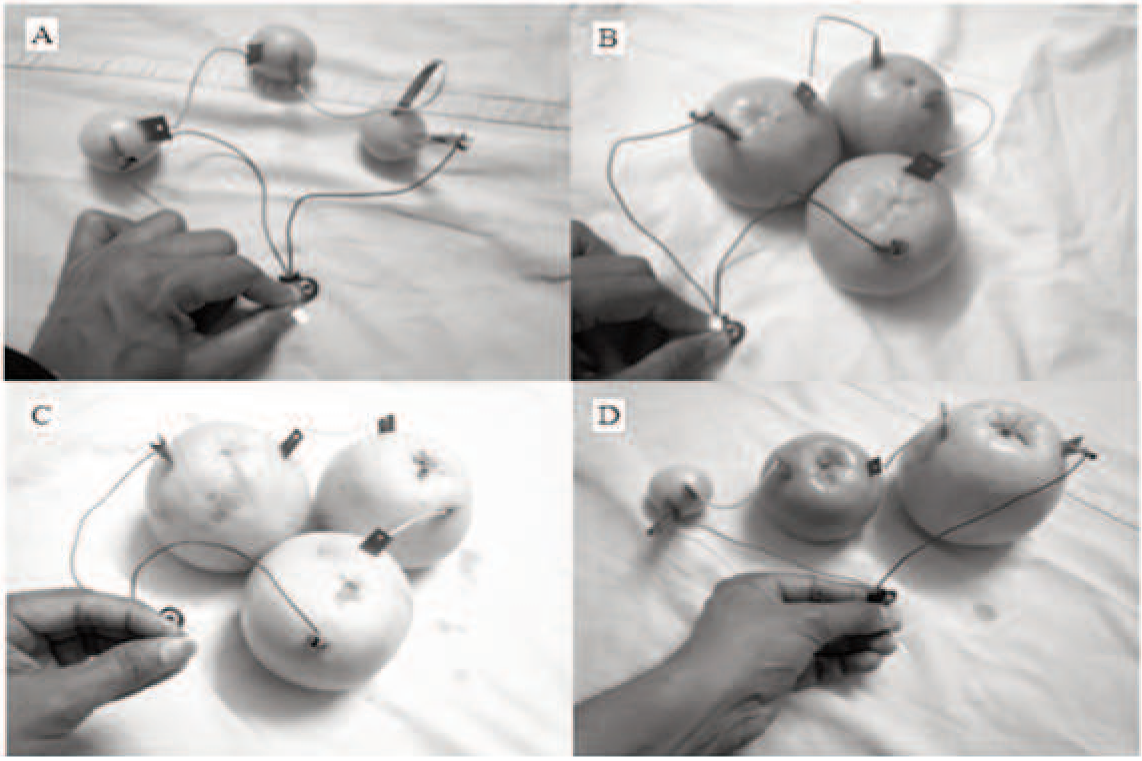

Figure 1: Bioelectricity generation by galvanic cell

lemon, orange, grapefruit and mixed fruits. The other is a cathodic chamber containing water in which air was continuously pumped by an aquarium pump. The two chambers were connected with a salt bridge (25% NaCl: 75% sand). One zinc electrode was submerged in the fruit juice of the anodic chamber and another electrode of copper metal was submerged in water. The two metal electrodes were connected together with a copper wire to compete the one unit of CFC. Then the numbers of the CFC unit were increased from one to four in a series by connecting the zinc electrode of one CFC to the copper electrode of the next CFC via copper wire. The electrical parameters with increasing number of CFC units were determined using the digital multimeter for each fruit juice (see Figure 2).

2.5 Microbial fuel cell (MFC)

2.5.1 Microscopic examination

The apparatus and glass wares used were sterilized either by autoclaving or a flame (wire loop) where required. The extract of fruit juices were subjected to microscopic examination before and after inoculation of microorganism. A reference slide with *E. coli* culture was prepared for comparison. The samples were incubated at 37°C for 7 days and the smears on glass slides were stained with standard procedure of gram's staining technique (Khan and Naz, 2014). The slides were examined through a lens having a resolution of 10/ 0.25 (160/0.17).

2.5.2. MFC construction

The MFC was constructed with the same electrical connection chambers as of CFC however, the microorganism (*E. coli*) was added to either of the fruit juice of lemon, orange, grapefruit and mixed fruits filled in the anodic chamber, which was sealed to prevent the entrance of air and thus forced the microorganism to aid the fermentation of the sugar contents of the fruit juice. The cell units were also connected in a series and parallel combination and the electrical parameters were determined using the digital multimeter for each sample.

3. Results and discussion

The drawbacks of conventional technologies of energy like fossil fuels which are non-renewable, being depleted and also considered as the major source of global warming and pollution stimulated us to conduct this research in which some basic parameters to generate the electricity from citrus fruit including lemon, orange, grapefruit and mixed fruit were investigated. Experiments were carried out using a galvanic cell (with two approaches namely direct method and indirect method), a fuel cell and a microbial fuel cell. In the direct method, whole fruit was used as a unit for the construction of a direct galvanic cell (DGC), whereas in the indirect method, fruit juices were used for the preparation of an indirect galvanic cell (IDGC, CFC and MFC). The galvanic cells (DGC and IDGC) were tested with and without the addition of NaCl solution as electrolyte. Furthermore, a conventional fuel cell (CFC) and a microbial fuel cell (MFC) were tested before and after the addition of microorganism (*E. coli*).

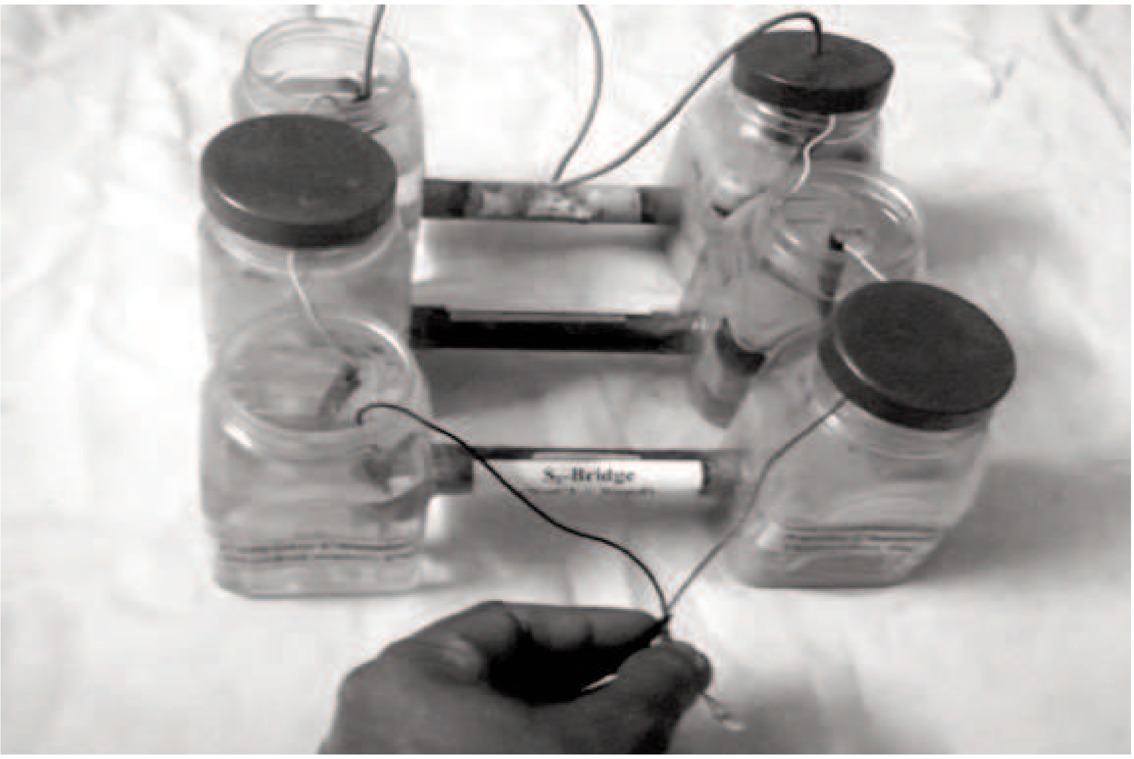

Figure 2: Bioelectricity generation by fuel cell

3.1 Galvanic cell

In a galvanic cell, proton (H^+) of citric acid dissolves the zinc electrode of the anodic chamber to produce zinc ions (Zn^{2+}) along with the liberated electrons which travel via copper wire to the copper electrode at the cathodic chamber and reacted with H^+ ions from the citrus fruit that generated bio-H_2 gas. This supply of electron generates electric current due to the potential difference of the two electrodes (Oon, 2007; Naidu and Kamakshiaih, 1995; Franco, 2005) (see Figure 3).

$$Zn \rightarrow Zn^{2+} + 2e^- \text{ (Anodic reaction)}$$

$$2H^+ + 2e^- \rightarrow H_2 \text{ (Cathodic reaction)}$$

$$Zn + 2H^+ \rightarrow Zn^{2+} + H_2 \text{ (Overall reaction)}$$

In the indirect method, the fruit juices were extracted and analysed for the determination of acid content, sugar, pH, total dissolved solids (TDS), salinity, water content, refractive index, conductivity etc. (see Table 1). The value of voltage and current in the indirect method was found to be lower but more stable than the direct method. This may be due to better homogeneity and less hindrance faced by ions in free flowing liquid medium as compared to the pulp of the whole fruit in the direct method. In the indirect method, the voltage and current does not get altered by increasing the amount (volume) of fruit juices in a glass container. When the same juices were divided up into four separate glass containers (galvanic cells) connected in a series, the voltage and power output were increased in a typical manner with an increasing number of cells and thus the LED light turn on.

Table 1: Physiochemical parameters of the juices of citrus fruit*

Testing parameters	*Units*	*Lemon*	*Orange*	*Grapefruit*	*Mixed fruit*
Acid content	% w/w	4.60	0.80	1.20	2.30
Carbohydrates	% w/w	10.62	12.20	8.33	10.57
Sugar content	% w/w	2.95	9.15	5.30	5.42
pH	-	2.31	3.77	3.18	3.37
TDS	$\mu g\ L^{-1}$	1.80	1.28	1.34	1.37
Salinity	$\mu g\ L^{-1}$	1.90	1.30	1.40	1.40
Water content	% w/w	39.30	51.2	47.80	44.5
Refractive index	-	1.37	1.39	1.33	1.34
Conductivity	μS	3.38	2.37	2.49	2.54

* All the data is replicated three times and mean values are included in the table

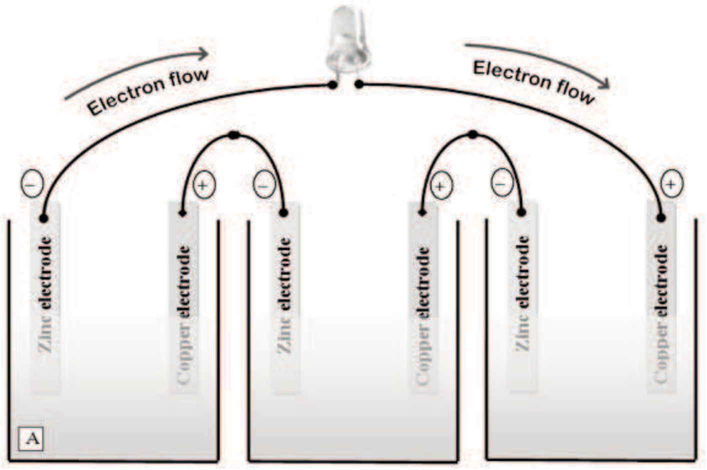

Figure 3: Circuit diagram of galvanic cells connected in a series

3.2. Conventional fuel cell

In a conventional fuel cell, carbohydrates of the citrus fruit juices in the anodic chamber were to undergo the self-fermentation by environmental microorganisms to produce biogases (CH_4, H_2, CO_2, N_2 etc.), where CH_4 and H_2 were utilized as fuel along with liberation of H^+ ions and electrons at the anodic chamber. The electrons moves from zinc electrode of the anodic chamber via copper wire and reach the copper electrode at the cathodic chamber in the form of current and the protons librated at the anodic chamber were transferred via a salt bridge to the cathodic chamber containing tap water, where it reacted with the air oxygen to produce water (John, 1983; Leon and Mugrwa, 1993; Badwal *et al,* 2015).

Anodic reactions:

$C_6H_{12}O_6 \rightarrow 3CH_3COOH + H_2$

$3CH_3COOH \rightarrow 3CH_4 + 3CO_2$

$3CH_4 + 6H_2O \rightarrow 12H_2 + 3CO_2$

$12H_2 \rightarrow 24H^+ + 24e^-$ (Oxidation)

$C_6H_{12}O_6 + 6H_2O \rightarrow H_2 + 6CO_2 + 24H^+ + 24e^-$ (Overall anodic reaction)

Cathodic reactions:

$6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O$ (Reduction)

$C_6H_{12}O_6 + 6O_2 \rightarrow H_2 + 6CO_2 + 6H_2O$ (Overall reaction)

The conventional fuel cell (CFC) and microbial fuel cells (MFCs) were arranged in series. The anodic chamber of each fuel cell contain either of the fruit juice (lemon, orange, grapefruit and mixed fruit) and the cathodic chamber contains tap water with continuous flushing of air. The electrical parameters were measured before and after the inoculation of the microorganism in a closed anodic chamber to prevent the entrance of air oxygen.

3.3. Microbial fuel cell

The reference slide was prepared by *E. coli* culture that displayed the rod shaped bacilli. The slide prepared by the fruit juice extract does not show the presence of *E. coli* instead random particles were observed. The slides of fruit juices prepared after the inoculation of *E. coli* showed few rod shaped *E. coli* (see Figure 4).

In a microbial fuel cell, microorganism uses carbohydrates of the citrus fruit juices as food and converts them to biogas, which is finally converted into H^+, with the loss of electrons via a fermentation pathway in the absence of air oxygen in the sealed anodic chamber. The electrons move from the zinc electrode of the anodic chamber via copper wire and reach the copper electrode at the cathodic chamber in the form of current and the protons librated at the anodic chamber were transferred via the salt bridge to the cathodic chamber containing tap water where it reacted with O_2 to produce extra ordinary pure water (Bennetto, 1990; Moawad, 2013; Delaney *et al.,* 1984) (see Figure 5). The values obtained for voltage, current and power output by DGC, IDGC, CFC and MFC are displayed in Table 2.

$CH_4 + 2H_2O4 \rightarrow H_2 + CO_2$ (Anodic reaction)

$4H_2 \rightarrow 8H^+ + 8e^-$ (Oxidation at anode)

$2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ (Reduction at cathode)

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (Overall reaction)

3.5. Comparative study

The voltage of the circuit was increased with the increase in the number of galvanic or fuel cells in series. Thus, the values of power output were also increased accordingly and the current of the circuit remains almost constant. The procedure was repeated with DGC and IDGC after the addition of NaCl (1ml of 1% solution) to lemon, orange, grapefruit and mixed fruit, which showed a slight increase in the values of the power output (see Figure 6).

MFCs showed higher values of power output in all cases (lemon, orange, grapefruit and mixed fruit) as compared to their counterpart CFCs. Moreover, the MFC of lemon showed highest values of power output among the MFCs of citrus fruit (orange, grapefruit and mixed fruit series). However, the power outputs by MFCs are still lower as compared

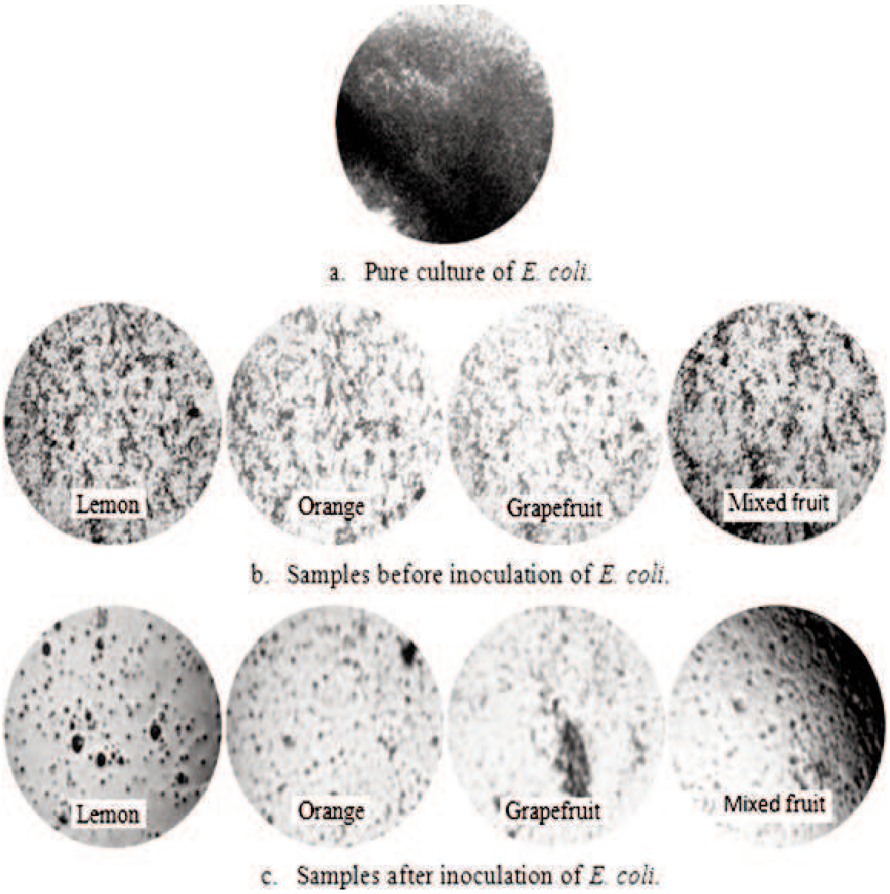

Figure 4: Microscopic pictorial representation

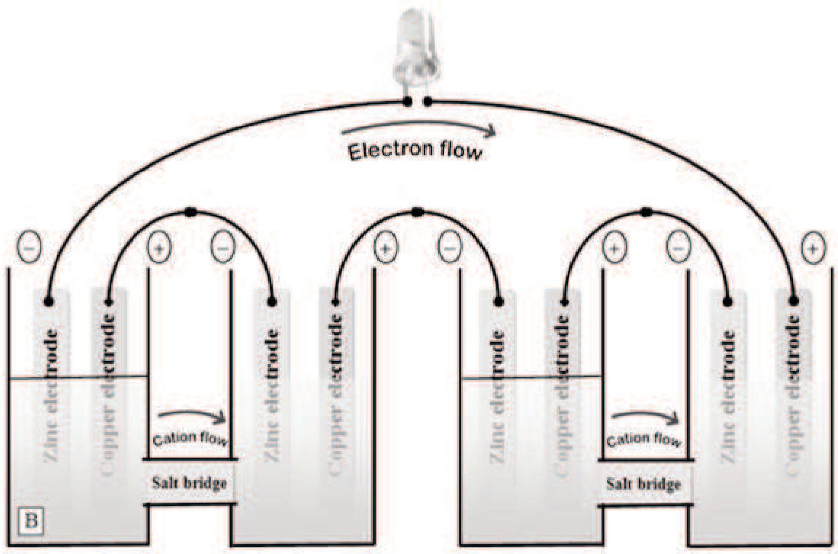

Figure 5: Circuit diagram of microbial fuels connected in a series

to their counterpart galvanic cells (DGC and IDGC). The difference in power output before and after the addition of microorganism is observed highest in the orange series. This is due to the fermentation of carbohydrates and acid contents (citric acid) present in oranges in the highest quantity as compared to other fruit and convert them into simpler compounds with the liberation of electrons and protons, which leads to surplus current (electrons) in the circuit and thus produced the highest power output difference. Therefore, it suggested that orange is a better choice for MFC in this experiment (*see* Figure 7).

