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An indicative assessment of investment opportunities in the African electricity supply sector

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Abstract
In the coming decades, demand for electricity will increase considerably on the African continent. Investment in power generation, transmission and distribution is necessary to meet this demand. In this paper a cost-optimization tool is used to assess investment opportunities under varying scenarios of GDP growth, electricity trade and CO_2 taxation. Business as usual fuel price outlooks are assumed, and related assumptions are relatively conservative. The goal is to find if there are economic indications that renewable energy might play a significant role in the expansion of the African electricity system. The results show that there is potential of renewable energy (RE) resources to have a significant share in the generation mix. By 2030, 42% and 55% of the total generation is powered by renewables in the high and low GDP scenarios respectively. Promotion of interregional trade can assist in unlocking RE potential across the continent, such as hydro in Central Africa and wind in East Africa; these regions are projected to be net exporters of electricity. Additionally, generation by off-grid technologies increases over time, reaching 12% of the total generation by 2030 in Sub-Saharan Africa.
Keywords: renewable energy, electricity trade, power generation investment

1. Introduction

Increasing the electrification rate is one of the key goals of African energy policy (Brew-Hammond, 2010). The continent, and particularly Sub-Saharan Africa (SSA), suffers from severe lack of power infrastructure. Even though 13% of the world's population resides in SSA, only 32.5% have access to electricity (The World Bank, 2013). At the same time, a number of countries, such as Somalia, Uganda and Rwanda have electrification rates that do not exceed 5%, while in rural areas, this figure is even lower (Brew-Hammond, 2010). This hinders economic growth and prevents rise in the standard of living for these countries (Collier and Venables, 2012; Javadi *et al.*, 2013). Lack of adequate infrastructure is threatening the smooth operation of major industries, such as mining (Visser, 2013).

Despite these obstacles, economies in Africa are growing at a fast pace. According to the IEA, GDP in Africa is projected to rise at an average rate of 3.8% annually between 2010 and 2035, resulting in a doubling in electricity demand over the same period (IEA, 2012). The current state of power generation infrastructure on the continent calls for considerable investments (Eberhard *et al.*, 2008) and, based on the IEA's New Policies Scenario, capacity additions of 261 GW would be required to meet the rising demand (IEA, 2012). However, even this increase in generating capacity will not be sufficient to bring the electrification rate to levels comparable to those of developed countries (Bazilian *et al.*, 2012). It should be noted that another study conducted by IRENA projects a higher demand for electricity than tne IEA's *World Energy Outlook*. In a business as usual scenario, the former estimates that capacity additions of 250 GW will be needed to fuel industrial growth and reach an electrification rate of 43% across the continent by 2030. In its Renewable scenario, which promotes investment in renewable energy technologies and off-grid power generation, an additional 32 GW is required by the same year to ensure universal access to electricity (IRENA, 2012a). Nonetheless, as approximated in the same study, financing needs for either of these scenarios are remarkable and challenging; $2.3 trillion for the Reference and $3 trillion for the Renewable scenario, with the difference originating mainly from elevated investment costs for generation, transmission and distribution infrastructure.

Experience with energy infrastructure in Africa in the past has exposed shortfalls in governance, capital and a skilled labour force, all of which can be necessary ingredients for a successful expansion of the current power system (Collier and Venables, 2012). However, the continent is endowed with extensive energy resources, which if exploited could improve the energy outlook to a considerable degree. Africa is rich in fossil fuels (U.S. Energy Information Administration (EIA), 2012), while there is great potential for low-cost electricity from hydropower and other renewable energy resources; primarily solar and wind (IRENA, 2012a; Kebede *et al.,* 2010). In fact, unexploited hydropower potential on the continent is estimated at 220 GW installed capacity (Eberhard *et al.*, 2011), which is comparable to the necessary capacity additions over the next two decades. Promoting large-scale projects, such as the 40 GW Grand Inga project (Showers, 2011), might provide the boost required to upgrade Africa's energy infrastructure (Bazilian *et al.,* 2012). Further, it is argued that decentralized generation of power can help provide electricity to remote areas, while at the same time conserve power via a reduction in transmission and distribution losses (Sebitosi and Okou, 2010).