In addition to above experimentation, a comparison of series and parallel sequence were made with lemon fruit and electrical parameters were used using DGC, IDGC and MFC methods. The results showed that, in parallel sequence, voltage

Table 2: Parameters obtained from citrus fruit by using different bioelectrical cells*

Souce	*No. of unit cells*	*DGC°*			*IDGC°*			*CFC¤*			*MFC ø*		
		V (v)	*I (mA)*	*P (mW)*	*V (v)*	*I (mA)*	*P (mW)*	*V (v)*	*I (mA)*	*P (mW)*	*V (v)*	*I (mA)*	*P (mW)*
Lemon	1	0.97	2.53	2.45	0.91	1.25	1.14	0.77	0.88	0.68	0.78	1.02	0.80
	2	1.94	2.45	4.75	1.89	1.24	2.34	1.51	0.83	1.25	1.55	1.00	1.55
	3^	2.84	2.25	6.39	2.72	1.25	3.40	2.33	0.79	1.84	2.36	0.99	2.34
	4^	3.76	2.24	8.42	3.66	1.29	4.72	3.02	0.75	2.27	3.07	0.95	2.92
Orange	1	0.86	0.98	0.85	0.82	0.82	0.67	0.72	0.48	0.35	0.74	0.89	0.66
	2	1.56	0.95	1.48	1.57	0.85	1.33	1.35	0.47	0.63	1.55	0.85	1.32
	3^	2.62	0.91	2.38	2.43	0.72	1.75	1.91	0.45	0.86	2.39	0.82	1.96
	4^	3.12	0.89	2.78	3.02	0.84	2.54	2.87	0.40	1.15	3.43	0.77	2.64
Grapefruit													
	1	0.91	1.21	1.10	0.88	1.82	1.60	0.78	0.68	0.53	0.83	0.79	0.66
	2	1.75	1.25	2.19	1.65	1.75	2.89	1.52	0.65	0.99	1.58	0.77	1.22
	3^	2.70	1.23	3.32	2.29	1.87	4.28	2.21	0.62	1.37	2.35	0.74	1.74
	4^	3.31	1.20	3.97	3.17	1.79	5.68	2.99	0.61	1.82	3.13	0.72	2.25
Mixed fruit	1												
	0.94	2.28	2.14	0.85	1.32	1.12	0.74	0.65	0.48	0.80	0.73	0.58	
	2	1.81	2.12	3.84	1.61	1.35	2.17	1.35	0.61	0.82	1.57	0.69	1.08
	3^	2.69	1.76	4.74	2.32	1.39	3.22	1.96	0.59	1.16	2.34	0.65	1.52
	4^	3.52	1.89	6.65	3.29	1.34	4.41	2.67	0.54	1.44	3.15	0.64	2.02

* All the data is replicated three times and the mean values were included in the table.
° Before addition of NaCl, ¤ Before addition of microorganism, ø After inoculation of microorganism, ^ LED light up

remain constant nearly at a value obtained with a single unit however, the current increased with increasing the number of galvanic or fuel cells in contrast to the series circuit, where the voltage was increased with the increase in the number of galvanic or fuel cells and the current in the circuit remains almost constant (Table 3).

Furthermore, comparison of power output showed that the lemon has displayed the highest values of power output by DGC among the other citrus fruit, followed by mixed fruit, grapefruit and orange respectively. However, the values of power output found less in IDGC, CFC and MFC respectively. Orange has the lowest value of voltage in DGC and thus showed the lowest value of power output. However, the orange showed competitive value of power output by MFC as compared to other fruit. Grapefruit has the highest power out in IDGC and thus considered as most suitable for this method. Mixed fruit showed the average values of other fruits and thus no benefit or loss is considered with this series (see Figure 8). The merits and demerits of different fuel cells (DGC, IDGC, CFC and MFC) have been summarized in Table 4.

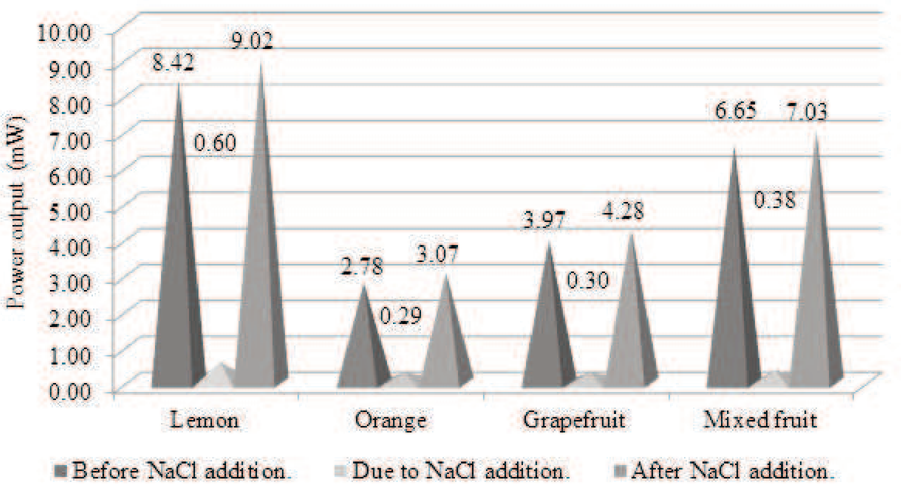

Figure 6: Comparison of power output of four units by DGC

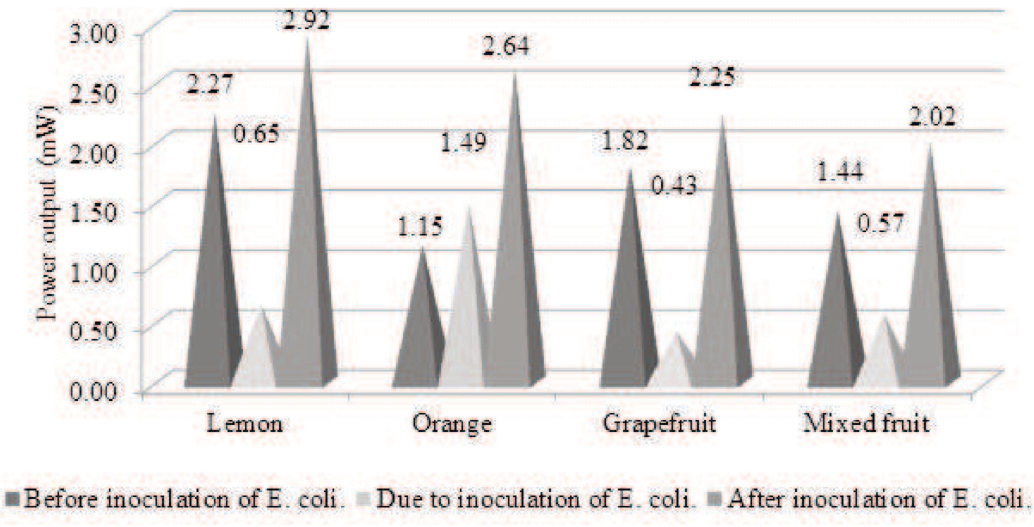

Figure 7: Comparison of power output of four units obtained by MFC and CFC

Table 3: Comparison of series circuit and parallel circuit of lemon cell*

Methods	*No. of unit cells*	*Series circuit V (v)*	*Series circuit I (mA)*	*Series circuit P (mW)*	*Parallel circuit V (v)*	*Parallel circuit I (mA)*	*Parallel circuit P (mW)*
¤DGC	1	0.97	2.53	2.45	0.97	2.43	2.36
	2	1.94	2.45	4.75	0.95	4.69	4.46
	3	2.84	2.25	6.39	0.96	6.93	6.63
	4	3.76	2.24	8.42	0.90	9.16	8.24
¤IDGC	1	0.91	1.25	1.14	0.92	1.33	1.22
	2	1.89	1.24	2.34	0.91	2.51	2.28
	3	2.72	1.25	3.40	0.93	3.63	3.38
	4	3.66	1.29	4.72	0.90	4.76	4.28
CFC	1	0.77	0.88	0.68	0.75	0.82	0.62
	2	1.51	0.83	1.25	0.73	1.54	1.12
	3	2.33	0.79	1.84	0.78	2.25	1.76
	4	3.02	0.75	2.27	0.76	3.08	2.34
MFC	1	0.78	1.02	0.80	0.77	0.99	0.76
	2	1.55	1.00	1.55	0.76	1.87	1.42
	3	2.36	0.99	2.34	0.73	2.79	2.04
	4	3.07	0.95	2.92	0.77	4.61	3.55

* All the data is replicated three times and the mean values were included in the table
¤ Without addition of NaCl

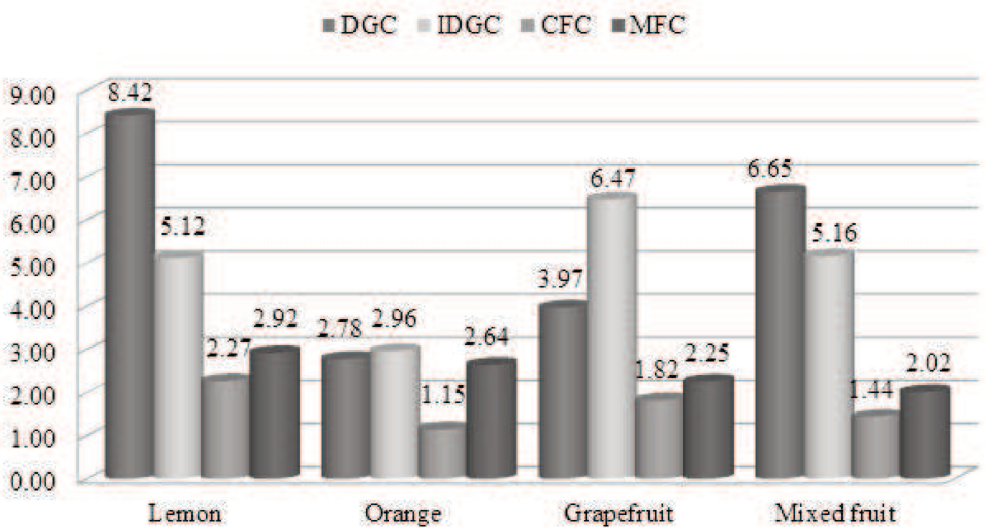

Figure 8: Comparison of power output of four units by different methods

Table 4: Merits and demerits of different types of cells

S. No.	Cell types	Construction	Principal	Merits	Demerits
1	DGC	Citrus fruit as whole were directly used as galvanic cell.	Zinc electrode get dissolved in acidic juice of citrus fruit and liberate electrons which travel from anode to cathode via copper wire in the form of current.	No need to develop specialized cell hence cost of construction is reduced. The power output was found to be highest in this cell.	Quantity of the juice in the fruit which is not free flowing and does not come in contact with electrode.
2	IDGC	The juice of the citrus fruit was extracted and transferred into glass vessel, which were used as indirect galvanic cell.	Same as DGC.	Results are steady due to free flowing liquid form of fruit juices.	Additional step of the juice extraction is involved.
	CFC	Double chamber construction connected with salt bridge. Anodic chamber contain fruit juice and cathodic chamber contain tap water with continuous air supply.	Fruit juices in the sealed anodic chamber produce different biogases which work as fuel. The librated electrons transferred through electrodes and protons transferred through the salt bridge to cathodic chamber where it reacts with air oxygen to form water.	Cathodic chamber contain water which is easily available hence only anodic chamber need to be filled with fruit juice which reduce the required quantity of fruit juices. It produced extraordinary pure water.	Power output is low as compared to galvanic cell. Cost of fuel cell construction is involved.
	MFC	Same as CFC Double chamber construction however, microorganism in the anodic chamber was inoculated.	Microorganism fermented the sugars in the fruit juice thus enhance the biogases (fuel) formation. The flow of electrons and protons from anode and formation of water at cathodic chamber is same as CFC.	Power output as compared to CFC increased however, still lower than galvanic cell. Addition of other substrates like sugar and dyes may enhance the power output. It also produced extraordinary pure water.	Highest cost of construction and materials will be involved. Contamination of other microorganisms may alter the power output. Microorganisms will also pollute the environment.

4. Conclusions

The physiochemical analysis of fruit juices showed that lemon has the lowest pH value (highest acid contents/ citric acid) which make this most preferable to utilized lemon for bioelectricity generation among the other fruit (orange, grapefruit and mixed fruit). The voltage of the circuit found to be increased with increasing the number of cells connected in series in all cases and the current remains almost constant. The current of the circuit was found to be increased with increasing the number of cells connected in parallel sequence in all cases and the voltage remains constant. The power output by DGC is found higher as compared to the IDGC, CFC and MFC method. The power output after the addition of the NaCl solution in all cases showed slightly higher values as compared to the values obtained before the addition of the NaCl solution in the galvanic cells. The power output by the MFC method is found higher due to the addition of microorganism as compared to their counterpart CFC method. Finally, the results showed that lemon generates the highest power output by the DGC method, and grapefruit showed the highest power output by IDGC. However, orange showed significant increase in power output by MFC as compared to CFC, which is considered due to highest sugar content in orange among the other fruit included in this article. The shortage of non-renewable fossil fuels will increase the cost of conventional electricity with time, and the advancement in the field of genetic engineering and bioelectricity technology will certainly result in the development of renewable, environmental friendly and a convenient source of energy around the globe.

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The effect of an angle on the impact and flow quantity on output power of an impulse water wheel model

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Abstract
Nowadays, the world is more focused on hydraulic energy, which scientists have initiated thorough analyses of hydropower resources. The potential of wind power generation is immense. It is an historical source of energy but wind power is not applicable in this case. In India, water can be used for both - as a source of electricity and for irrigation and agricultural use. Impulse type water wheels were employed until flow is accessible. According to available literature, there are three types of water wheels and the application of a particular type of water wheel depends upon the stream of water. In this article, an extremely uncomplicated category impulse water wheel is fabricated. To fabricate this water wheel, little engineering is required. The experimental results obtained indicate that intensity of generated power depends upon the angle of water impact on the turbine blade, height, quantity of water flowing in pipe etc. The aim of this article is to suggest an alternative source of economical and environmentally friendly green energy for a small quantity of fluid flowing. There are various sources of small quantity water such as large society storage tank water, sewer line water, canals water and many more. The construction cost of water wheels is not as much since it does not have an intricate blade profile.

Keywords: water head, impulse, water wheel, angle, flow quantity, green energy, prototype, fabrication

List of symbols

P = Power in Watts
η = Hydraulic Efficiency
ρ = Density of Water
Q = Volume of Water flowing in turbine
H = Water pressure head
F_x = Force exerted by water Jet
a = Cross-sectional area of Water Jet
d = Diameter of Jet
V_1 = Velocity of Jet at Inlet of Turbine Blade
V_{w1} = Velocity of the whirl at inlet in m/s.
V_{w2} = Velocity of the whirl at outlet in m/s
W_J = Work done by Jet on Turbine
β = Angle of Vane at outlet

Introduction

Water wheels are the oldest machines used for various purposes. Initially, water wheels were made from wood and efficiency of the wheels was very small because design of such water wheels was based on random selection of material, shape, dimensions etc.

Among all the renewable energy sources available, small hydropower is considered as the most promising source of energy. In many parts of the country, especially hill states, streams coming down the hills possess sufficient potential energy that can be utilized. The water wheels are used to convert the potential energy of water to mechanical energy. Flowing water is directed onto the blades of water wheels, creating a force on the blades which in turn, rotates the shaft (Khurana *et al.*, 2012).

In the modern scenario, the development of the water wheel is based on the principle of hydraulic engineering, proper material selection, consideration of aerodynamic forces etc. Therefore, the efficiency of modern water wheels has increased sharply. The development of steam engines and hydraulic turbines also has been a milestone in the development of water wheels. Nowadays, water wheels are rarely used but there is large scope for water wheels in the modern era for utilizing small water flow and salvaging kinetic energy (Muller *et al.*, 2004).

Table 1: Different types of water wheels with their parameters (Muller 2004)

S. no.	*Type of water wheel*	*Position of water entering*	*Head difference*	*Flow rates*
1	Overshoot	Upstream water level above the level of wheel axes	2.5m-10m	0.1 m^3/sec-0.2 m^3/sec
2	Breast	Upstream water level in the level of wheel axes	1.5m-4m	0.35 m^3/sec-0.65 m^3/sec
3	Undershoot	Upstream water level below the level of wheel axes	0.5m-2.5m	0.5 m^3/sec-0.95 m^3/sec

There are three types of water wheels namely, overshoot, breast wheel and undershoot. The difference between the three wheels is indicated in Table 1.

In the starting phase of the development of the water wheel, its various parts were made from hard wood. The specification of a water wheel has been shown in Table 2.

Table 2: Water wheels different parts, materials and dimensions
(Ibrahim et al., 2006)

S. no	Part name	Material	Dimensions
1	Wheel	Hard wood	150 cm-300cm
2	Water Chamber	Hard wood	25cm -35cm
3	Bearing	Steel	20cm -25 cm
4	Blade shaft	Hard wood	20cm-30cm
5	Blade Number	Hard wood	25-30
6	Blade Angle	-	30^0
7	Water Flow Angle	-	30^0

Because of the ecological and environmental restrictions in energy production, the use of small hydropower resources will be economical in future. Standard pumps could be considered as a low cost alternative for water wheels (Diana *et al.,* 2010).

The manual drawing of these characteristics is a long and, sometimes, a subjective process. Particular software will increase the speed and the quality of the process (Dorian *et al.,* 2004).

In modern engineering, water wheels are initially designed by CFD analysis and then the actual model can be fabricated. The efficient application of advanced CFD is of great practical importance, as the design of hydraulic turbines is custom-tailored for each project (Drtina *et al*., 2006). The parameters that should be considered for water wheel design are head difference, flow volume, different geometry of vanes etc. (Sonaje *et al.,* 2013).

A detailed study of the available literature for water wheels was conducted. According to a literature review and results presented by numerous scientists, indicate that efficiency/effectiveness of water wheels depends upon various factors. Some of the factors are the geometry of the blade, type, material etc. so as to minimize losses. But the most important factor is an economical consideration. India is a developing nation therefore there is a necessity to develop a low cost/maintenance water wheel. The suggested prototype is a low cost water wheel and applicable for wide range of flow quantity/head.

Prototype model and its description

An extremely simple prototype model has been fabricated. This model is very straightforward without considering any blueprint factors in cavity/blade design. Because the blades are uncomplicated, they are very cheap, and the efficiency of these water wheels changes marginally for small quantities of water flow. The dimensions of a proto-type water wheel are listed in Table 3.

Table 3: Dimensions of a prototype water wheel

S. no	*Water wheel component name*	*Dimension*
1	Shaft diameter	8 mm
2	Shaft length	300 mm
3	Turbine blades	8
4	Blade length	50.8 mm

Figure 1 shows a schematic diagram of a water wheel. The various components of a water wheel are a water wheel holding stand, two ball bearings for holding the rotating shaft, blades of the water wheel, dynamo-meter to convert potential energy into electrical energy, water pipe and water jet. The output power of the dynamo-meter can be measured with the help of an Ampere meter/voltmeter. The water wheel holding stand grasps water wheel shocks and vibrations for noiseless operations. The dimensions of the water wheel have been included in Table 3 with the diameter of the pipe through which water is flowing is 20 mm. Water of the test setup is collected in a separate tank and the difference in the water level specifies the flow quantity of water in the impulse water wheel. For protection, the entire experimental setup has been covered up by a transparent fibre glass sheet.

Result and discussion

With the help of a fabricated prototype water wheel, the effect of the angle of impact and flow quantity on output power had been calculated. The water wheel consumes hydraulic energy of the water and converts it into mechanical energy and then to electrical energy. There are various types of losses; some of those losses are leakage loss, mechanical

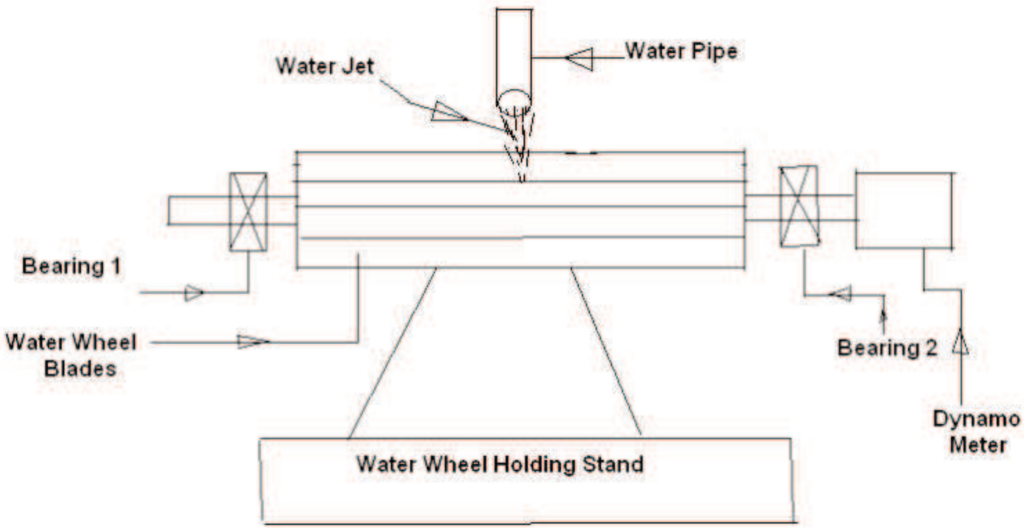

Figure 1: Schematic diagram of a prototype water wheel

loss, electrical loss etc. The basic equations which can be used to find hydraulic energy had been discussed by Tyagi (2012). Some equations which play a vital role for finding hydraulic energy are written from Equation 1 to Equation 7.

The total power available in falling water:

$$P = \eta \rho g Q H \tag{1}$$

The force exerted by the water jet on buckets (vanes) of the runner in the direction of motion is given as:

$$F_X = \rho a V_1 [\overline{V_{W1}} + \overline{V_{W2}}] \tag{2}$$

The work done by the jet on the runner per second is as follows:

$$W_j = F_X \times u = \rho a V_1 \left[V_{w1} + V_{w2}\right] \times u \tag{3}$$

Kinetic Energy (K.E.) of the jet per second is given as:

$$\text{K.E.} = 1/2 \rho a V_1 \times V_1^2 \tag{4}$$

Hydraulic efficiency η_h = Work done by jet per second ÷ K.E. of jet per second.

$$\eta_h = \rho a V_1 \left[V_{w1} + V_{w2}\right] \times u \div 1/2 \rho a V_1 \times V_1^2 \tag{5}$$

$$\eta_h = 2(V_1 - u)[1 + \cos\beta]u \div 1/2 \rho a V_1 \times V_1^2 \tag{6}$$

$$\{V_{w1} = V_1 - u\},\ V_{w2} = (V_1 - u)\cos\beta - u\}$$

For maximum efficiency u is $= 1/2 V_1$,

$$\eta_{h\max} = 1 + \cos\beta / 2 \tag{7}$$

Figure 2 demonstrates the deviation in output power for different values of pressure heads. In this diagram, three impact angles have been considered, and these angles are 90 degree, 75 degree, and 60 degree respectively. The outcome achieved by experimental analysis demonstrates that output power is directly related to the angle of impact on the blade of the water wheel. The results in Figure 2 also indicate that after a certain value of water head output power is approximately constant for particular dimensions of the water wheel. After a certain value of pressure head, there is no effect of increasing pressure on output power because a critical velocity of the water wheel is achieved. In the water wheel, the critical velocity is the parameter where the wheel attains the maximum velocity for a particular type of wheel. The value of the critical velocity depends upon numerous parameters, some of which are: wheel dimensions, and geometry of water wheel blade.

Figure 3 shows the variation of the water wheel output power versus flow quanity of water. The result obtained in Figure 3 indicates that after 1.5 l/s of water, there is no effect or only a marginal effect on output power. Again, water jet impact angles are similar to those discussed in the Figure 2. The result obtained in Figure 2 illustritates that the critical velocity for the prototype wheel had been attained at 1.5 l/s; and above this quantity there is no positive effect on output power.

Figure 4 shows the variation of output power versus angle of impact of water jet for different values of the incident angle when the head and water discharge are fixed at 110 mm and 1.1 l/s respectively. In this experiment, the angle of impact of the water jet varies from 0 degree to 180 degrees. The value of the output power varies almost linearly from zero to maximum from 0 to 90 degree and then reduces from maximum to zero from 90 to 180 degree. For given parameters the maximum value

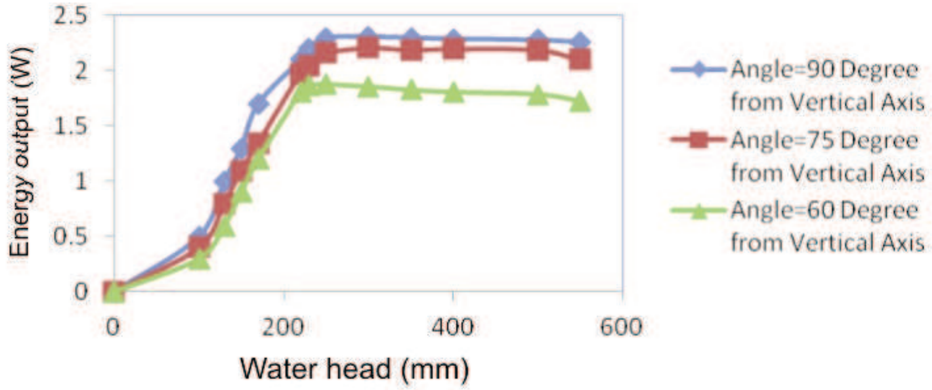

Figure 2: Variation of energy output (W) versus water head (cm) for different values of water head and discharge of water of 1.1 l/s

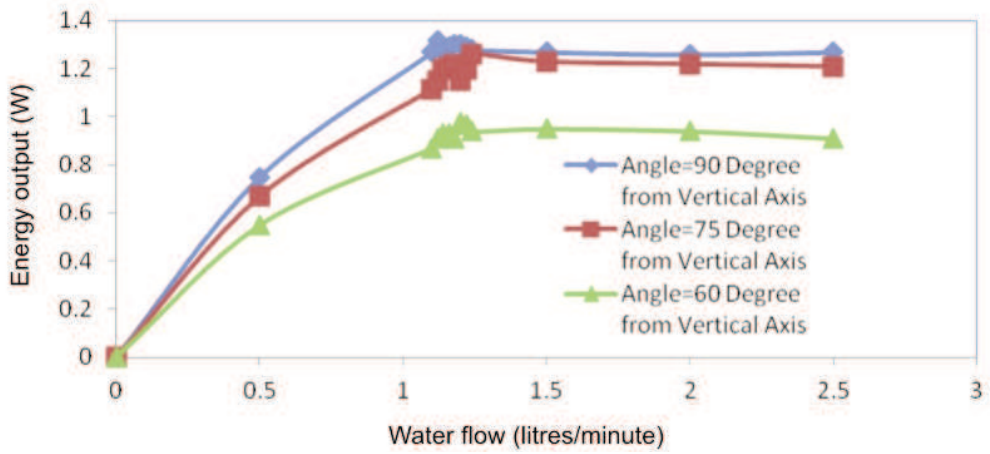

Figure 3: Variation of energy output (W) versus water discharge l/s for different values of water discharge and head of water of 110 mm

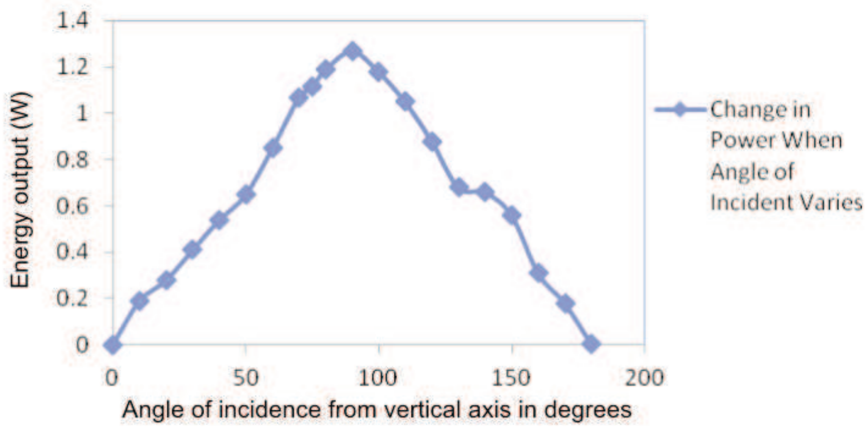

Figure 4: Variation of energy output (W) versus angle of impact in degree for different values of angle of incidence for head and discharge of water of 110 mm and 1.1 l/s

of output power is 1.27 watts, when the angle of impact is 90 degree.

Figure 5 shows experimental results for the water wheel model efficiency versus ratio of quantity of fluid to maximum quantity of fluid for a water head of 110 mm. The efficiency and fluid quantity ratio graph have been drawn for incident water jet angles of 90 degree, 75 degree, and 60 degree respectively. Above a ratio of quantity of fluid to maximum quantity of fluid of approximately 1.5 efficiency was approximately constant.. Above that value, the effect on output power is neglible.

Conclusions

A detailed study on the design of the simplest model water wheel has been investigated. In an experimental study, it was found that to make optimum use of resources such as blade manufacturing cost, available water head etc., the simplest type of water wheel will be a milestone for developing countries.

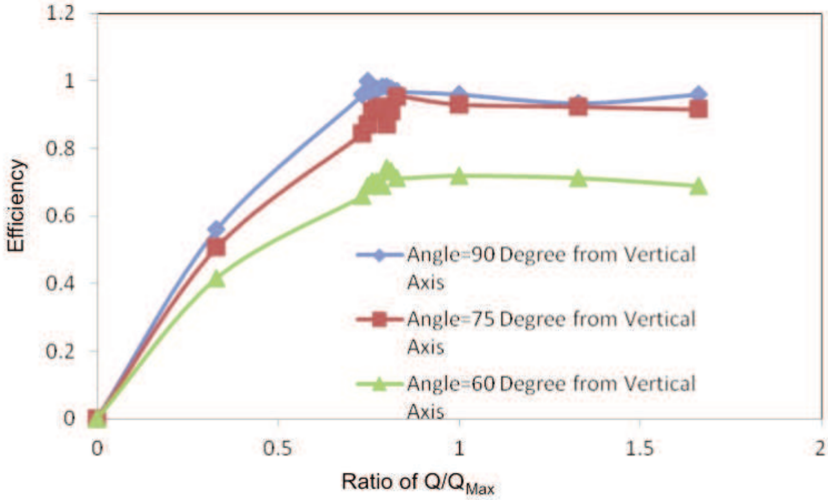

Figure 5: Variation of efficiency versus ratio of quantity of fluid to maximum quantity of fluid for different values of angle of incidence for a water head of 110 mm

Efficiency measurements were conducted for large range of water flow and for different angles of incidence. The results obtained by a proto-type water wheel indicate that water wheels generate maximum power when the angle of incidence of the water is 90 degrees from the blade. Efficiency measured by experiments indicates that the water wheel gave maximum power over a broad range of flows. This type of water wheel is very cost effective because it may be deployed for a blade on a water wheel without any curvature.

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CONFERENCE PAPER

Harnessing Nigeria's abundant solar energy potential using the DESERTEC model

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Abstract

The DESERTEC project, a European Union (EU) initiative to harness solar energy by means of Concentrated Solar Power (CSP) from Africa for use in Europe, shows the enormous potential that exists in alternative energy sources for the sub-region once there is political will. The Trans-Mediterranean Renewable Energy Corporation (TREC), a network of scientists and politicians who have taken it upon themselves to solve Europe's energy problem using sun from Africa, conducted three studies which evaluated the potential of renewable energy resources in the Middle East and North Africa (MENA), the expected needs for water and power in EU-MENA between now and 2050 and issues relating to the construction of an electricity transmission grid connecting the EU and MENA (EU-MENA-Connection), with a formula to turn the North African desert sun into electricity and transport same to Europe. This paper harnesses the TREC fact-finding studies in order to estimate how much the same ideas can be applied in many other parts of the world, Nigeria in particular. Investigation reveals that this association exists with huge potentials for an energy-starved country like Nigeria in harnessing her abundant hot sun in the north, which could go a long way in meeting the energy needs in that part of the country and beyond. Other benefits include unlimited supplies of clean electricity, agricultural gains, and creation of new industries, new jobs and new sources of income.

Keywords: concentrated solar power, DESERTEC, Nigeria, solar energy

1. Introduction

Almost every other source of energy being exploited by man is directly or indirectly tapped from the sun's reservoir. In fact, it is proven that the sun has as much effect on the process of establishing non-renewable energy sources as it does to renewable sources. At present, the amount of energy radiated from the sun, that is wasted unutilised, is 10 000 times the amount of energy required to run human activities worldwide.

Recurrent overdependence on fossil fuels has, apart from not sustainably meeting energy demands, been bedevilled with such drawbacks like political instability, pollution and corruption, to mention a few. Consequently, Nigeria fits appropriately as a good case in this study when the backdrop of the oil resource-curse is revisited. The recent Niger-Delta unrest, the indiscriminate flaring of gas and oil-spillage by multi-national oil companies (MNOCs), as well as the gulf existing between demand and supply are daunting realities in the Nigerian energy polity (Malumfashi, 2007; Colwell and Greene, 2008).

European scientists have gone out of their way to research and develop better means of energy generation using the DESERTEC initiative to boost energy supply and reduce adverse environmental impacts. This initiative has been modelled to tap into the Middle East and North Africa's (MENA) cheap but unutilised deserts and seas in positioning a new brand of solar energy technology christened – Concentrated Solar Power (CSP). This technology will involve the construction of large solar plants that will drive power generating turbines to produce clean electricity for a greater percentage of

Europeans in a collaboration that will also benefit the MENA regions in electricity generation, job creation and fresh water supply.

Independent research has revealed that this technology can be replicated anywhere else in the world where similar potentials for operation exist; such that it could even be easier to implement in countries like Australia, China, India and the USA (Red Paper). In West Africa, the sub-region to which Nigeria belongs, the sun supplies 80 times more energy than is needed to run human activities every day with abundant opportunities for solar energy to be tapped in large quantities in Nigeria's north (Bala et al., 2000; Chineke and Igviro, 2008). The great potential for solar radiation in Nigeria is the primary drive of this research paper in contrast to MENA's initiative with the aim to model something similar for an energy starved country like Nigeria.

In order not to portray the DESERTEC initiative as seamless, it is noteworthy to establish that the few instances where drawbacks like initial high cost of generation have been identified and mentioned, it is still not enough to deny the benefits inherent in this project.

2. The conceptualization and branding of DESERTEC

DESERTEC is an ambitious contraction developed in North Africa by the DESERTEC Foundation and managed by the Club of Rome and Trans-Mediterranean Renewable Energy Cooperation (TREC) – an international network of scientists, politicians and other experts in the development and implementation of renewable forms of energy (Red Paper; Archibald, 2009; James, 2009).

The project founded in 2003, was officially launched by twelve European companies in a consortium led by Munich Re on 13 July 2009 (Red Paper). The consortium, which will be based in Munich, hopes to start supplying Europe with electricity by this year (2015) and aims to produce solar-generated electricity with a vast network of power plants and transmission grids across MENA regions.

The mandate of TREC among other things, includes to provide clean, cost efficient energy for EU-MENA as soon as possible and based on economic cooperation between the countries in the region, oversee the power from deserts as a supplement to European sources of renewable energy thereby speeding up the process of cutting European emissions of CO_2 and increasing the security of European energy supplies. In order to achieve this mandate, TREC embarked in the conduct of three preliminary studies which have evaluated the potential of renewable energy resources in MENA, the expected needs for water and power in EU-MENA between now and 2050 and issues relating to the construction of an electricity transmission grid connecting the EU and MENA (EU-MENA-Connection as in Figure 1).

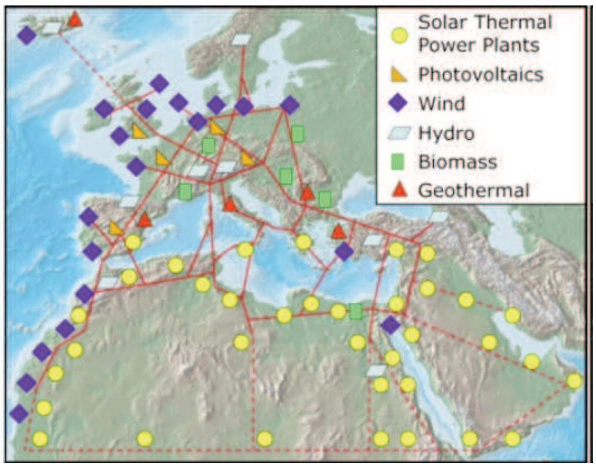

Figure 1: Euro-Super grid with a EU-MENA-Connection: Sketch of possible infrastructure for a sustainable supply of power to EU-MENA
Source: www.DESERTEC.org

The studies which were commissioned by the German Federal Ministry for the Environment, Nature Conversation and Nuclear Safety (BMU) with the German Aerospace Centre (DLR) taking the lead showed that, by using less than 0.3% of the entire desert area of the MENA region, enough electricity and desalinated seawater can be produced to meet the growing needs of these countries and of Europe (Red Paper). Power generation from wind energy is particularly attractive in Morocco and in areas around the Red Sea. Solar and wind power can be transmitted throughout the region via High Voltage Direct Current (HVDC) transmission lines, and to Europe with transmission losses up to 15%. Two of these studies, Concentrating Solar Power for the Mediterranean Region (MED-CSP) and Trans-Mediterranean Interconnection for Concentrating Solar Power (TRANS-CSP), which were conducted between 2004 and 2006, resulted to independent outcomes. The results of the MED-CSP and TRANS-CSP studies have been executively summarized (MED-CSP, 2005; TRANS-CSP, 2006).