Literature assessing Africa's power sector agrees that sizeable investments are called for to improve the current status. This paper presents results from scenarios of the African electricity sector in the medium term, jointly conducted by the Royal Institute of Technology and the International Renewable Energy Agency (IRENA). The objective is to provide an indicative estimate of the potential for electricity trade and investment opportunities in grid-connected and off-grid power generation projects in Africa. A special focus is given on the potential for renewable energy (RE) electricity investment. The authors do not undertake detailed project and grid integration studies necessary to determine specific potentials, nor regional disaggregation. Rather the focus is directed on an indicative cost benefit analysis. Building on this work, IRENA has developed more detailed, country-by-country regional power modelling for selected regions in Africa (Miketa and Merven, 2013a, 2013b).

An analytical model has been constructed, calibrated and used to quantify future power station investment and operation scenarios. The model calculates the lowest cost expansion of the electricity system needed to meet a growing demand for electricity on the continent. This expansion is subject to various constraints. The analysis deliberately does not take into account special geopolitical constraints that may slow the expansion of trade in the future. Rather, efforts are geared towards shedding light on the potential benefits of the latter, assuming that demonstrating the techno-economic feasibility may help accelerate the policy and investment support needed.

2. Material and methods

There are at least two well documented African electricity models available (Rosnes and Vennemo, 2012; Sofreco, 2011). In order to develop an economy-wide perspective of potential RE power plant investment these two models have been updated and refined with respect to: historical data, spatial definition, regional integration, time horizon, renewable and other energy resources availability, and power plant and performance data.[1] The existing Rosnes & Vennemo's model is useful for capturing overall investment needs within four African regions. That model utilizes exogenously defined demands for energy services. Selected policy goals impose technical constraints and economic implications.[2] Sofreco (2011) approaches the analysis differently. It undertakes a demand analysis for each country, and aggregates these into regions. It then assesses the potential for investment within, and trade between, each region to meet demand growth on a least cost basis. Sofreco also undertakes a detailed analysis of fossil fuel reserve potentials.

For this analysis, the following additions (and simplifications) have been made to Rosnes and Vennemo:

- Extending the modelling period to 2030, and increasing the temporal resolution to cover annual investments. This allows the provision of greater detail regarding generation and transmission investments between countries and regions. Furthermore, this allows closer consistency and testing of results with power pool investment strategies, as well as flexibly matching climate change trends.
- Covering (currently omitted) sub-Saharan countries and associated trade. This is important as inclusion of all these countries enables the modelling of potential increases in bulk renewable energy investments, and links. We augment the model based on the KTH-dESA power pool modelling (Broad *et al.*, 2012; IRENA, 2012a).

This will comprise a 'country by country' region as well as a macro-region in the pan African model.

Furthermore, the following updates have been made to both Rosnes and Vennemo and Sofreco:

- Modelling seasonal, daily and sub-daily representative 'time-slices' throughout the year. This is needed to include variations of demand and generation. It also allows parameters such as demand[3] and availability of bulk RE resources to be characterized in those times slices, which strongly influence trade and resulting investment requirements.
- Addition of the most recent estimates of renewable energy resource potential estimates (Hermann *et al.*, 2012).
- Reporting of CO_2 emissions for each scenario.
- Updated RE cost projections based on the IRENA's latest analysis (IRENA, 2013) and consistent with assumptions used in the IRENA's country-by-country power pool models (Miketa and Merven, 2013a, 2013b).