Unlike the main results of the TRANS-CSP study, which analyses the renewable electricity potentials in Europe and their capability to provide firm power capacity on demand, the third study, Concentrating Solar Power for Sea Water Desalination (AQUA-CSP), covering aspects of solar desalination which was completed towards the end of 2007 highlighted several good reasons for the implementation of large-scale concentrating solar powered desalination systems for the provision of clean water for the parts of the MENA region. The main results identified within the AQUA-CSP study have also been summarized (AQUA-CSP, 2007).

3. Concentrating solar power and desalination of sea water: The TREC formula

The aims to harvest the sun's energy – using a method known as concentrating solar power (CSP), from the vast North African desert and deliver it as electricity via high-voltage transmission lines to markets in Europe is what the DESERTEC initiative is all about and so, an understanding how the basics of the system operates cannot be overstressed.

The technologies necessary to realize the DESERTEC concept have already been developed and some of them have been in use for decades (Red Paper; Trieb and Müller-Steinhagen, 2009). The fundamental principle behind the CSP is similar to every child who has ever burnt a hole in a sheet of paper with a magnifying glass. Curved mirrors known as 'parabolic trough collectors' are used to collect sunlight. The energy is used to heat water, producing steam, which then drives turbines and generates electricity.

A. Solar collectors

CSP entails focusing the sun's rays with a reflective surface and putting that energy to work in the form of electricity. Parabolic-trough systems (Figure 2) focus the sun's energy onto a tube running their length. Temperatures in the tube can reach 750 degrees F. A medium in the tube – sometimes synthetic oil that transfers its heat to water, sometimes water itself – collects heat to drive turbines. Large CSP projects – essentially expansive fields of solar collectors, or mirrors, that concentrate rays from the intense desert sun to heat water, generate steam, drive turbines and produce electricity – are not exactly new in Africa.

A wide range of concentrating technologies exists, including the parabolic trough; dish Stirling, concentrating linear Fresnel reflector, solar chimney and solar power tower. Each concentration method is capable of producing high temperatures and correspondingly high thermodynamic efficiencies, but they vary in the way that they track the sun and focus light.

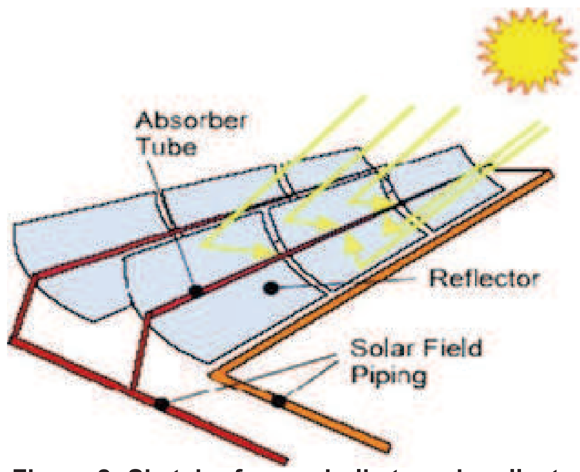

Figure 2: Sketch of a parabolic trough collector (A simplified alternative to a parabolic trough concentrator is the linear Fresnel mirror reflector)
Source: www.DESERTEC.org

However, the credit for favouring CSP over photovoltaic (PV) is supported in its ability to supply power on demand for 24 hours a day. Besides, PV is more expensive than CSP and needs expensive systems for storing electricity, such as pumped storage. The CSPs are known efficient fuel savers, which at the present produces heat at a cost-effective rate (MEDS-CSP, 2005; Pitz-Paal *et al*., 2005). Another feature that distinguishes CSP is the possibility of combined generation of electricity and heat to achieve the highest possible efficiencies for energy conversion (Trieb and Müller-Steinhagen, 2009).

B. Water tubes

The parabolic reflectors direct sunlight onto a tube suspended above their 200-foot lengths. Water inside the tubes boils and creates steam. The steam powers a 60–70 horsepower engine, which pumps 6,000 gallons of water per minute from the Nile River to nearby cotton fields. The system includes a number of technological improvements, including absorption plates with dual panes separated by a one-inch air space. The water can also be rechan-

Table 1: Capacity, costs and space: Development of the EU-MENA-Connection (marked 'HVDC') and Concentrating Solar Thermal Power (CSP) in the TRANS-CSP scenario between 2020 and 2050
Source: www.DESERTEC.org

	2020	2030	2040	2050
Transfer Capacity GW	2 x 5	8 x 5	14 x 5	20 x 5
Electricity Transfer TWh/y	60	230	470	700
Capacity Factor	0.06	0.67	0.75	0.80
Turnover Billion €/yr	3.8	12.5	24	35
Land Area km x km	15 x 15	30x30	40x40	50x50
CSP HVDC	3100x0.1	3600x0.4	3600x0.7	3600x0.1
Investment CSP	42	143	245	350
Billion € HVDC	5	20	31	45
Elec. Cost CSP	0.050	0.045	0.040	0.040
€/kWh HVDC	0.014	0.010	0.010	0.010

nelled to benefit agricultural demands.

C. Business advantages in solar power thermal plants

New solar thermal power plants with a total capacity of more than 2000 MW are at the planning stage, under construction, or already in operation. Favourable business conditions for CSP abound. For instance, where there is more sunshine, it is possible to realize cheaper feed-in tariffs, as for example, at good locations in Africa, America, China, India, Australia or MENA. In time to come, high initial investments will give room to long-term sustainable costs (Table 1). This is because the costs for raw materials for solar thermal power stations are rising more slowly than the price of fossil fuels. Therefore, CSP may become competitive earlier than previously expected (Red Paper).

D. High voltage direct current transmission lines

HVDC transmission has proved very reliable and much more efficient than the use of hydrogen as an energy vector. Using High Voltage Direct Current (HVDC) transmission lines, loss of power during transmission can be limited to only about 3% per 1000 km. Although there would be transmission losses up to 15% between MENA and Europe, they are more than offset by the fact that levels of solar radiation in MENA are about twice what they are in southern Europe. Furthermore, there is much less seasonal variation in levels of sunshine in MENA than there is in Europe.

E. Desalination of sea water – A by-product of the DESERTEC concept

The growing freshwater deficits in MENA will increasingly require seawater desalination which can be done using sustainable sources of energy. In brief, the DESERTEC initiative also enables the use of solar electricity for membrane desalination through combined solar heat and power for thermal seawater desalination to guarantee sustainability (Trieb and Müller-Steinhagen, 2009).

On the other hand, the considerable burden of desalination, though significantly reduced by the DESERTEC initiative, is not overlooked because the AQUA-CSP study analyses the environmental impact of a broad application of solar-powered seawater desalination to cover the expected freshwater deficits in MENA.

4. Harnessing DESERTEC concept for Nigeria and its comparative advantage

It is true that the advantages of DESERTEC for Europe look enormous; it frees the continent from dependence on Russian gas, rising oil prices, radioactive waste and CO_2-spewing coal power plants. Energy can be harnessed even at night such that excess heat produced during the day can be stored for several hours in tanks of molten salt. This way the turbines can produce electricity even when the sun is not shining. Moreover, the advantages for countries such as Libya, Morocco, Algeria, Sudan and especially Middle Eastern states, other than the solar power business triggering a truly sunny future, it would create jobs and build up a sustainable energy industry, which would translate to cash-inflow into these countries and an enabling infrastructure investment.

There is a similar advantage of DESERTEC for Nigeria's abundant solar reservoir. The annual average daily sunshine (measured with Campbell Stokes recorder) is 9 hours at the far northern boundary of Nigeria (Chineke and Igwiro, 2008)., this amounts to about 4.851x1012kWh of energy per day from the sun (Ojosu,(1990); Chineke, (2002).. Worth mentioning also is the fact that solar electric power could mean energy independence, economic value and environmental security. Above and beyond, it has the potential to supply a significant portion of the country's electric energy requirements, and lead to significant enhancements in living conditions, in sectors such as health services, communication, information and education. This form of electricity can also enhance the competitiveness of the country.

In the light of the present energy poverty in the country, production costs have been inflated leading to competition in the global market. Recent development have shown the preference of indigenous companies to relocate from Nigeria, where business has been qualified as being very expensive to sustain, to neighbouring West African countries where it is deemed cheaper. Indeed, access to electricity is a prerequisite for economic growth and sustainable livelihoods, and is thus a fundamental ingredient for the achievement of the United Nations Millennium Development Goals (Okoro *et al.,* 2006; Qurashi and Hussain, 2005; Modi et al., 2006).

There is no gainsaying that there is hope for Nigeria to turnaround its present deficiency in energy by implementing a national energy policy that substantially incorporates renewably energy which, no doubt, already exists on paper but lacks action as extensively reviewed in a recent research conducted by the authors Akuru, and Okoro (2010). This has been practised elsewhere and it is working.

Already, the DESERTEC concept which has been designed to insure the livelihood of mankind based on a lasting, developing, and peace supporting form of power production by bringing together political, economic, civil, and social interests can easily be duplicated in Nigeria with high probability of achieving the expected results. For example, other than an existing solar resource base, the fact that northern Nigeria is located inside Nigeria, technicalities for political, economic, and social furore are greatly reduced. The existing national supply grid can equally serve to support in the aspect of issues relating to the construction of an electricity transmission grid.

Whereas there has been extensive and on-going research as well as implementation of solar PVs and distillers for provision of clean water (Sambo, 2009); Committee on Creation of Science-based Industries in Developing Countries Development, Security, and Cooperation Policy and Global Affairs, 2008)], the possibilities for water desalination in Nigeria appear to be beyond the scope of this paper. However, it is hoped that with the prevailing pathetic situation of non-availability of clean and portable drinking water in northern Nigeria, research can be initiated to ascertain the prospects for exploiting it as an alternative to the provision of drinkable water. Similarly, the possibilities for wind power exists in the DESERTEC project as earlier mentioned and can be integrated into a concrete framework for Nigeria, who is equally endowed with abundant wind energy in the north.

It is equally certain that there will be creation of new jobs which will mean new sources of income for natives and nationals alike. Sharing or transfer of technologies is very possible in the long run for greater impact of results.

That the region in the north instead of the south would now be the hub of Nigeria's energy base is true to the fact, even if it may sound incongruous. This is because of the CSP plants can be used to meet both local and foreign energy demands which is expected to surpass whatever revenue that Nigeria gains from petroleum export at present.

5. Conclusion

The DESERTEC Concept has been termed sustainable, and it is so because according to its initiators, it meets all criteria for sustainability which is a necessary requirement for determined political support and action. The five focal points for national and international policy for all countries in EU-MENA support this claim (Trieb and Müller-Steinhagen, 2009).

1. Increase support for research, development and for the market introduction of measures for efficient supply, distribution and use of energy (efficiency focus).
2. Provide a reliable framework for the market introduction of existing renewable energy technologies, based on best practice experience and increase support for research and development for promising enhancements (renewable energy focus).
3. Initiate an EU-MENA-wide partnership for sustainable energy. Provide European support to accelerate renewable energy use in MENA (interregional cooperation focus).
4. Initiate planning and evaluation of an EU-MENA High Voltage Direct Current super-grid to combine the best renewable energy sources in this region and to increase diversity and redundancy of supply (interconnection focus).
5. Support research and development for shifting the use of fossil fuels from bulk electricity to balancing power production (balancing power focus).

Not only that, highpoints of opportunities for the MENA region has been brought to the fore and stressed in the light that duplicating it for any other scenario (available abundant solar), given the same conditions (congruent realizable framework), is very much possible. The basis for this hypothesis is that for countries like Nigeria where solar irradiation is high, similar or even better results can be obtained. Certain factors such as proximity of resource base, an existing electricity transmission backbone, and dwindling oil reserves due to overdependence and a non-renewability factor show that implementation in Nigeria can be achieved without difficulty. Clean water supply, jobs and income generation are other benefits that the DESERTEC initiative can lead Nigeria into if and when it is adopted.

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CONFERENCE PAPER

Efficiency analysis of an induction motor with direct torque and flux control at a hot rolling mill

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Abstract
This paper presents an efficiency analysis of an induction motor with direct torque and flux control at a hot rolling mill in South Africa. Two scenarios were evaluated: 1) where the induction motor was controlled at a constant speed with a variable thickness slab; and 2) where the speed of the induction motor was controlled according to the thickness of the slab. Both scenarios used the speed as reference to control the torque and flux of the induction motor. A comparison on the energy consumption of the induction motor for both scenarios was done by means of a detailed simulation model. The simulation model for this specific case study is explained in detail. The results obtained showed an increase in the efficiency of the induction motor from the original system (scenario 1) to the improved system (scenario 2). Part of this paper provides an overview on hot rolling mills.

Keywords: efficiency analysis; induction motor; hot rolling mill; direct torque control; flux control

1. Introduction

In this paper, the efficiency analysis of an induction motor with direct torque and flux control at a hot rolling mill in South Africa is presented.

The energy consumption of the induction motor is calculated and compared by means of a simulation model for the following two scenarios: 1) where the speed is kept constant with a variable thickness slab and 2) where the speed is controlled according to the thickness of the slab. Section 4 provides more detail on the results obtained from the simulation model for this specific case study.

A hot rolling mill plant near Witbank in Mpumalanga, South Africa, was investigated as a case study. The hot rolling mill plant has an installed capacity to produce 4000 MT of steel bars in a month. The monthly average production is currently 3400 MT (85% of the installed capacity).

The diameter of the bars being produced varies from 8 mm to 20 mm. The demand of the plant is 1000 KVA and the daily energy consumption is 10 MWh. The parameters and specifications of the hot rolling mill plant were used in the design process of the simulation model. Section 3 provides more detail on the simulation case study.

This paper provides an overview of hot rolling mills, a simulation case study where the specifications and parameters of the hot rolling mill plant near Witbank has been incorporated, results on the different scenarios and a conclusion on the results.

When metal is passed through a pair of rolls, it is termed rolling. Hot rolling occurs when the temperature of the metal is above the recrystallization temperature and cold rolling occurs when the temperature of the metal is below the recrystallization temperature (Degarmo, *et al.*, 2003; Roberts, 1983).

2. Overview on hot rolling mills

Figure 1 provides a diagram of a four-high hot rolling mill stand. This rolling mill is also known as a reduction mill. A slab is passed through two work rollers which reduces the thickness of the slab. The reduction in thickness is caused by a high compression force applied by hydraulic rams. The reduction in strip thickness causes a temperature rise at the roll gap, which is cooled by air and a lubricant solution (Pittner, *et al.,* 2011).

Hot rolling mills are usually equipped with sensors to measure the roll force at each stand, strip tension force, strip thickness, work roll speed, roll gap actuator (hydraulic ram) position and strip speed. The backup rolls are installed to provide rigid support to the working rolls and to prevent bending under rolling load (Pittner, *et al.,* 2011).

Figure 2 provides an overview diagram of the hot strip/rolling production process. After the refining and alloying processes (slab casting process), the molten metal is cast into semi-continuous casters of 10 – 25 Ton slabs (Achenbach, 2002).

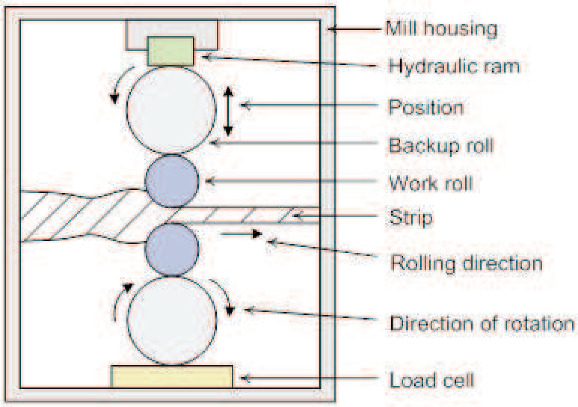

Figure 1: Four-high hot rolling mill stand

The slabs are then pre-heated in the pusher furnace and hot rolled by a single-stand hot rolling mill. The slabs are then passed through a tandem hot rolling mill, which provides strips with a thickness of 2.5 – 6 mm. The strips can then be coiled at a temperature of approximately 300°C (Achenbach, 2002). Schroder provides more detail on the mechanics of rolling mills (Schroder, 2011).

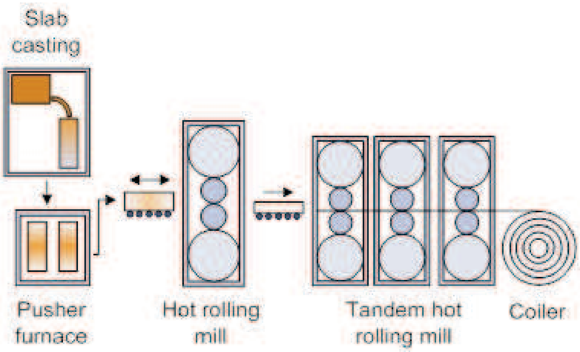

Figure 2: Hot strip/rolling production process

3. Simulation case study

This section provides the design of the simulation model from the specifications and parameters of the hot rolling mill plant.

Table 1 provides the parameters of the hot rolling mill. These parameters together with an adapted model of Blanchette, *et al.,* (2007) were used in the design process of the simulation model for this specific case study.

Figure 3 provides an overview of the control process for this specific case study. From the figure, it can be seen that a three-phase diode rectifier supplies a braking chopper. The braking chopper is a dynamic braking chopper with a DC bus capacitor which absorbs the energy produced when the motor decelerates.

The output of the braking chopper is connected to a three-phase PWM voltage source inverter which supplies the induction motor. A speed controller uses the speed of the induction motor (measured by means of a speed sensor). The speed controller uses a PI controller to produce flux and torque references for the DTC unit. The thickness of the slab is measured by means of a position sensor. A transducer converts this signal to a reference speed.

Table 1: Hot strip/rolling mill plant parameters

Parameter	*Dimension*
Distance between stands	3900 mm
Work roll diameter	505 mm
Backup roll diameter	1265 mm
Roll face	1870 mm
Rolling force	30,000 kN
Strip width	1235 mm
Overall reduction	80%
Asynchronous motor	110 kW

The torque and flux are calculated in the DTC unit and compared to their respective references. An optimal switching table is then used to generate the inverter switching pulses.

For scenario 1, the speed reference is kept constant and a variable thickness slab is selected. For scenario 2, the speed is controlled according to the thickness of the slab. More detail on the control of steel rolling mills is available at Pedersen, *et al.* (1998), Sbarbaro-Hofer, *et al., (*1992) and Ashok (2010).

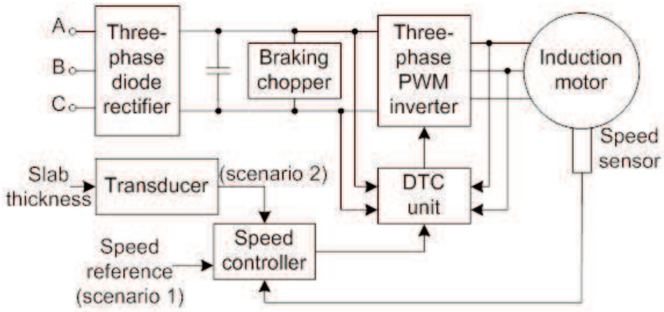

Figure 3: Overview of the control process

For the simulation model design as shown in Figure 4, an AC4 block from the SimPowerSystems™ library was used. The block models the direct torque control (DTC) induction motor drive with the braking chopper for the motor. A 110 kW induction motor (see Table 1 for the plant parameters) was used for this simulation.

The three-phase diode rectifier, braking chopper, three-phase PWM inverter, DTC unit and speed controller is simulated by means of the AC4 block. The AC4 block was adapted to incorporate the dynamics and parameters of this specific case study.

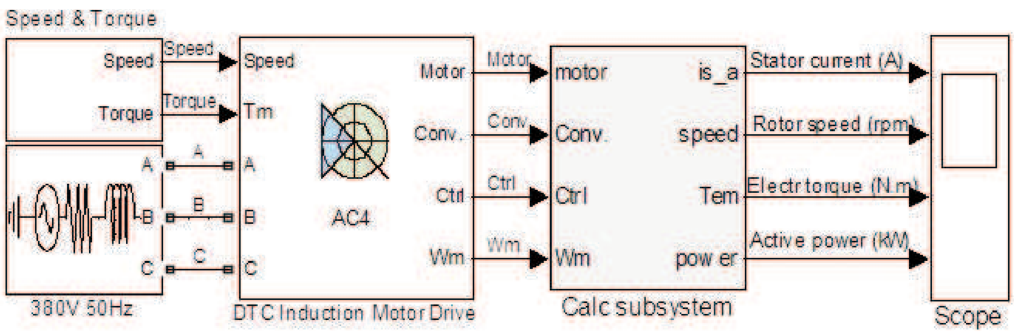

Figure 4: Overview of the simulation model

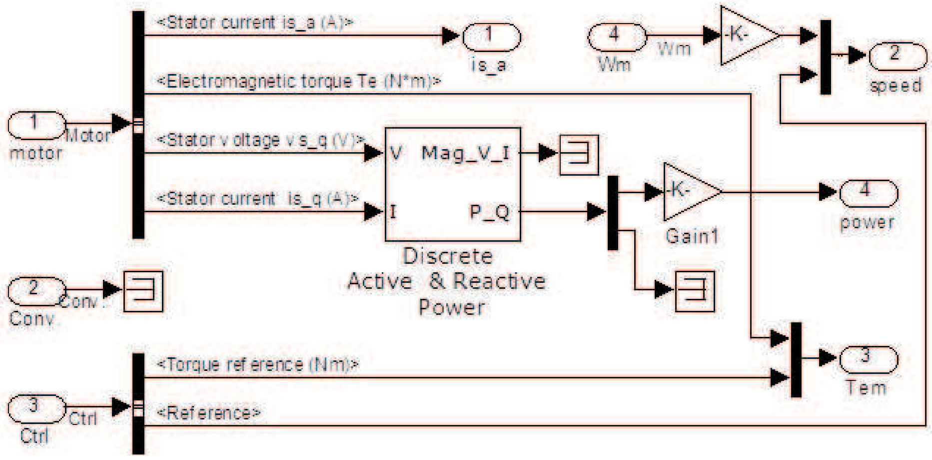

Figure 5: Calc subsystem

The speed and torque characteristics for the two scenarios are simulated by means of the speed & torque subsystem. Bose provides more detail on modern power electronics and AC drives (Bose, 2002).

Figure 5 provides the calc subsystem. This subsystem performs the calculations for the stator current, speed, electromagnetic torque and power. Grelet, *et al.*, 1997 and Krause, 1986 provides more detail on the analysis of electric machinery.

4. Results

This section provides the results of the simulation model for this specific case study. The results are divided into the following three sections: 1) scenario 1 (speed is kept constant with a variable thickness slab); 2) scenario 2 (speed is controlled according to the thickness of the slab); and 3) combined results (a comparison between the results of scenario 1 and scenario 2).

4.1 Scenario 1

In this scenario, the speed is constantly controlled at 150 rpm and a variable thickness slab is selected. In this scenario, the rotor is given 10 s to start-up before a slab is processed. Figure 6 shows the stator current, rotor speed and electromagnetic torque for this scenario.

The stator current peaks around 1500 A during start-up. The rotor speed dips the moment the slab enters the process. The actual speed (Data) then closely follows the control speed (Ctrl). The actual electromagnetic torque (Data) closely follows the control torque (Ctrl).

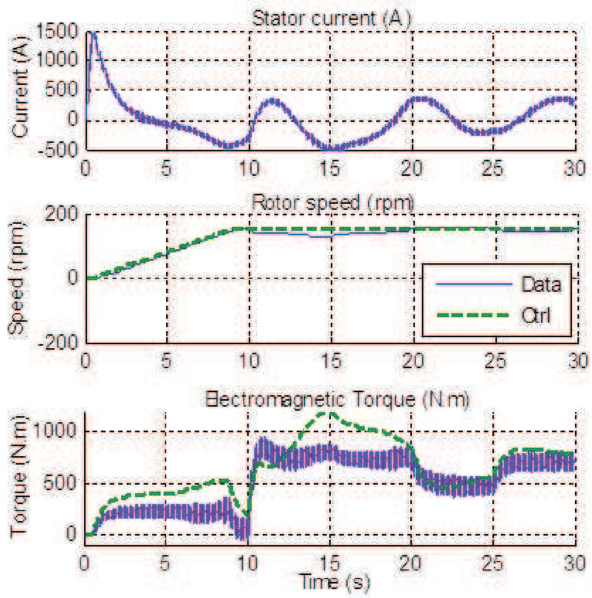

Figure 6: Scenario 1 – model analysis

4.2 Scenario 2

In this scenario, the speed is controlled according to the thickness of the slab. The same variable thickness slab is selected for both scenarios. In this scenario, the rotor is again given 10 s to start-up before a slab is processed. Figure 7 shows the stator current, rotor speed and electromagnetic torque for scenario 2.

The stator current again peaks around 1500 A during start-up and the rotor speed dips the moment the slab enters the process, but the speed is now controlled according to the thickness of the slab. The actual speed (Data) closely follows the control speed (Ctrl). The actual electromagnetic torque (Data) closely follows the control torque (Ctrl).

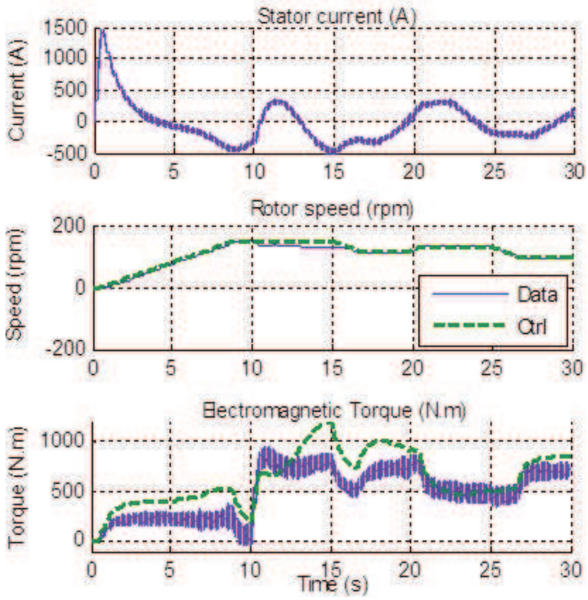

Figure 7: Scenario 2 – model analysis

4.3 Combined results

In this section, the active power for the two scenarios is evaluated. Figure 8 shows the active power and cumulative active power for scenario 1 and scenario 2. A lot of spikes are visible on the active power signals, and this is caused by the switching of the three-phase PMW voltage source inverter.

The result of the first 10 s for both scenarios is the same, since this is the start-up time of the rotor. Thereafter, different profiles can be seen. From the cumulative active power graph it can be seen that the cumulative power after 30 s for scenario 2 is less than that of scenario 1. The cumulative energy consumption resulted to an average improvement of 4.44% from scenario 1 to scenario 2.

5. Conclusion

In this paper, an efficiency analysis of an induction motor with direct torque and flux control at a hot rolling mill near Witbank(in Mpumalanga, South Africa, was done. The following two scenarios were evaluated: 1) where the speed is constantly controlled with a variable thickness slab; and 2) where the speed is controlled according to the thickness of the slab.

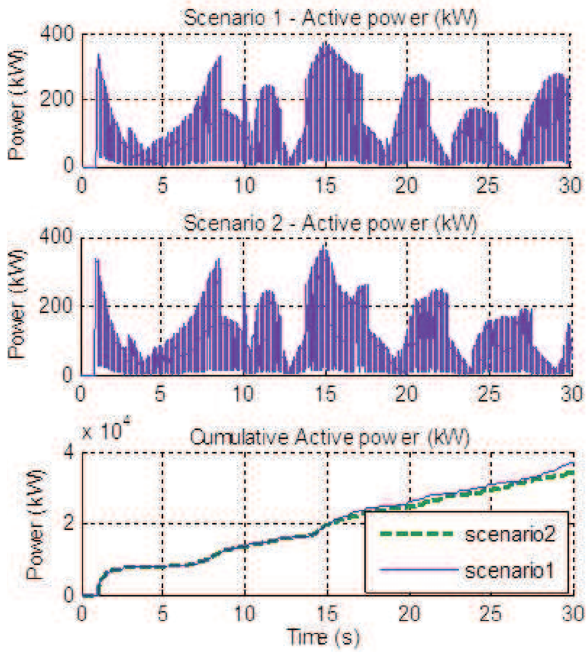

Figure 8: Combined power results

A simulation model was designed in Matlab® Simulink® in order to obtain results and evaluate the two scenarios. The specifications and parameters of the physical system were used in the design process of the simulation model.

From the combined results of the two scenarios, it can be seen that the cumulative power for scenario 1 is higher than that of scenario 2. The cumulative energy consumption resulted to an average improvement of 4.44% from scenario 1 to scenario 2.

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CONFERENCE PAPER

Contemporary wind generators

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Abstract

It is believed that wind energy is growing at a very rapid rate, especially in the last few years. When compared with other sources of renewable energy in the energy portfolio, it becomes evident that the bulk is wind energy-based. However, there are some backlogs to full manifestation of this technology ranging from initial high cost to performance and reliability issues, among others. But in spite of these bottlenecks, new research trends have been assertive in seeking out a sustainable solution for harnessing wind energy for power generation – especially in the design and construction of wind generators. In order to motivate and prime a sustainable energy mix among stakeholders, this paper is a shot at appraising the theory of these innovative wind generators towards ecological sustainability, economy, efficiency, and employment creation.

1. Introduction

Renewable energy is that source of energy which is abundant and continuously being replenished. No doubt, renewable energy comes with other benefits such as environmental friendliness, as well as being a source of electricity. The traditional means of generating electricity is by electrical generators running on fossil fuels e.g. petroleum and coal. The burning of fossil fuels to generate electricity is a dirty process, which leads to greenhouse gas (GHG) emissions *vis-à-vis* climate changes (Akuru *et al*, 2013).

While there are many sources of renewable energy, this paper will focus on wind energy, and it is too early to underscore this choice. In the interim, wind energy has been identified as the world's fastest growing source of renewable energy, growing at a worldwide average of 30% annually (Swift and Chapman, 2007), Figure 1 shows this growth. The global wind report for 2013 indicates that wind energy markets trends soared more in 2013 than ever before, and is anticipated to get even better in the coming years (Global Wind Report, 2014).

The bottlenecks associated with the implementation of wind energy for power generation is as much as its advantages and they continue to evolve with time. There are issues bothering largely on the unpredictable nature of wind speed and direction, grid integration, and trapping of excess wind power for storage. Others are site location problems arising from noise, and habitat nuisance. The issue of transmission is also worrisome because wind power sites are usually remote from urban locations where the utility services are. Most of these problems lead overall to high initial capital costs, which have contributed to a growing quest for improvement in wind generator designs, as well as other components comprising wind energy conversion (WEC). Consequently, the focus here will be on the new generators that are being developed in order to make wind power generation more efficient, cheaper, and cleaner.

The process of converting wind energy to electricity is rather involved, moving through various interconnected stages. The next section is dedicated to offer a basic description on the operational background of the wind generator technology. Following after, Section 3 will review the conventional wind generator concepts which will provide a background for further deliberating on the newer models in Section 4. The paper finishes with some concluding remarks in Section 5.

2. Overview of wind generator technology

A good historical account on how the WEC technology started can be obtained from Ackermann and Söder (2005).Basically, the conversion is per-

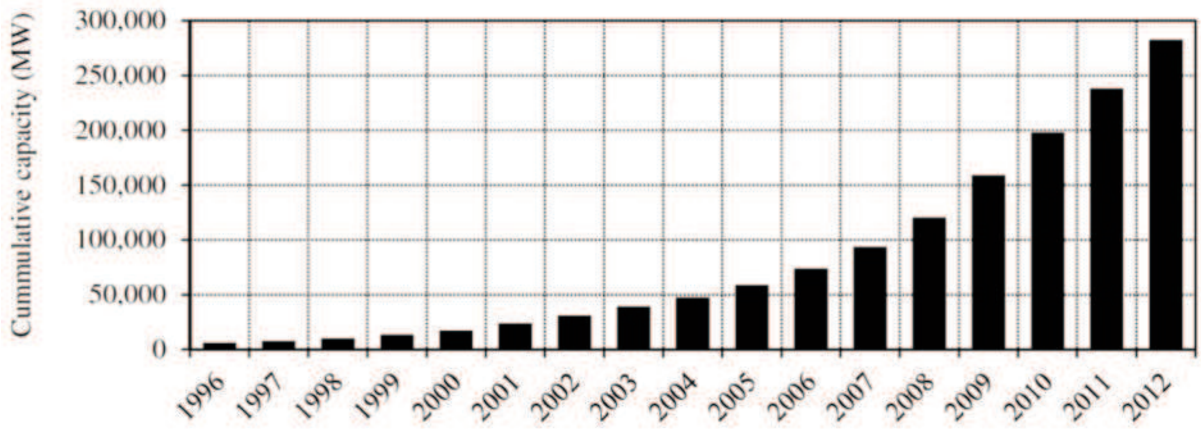

Figure 1: Wind energy: growth of worldwide cumulative installed total
(Potgieter, 2014)

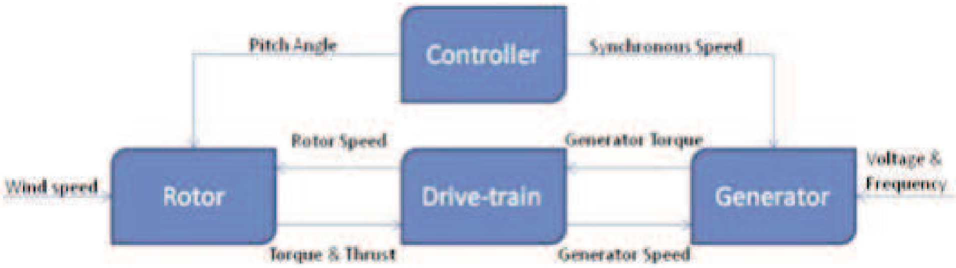

Figure 2: Process flowchart of a typical WEC system

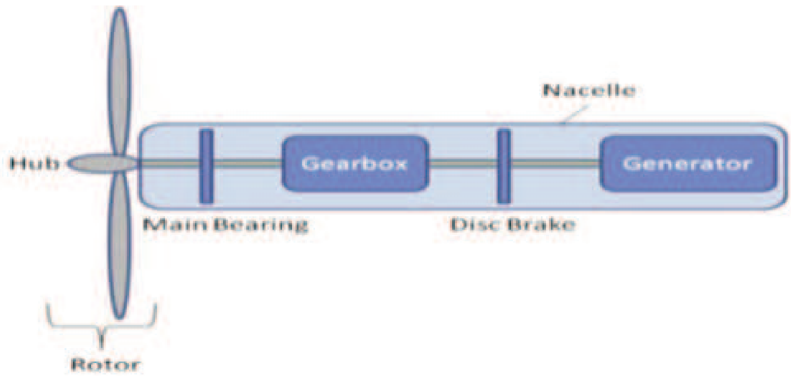

Figure 3: The main parts of a wind turbine

formed according to the flowchart as shown in Figured 2. Normally, wind energy is incident on a *rotor*, which then uses the mechanical energy produced to drive a *generator* that produces electricity, though the *interconnection* and *control* systems are also necessary components (Chang, 2002). This shows that the wind generator only forms a part of a complex WEC system called the wind turbine (Figure 3).

There are two basic configurations of wind turbines based on their axis of spin – the vertical axis (VAWT) and horizontal axis (HAWT) wind turbines – with the HAWT being the dominant model. The HAWT consist of a nacelle mounted on a tower. The nacelle is the part which contains the generator, the gearbox and the rotor. The gearbox provides options for altering the speed of the rotor to match the generator requirements. However, direct drive structures exist where *newer generator designs* are directly coupled to the rotors of wind turbines. The presence of gearboxes is usually responsible for the audible noise in wind turbines.

A wind turbine can also operate based on constant (fixed) or variable speed profiles, with variable speed offering greater efficiency. This is responsible for the system to be either geared or direct-drive generator types. Constant speed means that the wind turbine rotor speed is fixed irrespective of the wind speed, and it is determined by the grid frequency. The disadvantage of the constant speed system is its limited speed range leading to lower efficiency during wind fluctuations.

On the other hand, the power quality in variable speed systems is much better when compared with the constant speed systems due to a wider speed range, increased energy capture and reduced acoustic noise during wind fluctuations. To achieve variable speed mode, power electronic converters are used to provide constant frequency and constant voltage to the grid, whereas the rotor can independently vary. The disadvantage of the variable speed profile is more complex control and higher costs. Besides, wind turbines can be grouped into small, intermediate and large systems based on their output power capacity as shown in Table 1.

Wind speed is critical to the performance of a wind turbine; the stronger the wind the more power that will be available. As a matter of fact, doubling wind speed results in eight times more power considering the wind turbine output power expression in Abad *et al*. (2011) recalled in (1); where, P_t is power recovered from wind energy, ρ is air density, R is radius of wind turbine, V_v is wind speed and C_p is the power coefficient. Other factors that determine the power output include height of the turbine and air temperature.

$$P_t = ½\rho\pi R^2 V_v^3 C_p \quad (1)$$

In essence, wind generator technology is defined by four stages (Munteanu *et al.*, 2008):

- The turbine rotor which interacts with the incoming wind;
- The drive trains which either transforms or couples the speed of the rotor to match with that of the generator;
- The generator that converts mechanical energy which it receives into electrical power; and
- The electronic and electrical subsystem for control and grid interconnection.

Table 1: Power rating of wind turbine systems

Wind turbine	*Power rating*	*Typical load coverage*
Small	Less than 100 kW	Single homes (Off-grid)
Intermediate	10-250 kW	Villages or cluster of homes (Off-grid)
Large	Several MWs	Wind farms (Grid-connected)

3. Conventional wind generator models

The generators for wind turbines come in various structures, speed capabilities and sizes. Synchronous generators (both PM and non-PM types), as well as squirrel cage (SCIG) and wound-rotor (WRIG) induction generators have been used for small, medium and high power wind turbines. However, DC generators are not popular because of high maintenance requirements due to brushes and need for DC-AC inverters.

3.1 SCIG

SCIG are typically applicable to constant-speed systems with direct grid-connection, but with some disadvantages during *gusty* winds. In steady-state, the machine operates in over-synchronous regime – synchronous speed exceeded by grid frequency-imposed rotational speed. The set-up of SCIG is shown in Figure 4a, and a summary of its advantages and disadvantages is shown in Table 2. To overcome the power factor issues, SCIG are equipped with capacitor banks for reactive power compensation. Also, when full converters are implemented, there is complete control of the active and reactive power exchanged with the grid (Abad et al., 2011). The soft-starter act to regulate the inrush currents during grid connection.

3.2 WRIG

A quick fix to SCIG is the WRIG (Figure 4b), which is incorporated with a variable external rotor resistor which can be adjusted to control the slip (0–10%) of the generator, making it a basic variable-speed WEC system. This generator does not require slip rings because the additional variable rotor resistance can be changed using an optically controlled converter mounted on the rotor shaft. The control of the slip enables the power output in the system to also be controlled, and the fluctuations can be reduced.

3.3 DFIG

The doubly-fed induction generator (DFIG) is in a class of fully developed variable-speed generators, even though it is *usually* an improved WRIG version. It is acclaimed to be the leading technology in wind energy generation in recent years (Abad *et al*., 2011). As shown in Figure 4c, the *doubly-fed* connotation is as a result of this variety of WRIG being connected directly to the constant-frequency grid on the stator, while the rotor is fed by a back-to-back (AC-AC) converter that is also connected to the grid. The stator outputs power into the grid, while the twin converters control the generator active and reactive power on the rotor side and DC-link voltage on the grid side, respectively. It is mentioned that the size of the converters is not rated to the total generator power but to the selected speed variation range (Ackermann and. Söder, 2005).

When the slip is negative, the rotor feeds power into the grid and it absorbs power from the grid when the slip is positive, demonstrating that power flow is *proportional to the slip*. The main characteristics of DFIG have been summarised as follows (Abad *et al.,* 2011):

- Limited but wider operating speed range (±30%);
- Small-scale power electronic converter (reduced power losses and price);
- Fully decoupled active and reactive power control;
- High maintenance due to slip-rings;
- Presence of gears.

Table 2: Basic features of SCIG

Advantages	*Disadvantages*
Mechanically simple	Low full load power factor due to active and reactive power compromises
Low maintenance cost due to absence of brushes cost	Electrical fluctuations as a result of mechanical stress
Very robust	Limited control
Very stable	Need for gears
Higher efficiency is possible with two winding sets for low and high wind speed (variable) operations or combined effect of two SCIG	

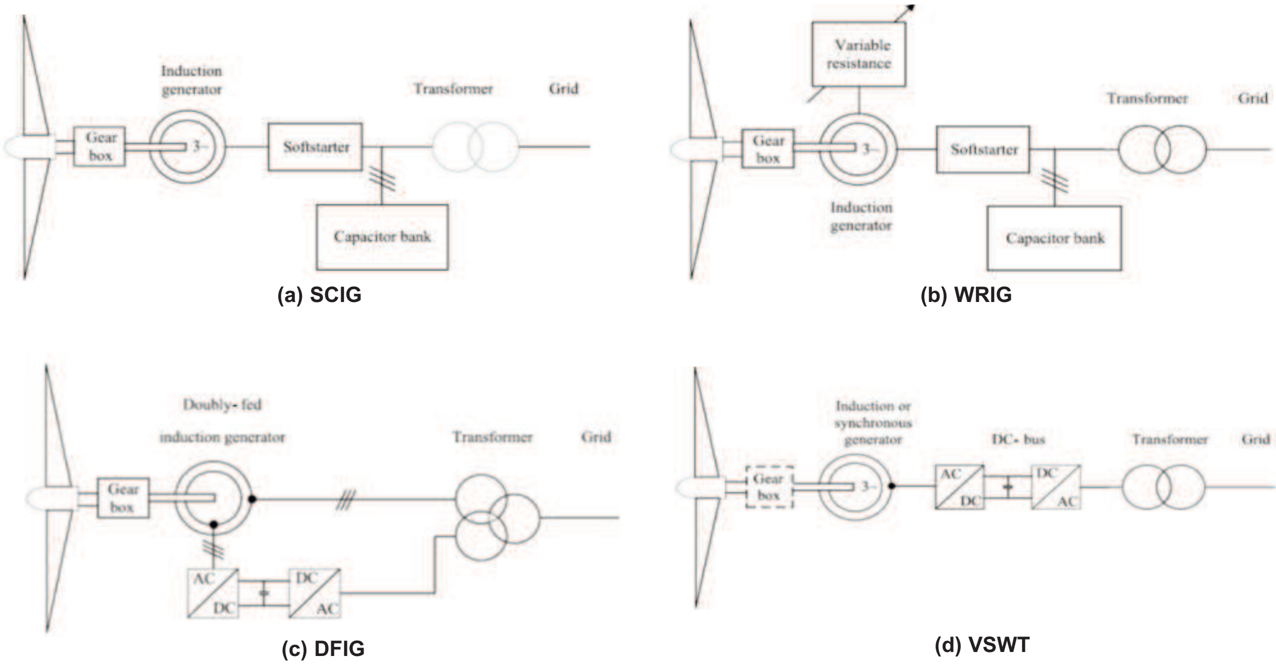

Figure 4a-d: Topologies of conventional wind generators (Munteanu *et al.,* 2008)

3.4 Synchronous generators

Synchronous generators which is the brainchild of modern wind generators, can either be wound-rotor (WRSG) or permanent magnet (PMSG), with the latter gaining more popularity due to key features such as considerable reduction in volume of excitation systems, higher air gap magnetic flux densities, better dynamic performance, and nowadays cheaper options (Gieras, 2008). They operate similar to DFIG with a back-to-back converter (rated to the generator power), but with higher efficiency. The grid-side converter provides voltage regulation, and the rotor of the wind turbine is not at a risk of losing synchronism because it is isolated from the grid. It can be operated as fixed speed or variable speed systems, offering advantages such as *one-way* speed control, wider speed range and longer air gaps which helps to improve stability (Madani, 2011).

The advantage of WRSG over PMSG is that it can by itself produce reactive power which it uses to regulate better voltage; however, because of the need of brushes it is usually limited among such wind generator options. Moreover, unlike PMSG, weight and size of WRSG increases sharply as pole numbers increase.

Salient pole PMSG operate at low speeds because of its higher pole numbers, and thus *may not* be geared for low and medium speed applications as pictured in Figure 4d. In WEC systems, a set-up without a gearbox offers huge advantages in that it removes the unconventional transformation from very low speeds to higher speeds. Synchronization during start-up, voltage and reactive power regulation and demagnetization due to high temperature exposures are some concerns in PMSG applications that are attracting renewed research. Overall, the many advantages of SG make them superior to IG as wind generators, its significant weight reduction being fundamental.

4. Design trends in contemporary wind generators

In the last three decades, progress in wind electric machine technology has seen newer topologies developed. Ragheb (2010) listed five major developments that describe modern wind machines as:

- Design of hub structures;

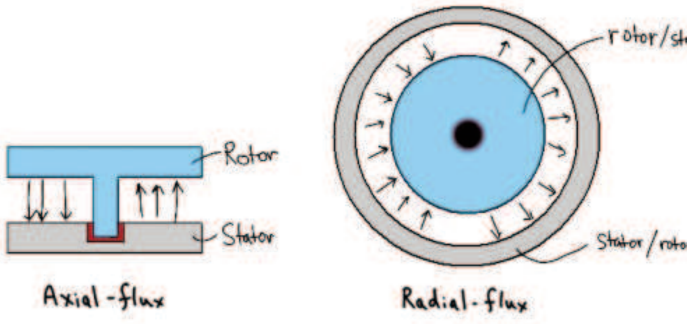

Figure 5: Cross section of axial and radial flux direction in a typical PMSG, respectively

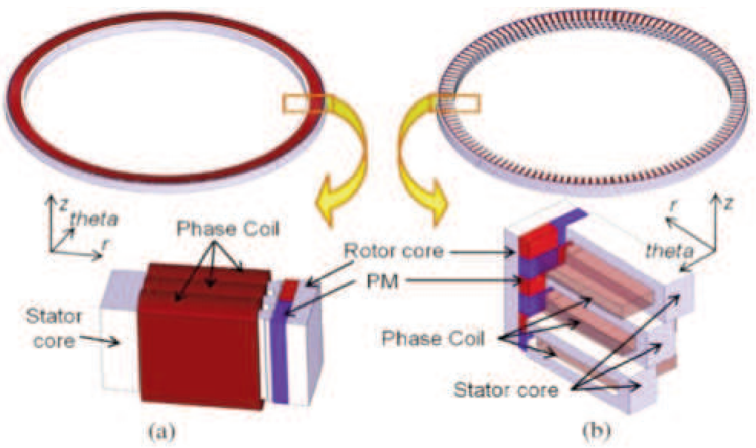

Figure 6: Cut-out of (a) LFM, (b) TFM

- Increase in higher capacity turbines reaching 5-10 MW;
- Preference for variable speed turbines;
- Adoption of gearless wind turbines;
- Evolution of permanent magnet excitation.

In another instance, Gieras (2008) identified some concepts that drive the technology advancement of electric machines today to include mechatronics, microelectromechanical systems (MEM), superconductivity (SC), solid state converters, energy conservation, power quality and sustainability. Gradually, there is a shift from the conventional wind generators which we have known to very unusual designs that offer superconducting excitation systems, efficient control, excellent power quality, weight and size reduction, environmental friendliness, improved performance, increased reliability, and even cost effectiveness. Some of these generator concepts are further discussed.

4.1 PMSG

In Madani (2011), the choice of PMSG for his wind generator design is predicated on the fact that they are more amenable to higher torque densities when compared to other contemporary machines for the same weight and size. However, since cost remains a major concern with PMSG, various topologies are being innovated for low speed and variable speed applications.

4.1.1 Air gap orientation

Axial flux (with disc type rotors) and radial flux (with cylindrical rotors) are two ways in which air gap orientation can be defined in PMSG as shown in Figure 5. If the flux direction is perpendicular to the axis of the air gap, the machine is called radial; whereas, if it is parallel with the air gap axis, it is axial. The conventional types of PMSG used in wind systems are radial machines (RFPM), and because of its popularity, cost of production is lower. Axial flux (AFPM) topologies have been the earliest electrical machines but were shelved for RFPM due to the following reasons (Gieras et al., 2008):

- Strong axial (normal) magnetic attraction force between stator and rotor;
- Fabrication difficulties in making slots;
- High cost of manufacturing;
- Difficulty in assemblage and air gap construction.

In recent times, breakthroughs in PM materials have revived the interest in axial flux machines, which possess high torque density and compactness, and are good candidates for low-speed direct-drive wind systems since a large number of poles can be accommodated. However, a major drawback of AFPM is its very complicated manufacturing process.

4.1.2 Direction of magnetic field loop

Based on the flux path, electric machines can be categorized as longitudinal flux machines (LFM) or transverse field machines (TFM) - (see Figure 6). LFM has their flux path longitudinal or axial to the direction of motion, while TFM flux lines lie in planes transverse to direction of motion and their windings are torus or ring shaped. LFM are the conventional machines, having concentrated or distributed windings, and are good for direct drive applications because of their high torque and low torque ripple characteristics. TFM also possess high torque densities, but they possess torque ripples. The potentials of TFM in the wind system are manifest in their capacity to produce more power densities than conventional machines and have been suggested for large direct-drive PM wind generators due to its active mass reduction (Bang, 2010).

4.1.3 Rotor positioning

There are two possibilities on the position of rotors in wind generators – internal and external rotors (Figure 7). In external rotors, the rotor surrounds the stator outer diameter and usually houses the magnets in their inner circumference. The advantages of this structure are that the rotor is equipped with a greater pole number and can provide good support for the magnets. Outer rotors have been used in small HAWT. On the other hand, inner rotor machines are more common in wind generator applications, where they offer better cooling for the armature windings placed on the stator.

4.1.4 Magnet arrangement
PMSG can also be categorized based on the magnet arrangement in the rotor. The commonest types are the surface mounted permanent magnets (SMPM), where the magnet is mounted on the surface of the rotor. SMPM is the preferred configuration because of simple rotor geometry where there is no saliency, but there is high risk of demagnetization. Others are, inset and buried magnets. In inset machines, flux leakage is high because there are iron interpoles which create saliency. But in comparison with SMPM, they possess higher torque density due to additional reluctance torque making them good candidates for direct-drive applications in wind generators.

Inset machines are also called interior permanent magnet (IPM) machines. A major advantage of this structure is that weak PM materal such as ferrite can be employed. It is also good in preventing demagnetization. This topology is applicable in high-speed wind systems due to mechanical strength of the rotor against centrifugal force, but it is fraught with high flux leakage.

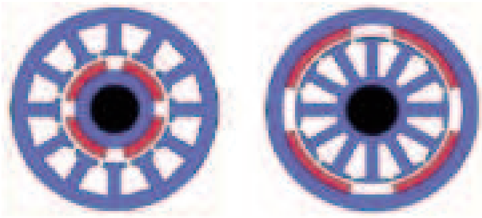

Figure 7: Internal (left) and external (right) rotor PMSG

4.1.5 Winding selection
Two types of windings are overlap and non-overlap windings. Overlap windings are the conventional windings which can either be distributed or concentrated. Distributed winding is associated with long end windings that result in higher copper losses and longer axial lengths, a key disadvantage. Contrary, concentrated windings are built with shorter end windings that lead to reduced joule losses, high efficiency and fault-tolerant applications in PMSG for wind systems.

Concentrated winding is a terminology which is becoming familiar with non-overlap windings. Non-overlap (fractional-slot) windings bring an improvement to traditional concentrated windings in that it is possible to have reduced mutual coupling among phases, reduced manufacturing costs, low torque ripple, as well as higher winding factors and higher

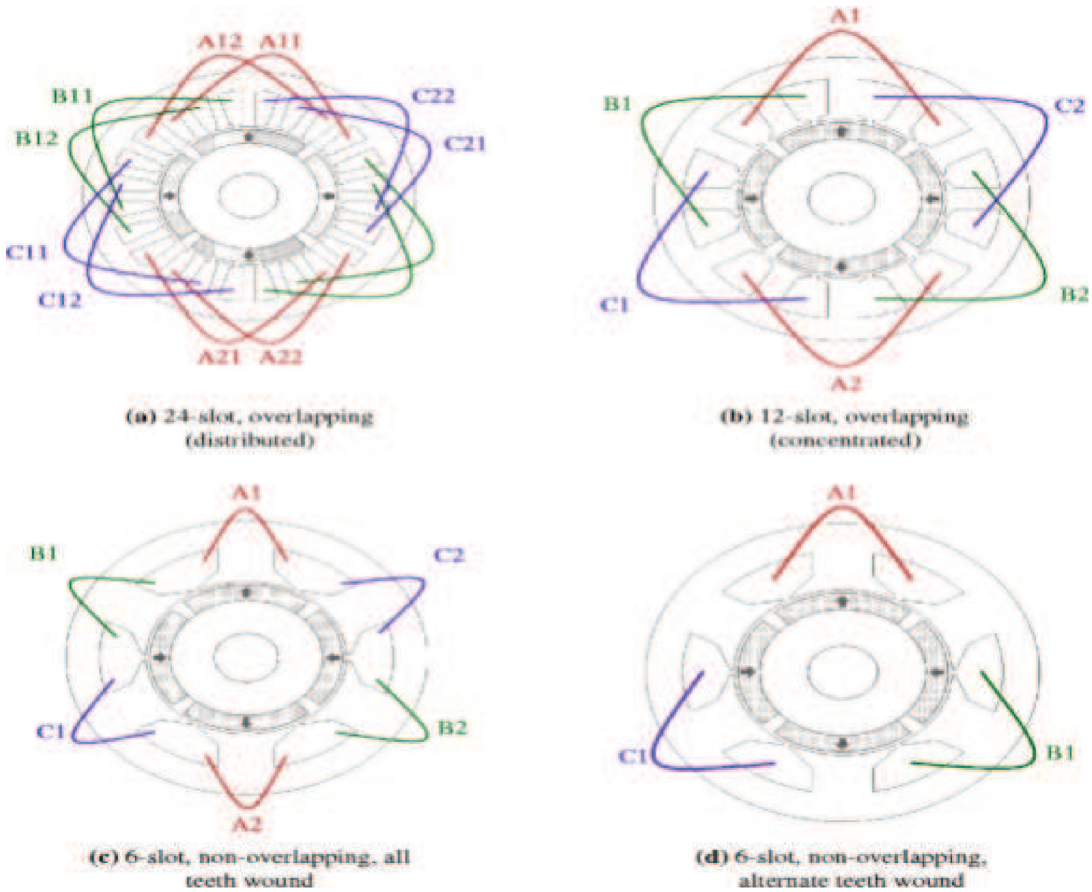

Figure 8: Typical stator winding configurations

torque densities. Multiple layers are possible as this reduces the harmonic content of the MMF which is a major drawback. It is reckoned that these MMF harmonics cause an alternating magnetic field in the rotor giving rise to rotor losses (Libertt and Souland, 2003). It has also been reported that employing concentrated windings in PM generators for low speed direct-drive applications is very attractive because of their simple structure, higher pole numbers and shorter-end windings (Gieras *et al.,* 2008). Figure 8 shows the various winding configurations discussed.

4.2 Drivetrains

Two drivetrains have been mentioned earlier: geared and direct-drive (gearless) systems. Until recently, wind generation systems consisted of a gearbox connected to high-speed variable speed generators. Today, wind energy systems can be distinguished by the presence or absence of gears. Gearless systems are still very new, and are largely due to advances in PM generators.

4.2.1 Geared

The function of a gearbox is to transform mechanical speed from low to high speed by means of a step-up system. Two main configurations in use are the single-stage (1G) and three-stage (3G) geared drivetrains. In the 1G concept, the generator, gearbox, main shaft, and shaft bearing are all integrated within a common housing. Multiple-gearbox schemes like the 3G concept is designed to further reduce the generator size and improve efficiency in variable wind concepts, and is usually connected to a full-scale power converter leading to losses more than in the other drive concepts. Moreover, it is costly, decreases drive efficiency and needs maintenance. The main advantage of geared systems is their ability to ensure a wider speed range.

4.2.2 Direct-drive

This concept requires that SG is directly connected to the turbine without making use of gears. Actually, WRSG and PMSG are applicable to this technology, but the future is more with PMSG. The advantages of this scheme are simple drivetrains, high efficiency, reliability, low speed applications and absence of noisy gear boxes, thus making it a cheaper bargain. There are also hybrid drivetrain systems that utilize a medium-speed generator, which combines fewer gearing stages and converter-fed PMSG.

4.2.3 Full converter concepts

There are three converter concepts based on the speed drivetrain of a wind generator, namely; high-speed (HSFC), medium-speed (MSFC) and low-speed (LSFC) full converter concepts. Their characteristics are summarised in Table 3.

Table 3: Electrical drivetrain concepts

Parameter		HSFC	MSFC	LSFC	
Speed range		2000 rpm		500 rpm 30 rpm	
Weight	Lowest	Intermediate		Highest	
Size	Smallest	Intermediate		Largest	
Gearbox	Present (3G)		Present (2G/1G)		Absent
Generator Synchronous		Asynchronous/Synchronous Synchronous			

4.3 Power electronics

Another concept that has impacted the development of new wind generators is the strides recorded in power electronics technology. Power electronics have developed various topologies of converters such as back-to-back, matrix and multi-level converters. Some of the achievements of power electronics by means of efficient power converters are in gearless variable speed control, power amplification, power conversion, grid interconnection, and frequency/voltage regulation. Although, a major setback is that they contribute to overall system losses and cost implications.

4.4 Innovative wind generator concepts

Before now, the dominating wind generators have been DC commutating machines, AC induction and AC synchronous machines. Presently, there are far too many other concepts for wind generating systems that cannot be fully debated in this paper because they are either both developed but are yet established for wind generating systems, or are still relatively new and are being tested, or have been proposed and information about them is very scanty. However, a number of them will be mentioned here for reference purposes:

- Synchronous reluctance generator (SynRG) (Tokunaga *et al*; 2011)
- Switched reluctance generator (SRG) (Choi *et al,* 2014);
- Brushless DFIG (BDFIG) (Long *et al*., 2013);
- Split–PM induction generator (S-PMIG) (Potgieter, 2011);
- Slip synchronous–PM generator (SS–PMG) (Potgieter, 2014);
- Switched-flux generator (SFG) (Sulaiman *et al.,* 2013; Kayano *et al.,* 2010; Ojeda *et al*., 2012)
- Ferrite–assisted reluctance synchronous generator (FA–RSG) (Baek *et al,* 2009);
- Magnetic gears and pseudo–direct drive (Wenlong, 2011);
- Superconducting machines (Jensen et al, 2013);
- PM Field–intensified synchronous reluctance generator (FI–RSG) (theoretical).

4.5 Leading manufacturers and countries

There have been a number of manufacturers leading the research, design and production of wind turbine concepts and generating systems worldwide.

Key among them are Vestas (Denmark), GE (USA), Enercon (Germany), Gamsea (Spain), Suzlon (India), Siemens (Germany), Repower (Germany), Nordex (Germany), Ecotècnia (Spain), Mitsubishi (Japan), JSW (Japan), ScanWind (Norway), Vensys, STX Windpoer, EWT, MTorres, Leitwind, and Goldwin (Ragheh, 2010; Bang, 2010). Over the years, some of these manufacturers get bought over by larger companies; for instance GE bought ScanWind in 2009. Vestas Wind Systems A/S is the largest manufacturer in the world with a total 51547 wind turbines installed at a capacity of over 31 188 MW in 73 countries (Vestas, 2014).

The world leader in wind power installed capacity is China with over 90 GW installed capacity, while Germany remains Europe's superpower at 34.25 GW (Global Wind Report, 2014). Egypt has the largest capacity in Africa at 550 MW, followed by Morocco and Ethiopia. The recent annual growth in wind power installations have been put at 12 per cent, and certainly this trend will continue to intensify.

5. Conclusion

Wind generators are integral to wind energy conversion systems as revealed by the review undertaken in this paper. Little wonder, the vista of electrical machines in recent years, where wind energy has received growing attention, has surpassed any era of its existence. This is evident in the fact that all aspects of the traditional electrical machine is being dissected and routinely transformed to meet growing demands of this time. There are many considerations for this development as already highlighted in this paper that have specially considered one category of electrical machines – wind generators. The advantages of wind power generation, in spite of obvious challenges, are huge. Wind power generation leads to cleaner power options, as well as a source of income. There are many other benefits like the impact of computational modelling and simulation that are critical to contemporary designs of wind generators, but have not been expounded here. Therefore, the emphasis of this revision is an immediate call to action for sustained renewable energy deployment as an *immediate* alternative to fossil fuels, bearing in mind that wind is abundant, more amenable to large power capture, safe, and somehow, cheap.

Also worthy of mention, is the fact that electricity generation have always been electrical generator-based and so, wind energy generation is closest to conventional electricity generation, as what is only required is to change the source of fuel in these machines into wind. The potential of using modern wind generators in sites where wind supply is very low has been demonstrated (Kayano *et al.,* 2010), making it attractive for all and sundry. Then of course, there is the increasing drive for research and development in wind power generation and the promise it holds for a sustainable energy mix. Last of all, one remarkable revelation in this evaluation is the bias for direct-drive applications in the design of modern wind generators.

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CONFERENCE PAPER

Impact of renewable energy deployment on climate change in Nigeria

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Abstract

It is well known fact that the rate of industrial growth of any country is a function of the amount of energy available in that country and the extent to which this energy is utilized. The burning of fossil fuels to generate energy is a dirty process. Greenhouse gas (GHG) emissions result when fossil fuels are produced and consumed and these emissions contribute to climate change. Nigeria as a country is highly vulnerable to the impacts of climate change because its economy is mainly dependent on income generated from the production, processing, export and/or consumption of fossil fuels and its associated energy-intensive products. Hence, it is on this premise that this paper is researched to review the energy sources being used in Nigeria and investigate its impact to climate change. Findings reveal Nigeria's over-dependence on fossil-generated energy with associated adverse environmental effects, among other things. Recommendations for the integration of renewable energy into Nigeria's energy mix, beyond other measures, have been offered, especially with reference to the salient environmental benefits that accrue to it.

Keywords: Climate change, fossil fuels, GHG emissions, renewable energy

1. Introduction and brief literature highlights

Energy is an essential ingredient or tool for socio-economic development and an index of prosperity in any nation (Akuru and Animalu, 2009). It is one of the basic requirements of human society and vital for human life and for technological advancement. In general, energy can contribute to widening opportunities and empower people to exercise choices. The place of energy and power in the sustenance of economic activities, and their contribution to the standard of living cannot be over-emphasized for any nation. As a result, the demand for energy today is far greater than ever in our highly technological world.

In Nigeria, energy is the mainstay of growth and development because it serves as a tradable commodity for earning the national income, which is used to support government development programs (Sambo, 1997). Due to population growth, inevitable industrialization, more agricultural production and improving living standards, Nigeria needs more energy to meet the rising demand. It also serves as an input into the production of goods and services in the nation's industry, transport, agriculture, health and education sectors, as well as an instrument for politics, security and diplomacy. The energy chain to deliver these cited services begins with the collection or extraction of primary energy, which is then converted into energy carriers suitable for various end-uses.

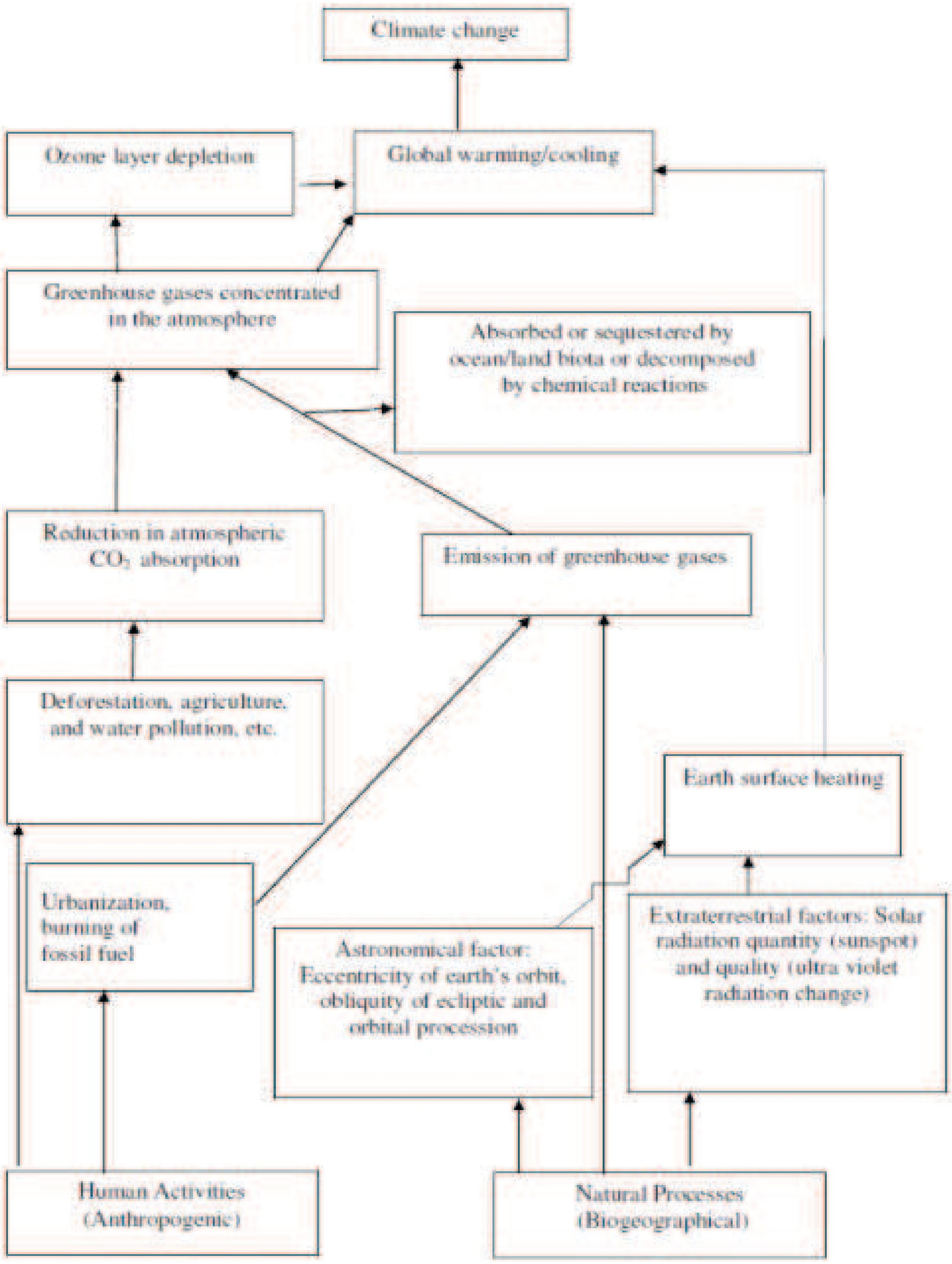

Figure 1: Causal factors of climate change

Source: Odjugo, 2010

In an earlier paper (Akuru and Okoro, 2010), the statistics of energy and its contribution to Nigeria's GDP has been set forth, though these values could increase if over 90% of energy used by rural dwellers is accounted for. Currently a high proportion of Nigeria's total energy output is generated from fossil fuels such as oil and coal. In general, the quest for an option to conventional power schemes for extension to remote and rural locations of developing countries like Nigeria arises from the high costs associated with the extensions, as well as the maintenance, of the power grid system to rural areas. This has led to a considerable interest in the development and application of renewable energy resources. Interest in renewable energy has traditionally grown from the need to expand energy resources to reach remote and rural locations. However, the use of conventional sources and fuelwood to generate energy has continued to generate dire environmental consequences.

Renewable energy is that form of energy obtained from sources that are essentially inexhaustible, unlimited and rapidly replenished or naturally renewable such as wind, water, sun, wave, refuse, bio-fuels etc. Nigeria is endowed with sufficient renewable energy resources to meet its present and future development requirements as well as complement its current oil-dependent economy

(Akuru and Okoro, 2010; Nigeria's First National Communication, 2003).

Greenhouse gas (GHG) emissions are produced when fossil fuels are produced and consumed and these emissions contribute to climate change. Climate change is caused by two basic factors (Odjugo, 2010), which include natural processes (biogeographical) and human activities (anthropogenic) summarized in Figure 1. Nigeria as a country is highly vulnerable to the impact of climate change because its economy is mainly dependent on income generated from the production, processing, export and/or consumption of fossil fuels and associated energy-intensive products Nigeria's First National Communication, 2003). It is well established that the activities of developed nations are mostly accountable for climate change, but developing nations are those suffering more due to inability to cope as a result of poverty and low technological development (Odjugo, 2010).

Several studies have focused on climatic impacts in Nigeria and the results are appalling (Odjugo, 2010; Odjugo, 2005; Chindo and Nyelong, 2005; Adefolalu *et al.,* 2007; Odjugo, 2010). Other independent studies have linked climate change with the economy (Yahaya *et al*., 2010) and global warming) of Nigeria (Odjugo, 2011). The spill over effects of climate changes are increasing temperature (global warming), sea level rise leading to population displacement as well as land disputes, draught and desertification, unpredictable rainfall with negative impacts on agriculture, human health problems, etc. On the other hand, the visible effects of climate change have resulted in setting up measures to address it. Such mitigation options include emission cuts, reduction in water pollution, afforestation and sustainable energy investments (Odjugo, 2010; Odjugo, 2011). Based on the comparative impacts of climate change at regional levels, this paper is an attempt to review the dire consequences of Nigeria's over-dependence on fossil-fuel-based energy resources and its impact on climate change and propose a viable alternative into its energy mix.

2. Methodology and research

The following questions have been developed to guide the process of this research:

a) To what extent are fossil fuels being used in energy production and associated activities in Nigeria?
b) What are the indices used to measure the impact of climate change and to what extent has/could it affect Nigeria?
c) What proactive measure(s) need to be taken to address the possibility of a negative impact assessment?

The impacts of climate change in Nigeria in the coming years are expected to result from global changes in climate. This change will in turn be based on increases in the concentrations of the greenhouse gases including carbon dioxide, methane and nitrous oxide. Increasing concentrations of greenhouse gases in the atmosphere enhances the potential of the atmosphere to conserve heat and therefore bring about global warming. Thus, increases in the concentrations of the major greenhouse gas emissions within the country is a function of the emissions of these gases and will depend, in the main, on increases in the consumption of fossil fuels, among other factors. In other words, expected global climate change will depend basically on global population increases, global energy consumption, and global changes in land use pattern (Nigeria's First National Communication, 2003). Rich-income countries can be blamed elaborately for greenhouse gas emissions but not exclusively. This is because even if drastic efforts are made by the developed world to reduce greenhouse gas pollution, there is even a greater risk that greenhouse gas emissions in the developing world if unabated, would translate into worsening rates, caused by rapid industrial growth, in a not distant future (Odjugo, 2010).

Thus, the methodology adopted here, though qualitative, relies heavily on secondary data consisting mainly of existing records and documentation in various forms including data both from the energy sector in Nigeria and the National Population Commission and other sources relevant to the study**.** The general approach was to reuse mostly the results of the available data that have been previously published and model them to suit the objectives of this research. The various data sets were then analysed and the results interpreted and resolved into presentable formats using tables, charts and graphs.

a) Data

The rate of population growth in Nigeria is summarized in Figure 2. Energy Consumption by Source is the total amount of primary energy consumed from the usage of a specified fuel. Primary energy includes losses from transportation, friction, heat loss and other inefficiencies. Specifically, consumption equals indigenous production plus imports and stock changes, minus exports and international marine bunkers; the IEA calls this value Total Primary Energy Supply (TPES) (Earth Trends Country Profile, 2003). Table 1 provides details for the distribution of energy source and the amount consumed in metric tons equivalent of oil in Nigeria. All energy consumption values presented here are calculated and reported by the International Energy Agency (IEA) based on an energy balance methodology using metric tons of oil equivalent (toe) (Earth Trends Country Profile, 2003).

Table 1: Nigeria's energy consumption by source, 1999 (in 1000 metric tons oil equivalent)
Source: Earth Trends Country Profile, 2003

Source	*Consumption value*
Total fossil fuels	14,410
Coal and coal products	37
Crude oil and natural gas liquids	9,349
Natural gas	5,261
Nuclear	0
Hydroelectric	486
Renewables, excluding hydroelectric	72,390
Primary solid biomass (includes fuelwood)	72,390
Biogas and liquid biomass	0
Geothermal	0
Solar	0
Wind	0
Tide, wave and ocean	0

Table 2: Structure of Nigeria's GHG emissions, 2005
Source: World Resources Institute's Climate Analysis Indicators Tool (CAIT), 2005

Sector	%
Energy	54.9
Industrial	0.5
Agricultural	38.7
Others	5.9

Table 3: GHG Emissions for Nigeria by sector in 2005
Source: World Resources Institute's Climate Analysis Indicators Tool (CAIT), 2005

Sector	$MtCO_2$	%
Energy	126.7	28.6
Electricity & Heat	12.5	2.8
Manufacturing & Construction	4.1	0.9
Transportation	20.5	4.6
Other Fuel Combustion	17.5	4.0
Fugitive Emissions	72.1	16.3
Industrial Processes	1.5	0.3
Agriculture	101.5	22.9
Waste	15.4	3.5
Land-use Change and Forestry	194.8	44.0
International Bunkers	2.6	0.6
Total	442.6	

Since greenhouse gas (GHG) emission lead to climate change, data on key indicators of GHG emissions in Nigeria are shown in Table 2 and a further breakdown of the components of the energy sector is provided in Table 3.

The total amount of GHG emissions for Nigeria is further broken into its three major gas types which include methane (CH4), Carbon dioxide (CO2) and Nitrous oxide (N2O), with the emission profile showing CO_2 having 33% from the total emission as at 2005, second to N2O with 50.8% (Nigeria and Climate Change Road to COP15; Ogunlowo, 2013). CO_2 which contributes to the bulk of emissions from the energy sector, based on fuel combustion and other related processes, is expected to increase as Nigeria becomes more industrialised at the rate of over 3 Mton per year. The key drivers of CO_2 emissions have been linked to population, economic activity and the CO_2 intensity of the economy (Nigeria and Climate Change Road to COP15). Table 4 is therefore extracted to account for these dependencies.

b. Results

The link between population and energy has been reported in two phases (Darmstadter, 2004). The first link relates to levels and changes in economic development approximated by income or gross domestic product (GDP) per capita. In this case, as income per capita rises, so does per capita energy use. The second link on the other hand, stresses that even at comparable levels of per capita GDP, the volume of energy use will differ among countries and regions, depending on the structural characteristics of the economy, spatial features, climate, fuel prices, government policies, and others. Normally, a country's growth rate is a factor in determining how the infrastructural needs of its people are produced and consumed. To this end, the pattern on Figure. 1 shows that Nigeria's population has risen steadily from an estimated 2.1% in 1960s to about 3% in recent times. Though there was steady decline in the 1990s, the rate is still very high.

Quantifying the linkage between changes in population and energy consumption, three broad factors go into the determination of changes in total energy use. These items are expressed in Equation 1 as percentage changes (Darmstadter, 2004).

$$\text{Population} + \text{GDP per capita} + \text{Energy per unit of GDP} = \text{Energy} \quad (1)$$

Using the data presented in Table 5, the energy consumed in Nigeria for 2011 is approximately 17.56%. This result shows that there is an active relationship between growth in population and energy use. To extend the result in Table 5, the extent which energy is used can also tell on the environmental impact. An increase in energy use will mean that the threat from climate change and other environmental degradation, especially from a fossil-fuel based economy, will become aggravated.

Table 4 shows explicitly that CO_2 emissions in Nigeria have increased over the years based on the current trend. The information provided has been used in Figure 3 to forecast what the trend would be by the turn of this century. Nigeria has its economy to be largely crude-oil based and with a teeming

Table 4: Key Nigerian trends and global ranking (for all GHG emissions)
Source: World Resources Institute's Climate Analysis Indicators Tool (CAIT), 2009

	*Rank**	*Units*	*1990*	*2005*	*Av. annual growth*
Total GHG emissions	26	Mt CO_2 eq	182.7	299.2	3.30%
Total GHG emissions incl LUCF (2000 data)	20	Mt CO_2 eq	330.4	442.6	3.00%
Population	10	People 2000 Intl	9445 000	141356000	2.70%
Income Per Capita	144	Dollars/cap	1464	1731	1.10%
GHG Intensity of Economy	21	Tons CO_2 eq/Million 2000 Intl Dollars	1322.00	1223.10	-0.50%

* Rank out of 186 nations or groups of nations in terms of absolute value of 2005 data

population growing at an average of 2.7%, it is anticipated that in the coming years, CO_2 emissions will significantly increase. In considering CO_2 emissions from combustion only, 158.42 million Nigerians were responsible for emitting a total of 54.90 Mt of CO_2 as at 2010 (2012 Key World Energy Statistics).

Table 5: Structure of Nigeria's GHG emissions, 2005
Source: Online

Population	3.0%
GDP per capita	7.58%
GDP per unit energy use	6.98%

CO_2 emissions by sources and sector for Nigeria are summarised in Figures 4 and 5. This shows the country's huge reliance on conventional energy sources as a large part of the country's emissions emanate from gas flares, which results from burning of gases released in the process of petroleum extraction. Similarly, the sector with the greatest amount of emission is the transportation sector, largely operated on processed fossils fuels.

The content of renewable energy deployment in Nigeria is abysmal. Renewable energy is available in abundant potentials however; integration into the energy mix has been sluggish and disproportionate. From Table 1, it is evident that renewable forms of energy practically do not add to the country's energy mix despite the fact that Figure 4 reveals its zero emission characteristics.

c. Findings and discussions

The research undertaken in this paper has revealed that Nigeria relies heavily on fossil fuel. About 40% of its national GDP, over 80% of government's revenue and over 90% of Nigeria's foreign earnings come from crude oil related activities (Nigeria and Climate Change: Road to COP15). This submission is premised upon certain indices such as population and economic development which have been highlighted with high possibility to affect the way energy is consumed

In estimates, the gross emissions of GHGs have been documented as the internationally accepted common framework to report emission inventories of GHG emissions (IPCC/OCED, 1991). The source-emission relations for any GHG are given by the equation:

(2)

E = is emission of pollutant I from the consumption/production of a product whose quantity is rep-

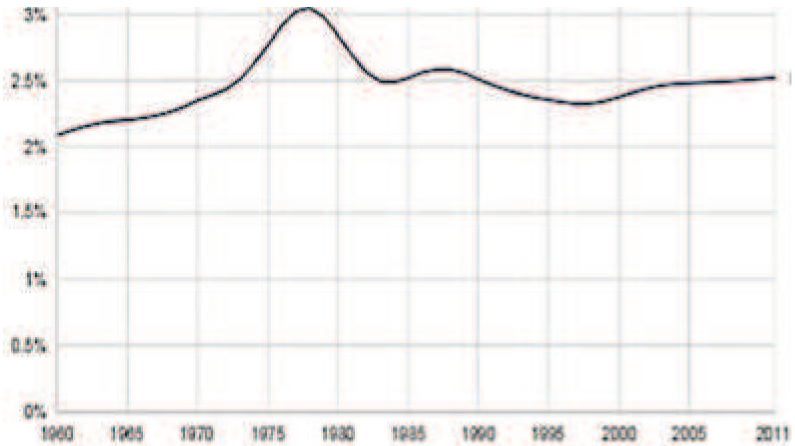

Figure 2: Population growth rate for Nigeria
Source: World Bank, 2013

resented by an activity (A) index and F is the emission factor for the pollutant i (emissions per unit activity A). The total emission of pollutant i for each process is then added over the total number of similar and diverse process k (sectors and sub-sectors), as well as over spatial grids of interest. An emission inventory therefore aims to obtain accurate estimates of the unknowns A and F for each sector and generic sources. The values of A per sector in any country are obtained from available published national data.

For the energy sector, emissions may be provided through the top-down (TD) method which provides aggregate emissions based on certain factors such as production, imports, exports etc. of primary and secondary fuel without details of sectoral fuel use. The expressions for the primary and secondary fuels are given in (3) and (4) respectively.

$$C_a = P + I - E - IMB - SC \quad (3)$$

$$C_a = I - IMB - SC \quad (4)$$

C_a is the apparent energy consumption by fuel type; P= production; I = imports; E = exports; IMB = international marine bunkers; SC = stock change for both primary and secondary fuels.

It is also shown in (5) that the aggregate emission of carbon from all fuels is based on the fuel carbon content, heating values, oxidation fraction and production/consumption data.

$$E_c = C_a \times Fc \quad (5)$$

Ec is the aggregate emission factor in Gg-C, is the apparent energy consumption in PJ and is the carbon emissions factor in tC/TJ.

The Intergovernmental Panel on Climate Change (IPCC) provides a more accurate method for national GHG inventory based on the bottom-up (BU) approach for the energy sector which provides techniques for emission factor estimates for all subsectors processes based on the downstream energy technologies and technology efficiencies. Emissions from BU are based on the application of (5) to each downstream energy technology.

The results obtained applying these methods confirms that gas flaring, transportation and electricity generation (Figures 4 and 5) are the most significant energy consumption processes in Nigeria leading to GHG emissions (Nigeria's First National Communication, 2003). Also energy and land use sectors (Table 3) were observed to be the main contributors of CO_2 to emissions. Again, these emissions are still low when compared with those of industrialised countries.

Having established an increasing population and that the content of Nigeria's energy mix is fossil fuel based with commensurate propensity to emit CO_2 – a by-product of GHG – there is a high risk of climate change happening already, and continuing if unabated (IPCC/OCED, 1991) Climate change impacts development the same way population and energy do.

Nigeria is highly vulnerable to negative impacts of climate change along its large coastal territories, such as, degradation of agricultural lands, desert encroachment, depleting water resources and low agricultural output among others. For instance, with the majority of Nigerians surviving on agricultural proceeds, the effect of climate change on rainfall makes it vulnerable. However, this research has primarily focused on how much the current energy mix in Nigeria has impacted climate change. The findings so far are that Nigeria is dominated by fossil fuel energy sources which have made it vulnerable to the adverse impacts of climate change. In general, the exploration of petroleum resources in the last 40 years has resulted in massive injection of hydrocarbons into the atmosphere as well as considerable environmental problems (Winkler *et al.*, 2007). In this regard, this has led to higher demand for electricity, changing patterns in hydroelectric power facilities, as well as, destruction of existing power facilities.

Nigeria's GHG emission is at variance with that of developed countries, where it is mainly from fossil fuels (Nigeria and Climate Change Road to COP15). There is equally large contribution of GHG emissions from the agricultural sector as shown in Table 3. Much of the emissions from the energy sector come from gas flaring (see Figure 4). Again, the results from Table 3 which accounts for estimates in emissions from land use and forestry, shows the greatest percentage for emissions from land use at 44%.

It can be argued though that the emissions of GHG in Nigeria is generally low based on available data, but as Nigeria becomes more industrialised with time and with a high population growth rate, the figure is expected to rise drastically based on the estimated values presented in Figure 3, if nothing is done to checkmate the trend.

Mitigation options and future actions

The need to tackle the negative impacts of climate change in Nigeria is apt because of its devastating long term effects on the environment and economy. Already, this paper has revealed that energy plays a dominant role in the Nigerian economy and its dominance is expected to increase as population increases and as the industrial sector expands, which are bound to happen, the corresponding effects lead to climate change.

It is identified that the key institutional factors that defines mitigation capacity include effectiveness of government regulation and carbon cuts, education and skills, public attitudes and level of awareness (Nigeria and Climate Change Road to COP15). To this end, mitigation options can come as economic capacity, extensively highlighted in reference awareness (Nigeria and Climate Change Road to COP15), and resource management, the former cited as being more critical to the reduction of GHG emissions (Winkler *et al.,* 2007). The opportunities for Nigeria to tackle climate change by adapting to clean energy projects is notwithstanding very substantial to emission reduction and spiced with great potentials. For example, specific clean energy technologies have been identified in the power, industry, transportation and household sectors, though with minimum public awareness and weak institution. In Nigeria's energy policy, the integration of renewable energy is highly encouraged; however, there are no strict regulations, targets or projects to realize the general policy (Akuru and Okoro, 2010).

In the energy sector, there are two possible scenarios for GHG mitigation. These are the baseline and GHG abatement scenario (Nigeria's First National Communication, 2003)). The baseline scenario is what is obtainable in future energy patterns if inefficiencies occurring as omission in the current systems are not carried into the future, these omissions do not include all firm or proposed projects or policies. On the other hand, the abatement scenario is achieved by introducing a number mitigation efforts into the baseline scenario. These include:

- Efficiency improvement options
- Increased use of renewable energy
- Supply-side options and introduction of new technologies

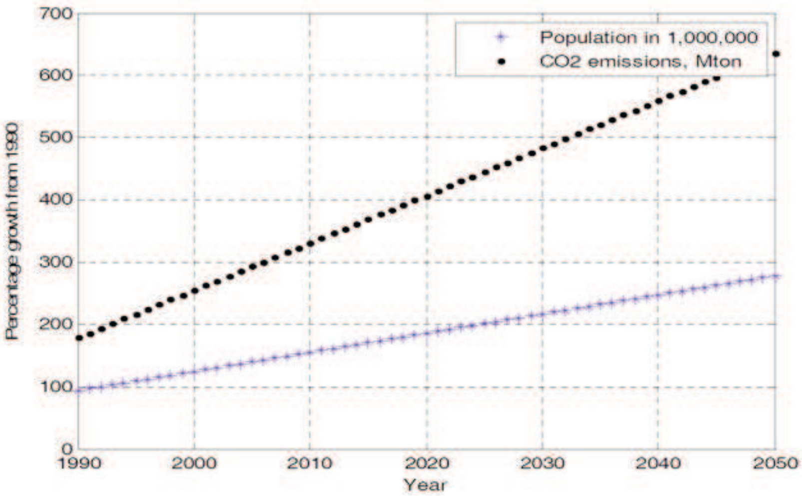

Figure 3: Population and CO_2 emission trends in Nigeria (1990-2050)

- Options for increased use of natural gas with respect to gas flaring

The GHG emission scenario for the energy sector alone is projected as shown in Figure 6. In this case, only total CO_2 emission is considered. The total emission in 1995 was 110 and is expected to rise to 230 Tg CO2 by 2030 in the base line scenario, at an annual average growth rate of 2.86%. From the abatement scenario, the cumulative reduction from baseline is 975 Tg CO_2. The impact of abatement is further reflected in Figure 7 where projections for the total primary energy consumption for Nigeria have been captured. By 2030, abatement is projected to increase the overall contribution of hydro to energy supply from that of the baseline scenario. The total energy consumption

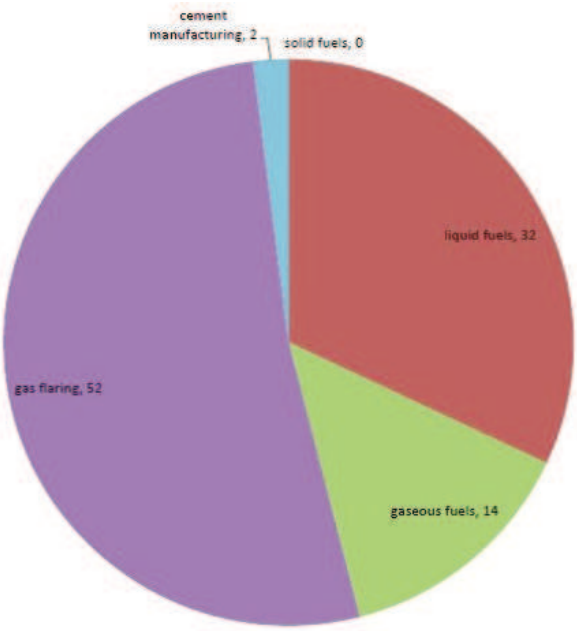

Figure 4: CO_2 emissions by source, Nigeria, 1998
Source: EarthTrends Country Profile, 2003

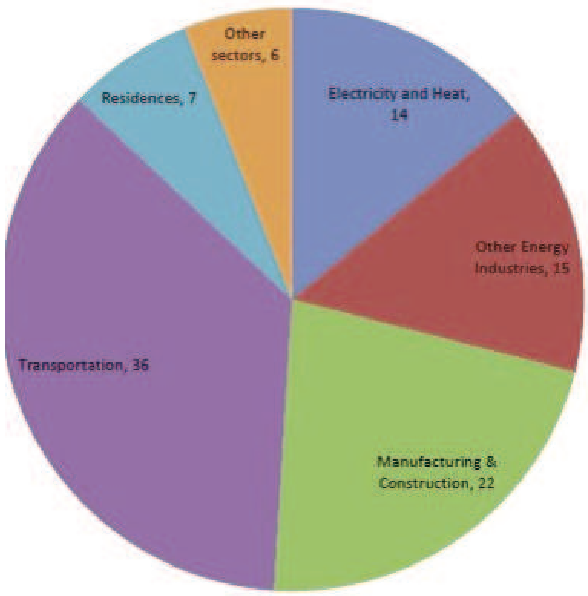

Figure 5: CO_2 emissions by sector, Nigeria, 1999
Source: EarthTrends Country Profile, 2003

which was 1270 PJ and 1718 PJ in 1995 and 2010 respectively is projected to 3140 PJ in 2030 in the baseline scenario.

The current structure of electricity in Nigeria is from gas and hydropower. Also, a considerable amount is also derived from diesel and fuel oil, while private generators are being run on gasoline and diesel. Hydroelectricity which is renewable has a lot of potentials in Nigeria's energy mix and Figure 7 shows this advantage in the abatement case of the projected hydroelectricity rise from 6% in 2010 to 7% in 2030. This increase is substantially based on its absolute contribution to the energy mix. This is an increment of 111% for the 2010 abatement case.

To quantify the projected emission reduction potential, a simple formula, equation (6), called the aggregate reduction potential has been developed to measure the technical potential of any mitigation measure (Nigeria and Climate Change: Road to

Figure 6: CO_2 emission from the energy sector projection for Nigeria (1995-2030)

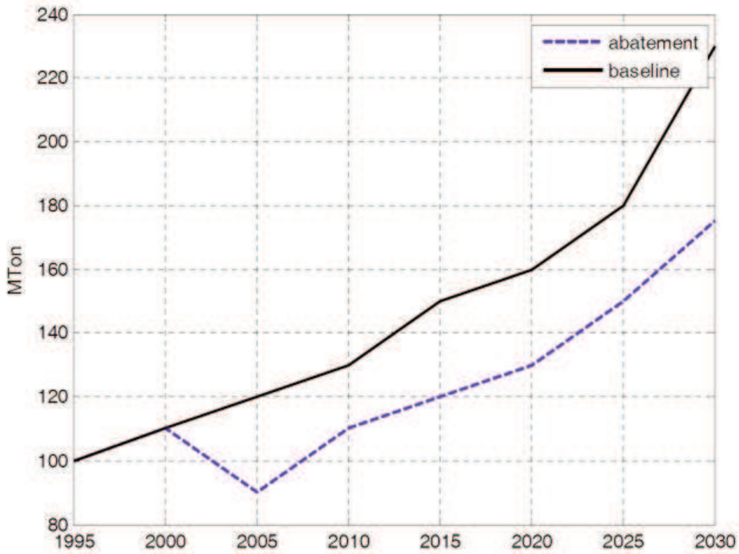

Figure 7: CO_2 emission from the energy sector projection for Nigeria (1995-2030)

COP15).

Where:

E_0 = annual emissions at year 0.
b = final year
α = initial rate of GHG emissions increase
β = annual rate of GHG emissions increase after mitigation efforts
t = time in years

Worth mentioning is the fact that whatever climate change projections that are available at the moment are subject to uncertainties between two extremes – some of the most recent findings are established facts or robust findings, while others are regarded as speculative (IPCC, 2000). Thus, whatever climate change projections that are available at the moment are subject to uncertainties.

In summary, Table 6 presents an assessment of some of the results of mitigation as discussed here. From the result, it is evident that some of the options can be implemented at a net negative cost. Moreover, based on incremental cost per CO_2 removed, it is observed that renewable energy options promise a significant impact in the Nigerian energy system; therefore, the suggestion is for an action plan to revisit Nigeria's energy system by deliberately and systematically integrating renewable energy into the country's energy mix beyond other measures discussed.

4. Conclusion and recommendations

It is true that it is impossible for man to stop the natural causes of climate change (Singer and Avery, 2007); however the human causes can be stopped or drastically reduced with the right approach. It is noteworthy to point out that a number of human activities have contributed and are still contributing to the depletion of the ozone layer, which causes global warming. This paper has been written to highlight a number of these human activities and how it is contributing to climate change in Nigeria. Currently, Nigeria's energy sector is fossil fuel dominated and its associated processes lead to GHG emissions and ultimately, climate change. If the current trend is unabated, then climatic variability currently being experienced is definitely going to increase and intensify and the resultant impact will be catastrophic for the future of the country. The case that Nigeria's contribution to global warming is insignificant when compared to that of developed countries is unsupported given the current trend that threatens to spare no one. Hence, this paper has attempted to correlate using certain indices, the disturbing extent to which climate change is affecting Nigeria. The results reached on the proliferation of climate change via Nigeria's fossil-based economy is very revealing and so requires urgent mitigation actions and proactive measures of which the deployment of renewable energy into the country's energy mix has been advanced amongst other things.

To this end, the Nigerian government should induce the deployment of renewable energy sources in stand-alone capacities as well as grid-based to boost energy security and its availability. To reduce the emission of GHGs, clean and environment-friendly technologies are required. Automobiles can be upgraded to operate on modern fuels such as ethanol, solar engines, electric or hybrid engines. Gas flaring being perpetrated by oil producing companies should immediately be halted, harnessed and defaulters made to pay penalties where necessary. Regulators of the energy sector should encourage operators and consumers to

Table 6: Ranking of abatement options

Source: Nigeria's First National Communication under the United Nations Framework Convention on Climate Change, Federal Republic of Nigeria; Nov. 2003

Mitigation option	*Incremental cost (US $m)*	*CO_2 reduction capacity (Mton)*	*$/Ton*
CFL Lighting	-131	5.155	-58.00
Improved kerosene stove	-131	6.122	-21.40
Displacement of fuel-oil by gas in cement	-138	7.49	-18.42
Improved elec. Appliances in the residential sector	-161	9.566	-16.83
Efficient motors in industry	-171	10.738	-15.92
Small-scale Hydro (<10 MW)	-427	41.313	-10.34
Kainji hydro power plant (retrofit)	-351	50.01	-7.02
Improved woodstove in residential sector	-72	18.369	-3.92
Large-scale hydro	-686	197.353	-3.48
Central solar	-24	18.735	-1.28
Improved refrigerators	154	15.793	9.75
Residential solar PV	74	5.883	12.58
Gas flare reduction	45334	919.201	49.54
Efficient gasoline cars	17478	247.05	70.75
Improved air conditioners	218	1.54	141.56
Efficient diesel trucks	9060	60.096	150.76
Improved electrical appliances, industrial and commercial sectors	2485	14.431	172.20

adapt to or adopt energy efficiency measures in both the supply and consumption of energy respectively. International frameworks are to be pursued so as to force developed countries to implement vis-à-vis strengthen vital global treaties such as the Climate Convention and Kyoto Protocol. Such actions to encourage policies like the clean development mechanism (CDM) is another avenue through which large-scale investments can be attracted into the country for financing clean projects and in return grant carbon credits to developed countries. In the main, the supplementary benefits of turning to renewable energy resources are improvement of current abysmal condition of employment of tertiary graduates by creating jobs, opportunities for new investors, economic improvement, sustainable energy development, environment-friendly technologies and health advantages.

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Forster and van Dyk

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2015	1	14	400	4	14.00
2014	4	43	1172	13	10.75
2013	4	33	687	15	8.25
2012	4	30	838	18	7.50
2011	4	21	586	4	5.25
2010	4	14	236	4	3.50
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