The model developed for this paper is a linear cost optimization energy systems model. The analysis utilizes NPV costs. For each region over twenty generic generating technology (or configurations of specific technology) options are considered (Table 1). These include fossil, nuclear and renewable electricity generators. Renewable options are classified by other characteristics, such as by wind regimes, cost regimes, or storage potentials. Since renewable energy holds strong promise for supplying off-grid power providing access in unconnected areas, this study assumes that in 2030 up to 12% of the residential-commercial demand in South, West, East and Central Africa is met by off-grid technolo-

Table 1: Power plant parameters used in the model
Miketa and Merven (2013b)

Plant type	*Investment cost ($/kW)*	*Fixed O&M ($/kW)**	*Variable O&M ($/MWh)*	*Efficiency*	*Life (yrs)*	*Capacity factor*	*Availability*
Diesel Centralized	1070	0	17	35%	25	80%	90%
Diesel 100 kW system							
(industry)	659	0	55	35%	20	80%	90%
Diesel/Gasoline 1kW system (residential/ commercial)	692	0	33	35%	10	80%	90%
HFO	1350	0	15	35%	25	80%	90%
OCGT	603	0	20	30%	25	85%	93%
CCGT	1069	0	3	48%	30	85%	93%
CCGT Associated Gas	1069	0	3	48%	30	85%	93%
Supercritical coal	2403	0	14	37%	40	85%	94%
Nuclear	5028	93	1.37	33%	60	92%	93%
Renewables	*Investment cost ($/kW)*	*Fixed O&M ($/kW)**	*Variable O&M ($/MWh)*	*Efficiency*	*Life (yrs)*	*Capacity factor*	*Availability*
Hydro (run of river)	1282	21	1.14	100%	50	54-80%	67-80%
Hydro (dam)	2718	21	1.14	100%	50	60-100%	90-100%
Small Hydro	4000	0	5	100%	50	50%	100%
Biomass	2500	0	20	38%	30	50%	93%
Bulk Wind (30% CF)	2000	0	16	100%	25	30%	90%
Bulk Wind (40% CF)	2000	0	14	100%	25	40%	85%
Solar PV (utility)	2000	0	20	100%	25	25%	100%
Solar PV (rooftop)	2100	0	24	100%	25	20%	100%
Solar PV rooftop (1 hr storage)	4258	0	24	100%	25	22.5%	100%
Solar PV rooftop (2 hr storage)	6275	0	24	100%	25	25%	100%
Solar thermal without storage	3000	0	22	100%	25	35%	100%
Solar thermal with Storage	5400	0	19	100%	25	50%	100%
Solar thermal with gas co-firing	1388	0	19	53%	25	85%	93%
Geothermal (cheap)	3500	30	1.03	100%	25	85%	100%
Geothermal (expensive)	4500	0	1.03	100%	25	85%	100%

** Fixed O&M costs have been incorporated within Variable O&M costs for the majority of technologies.*

gies. The assumption is taken from the results of the aforementioned IRENA's country-by-country studies where three decentralized generation options are explicitly modelled; rooftop photovoltaic, small hydro and small diesel generators. The electricity generation data used in the model are based on the international literature,[4] and aggregate country level data[5] into a five region macro representation of the African continent. The regions modelled are classified as Southern,[6] Western,[7] Central,[8] Eastern[9] and Northern[10]Africa – each with different demand[11] and resource profiles. Future international fossil fuel prices are based on IEA's projections (IEA, 2012).

One primary aim of this exercise is to provide an indication of the potential for electricity generation from renewable energy sources. Partly due to the coarse nature of the analysis, conservative assumptions were made in regards to RE investment potentials, while the results, even though are robust, would still need to be filtered through the lens of specific project data and related analysis.[12] Results for the period 2008 to 2030 are reported.

3. Results and discussion

3.1 RE growth

The analysis is initially undertaken with the objective of meeting a growing demand for electricity at the lowest possible cost. Thus, when RE is chosen by the model there are two key implications. Firstly, this indicates that RE technologies are cost-competitive and can reduce the cost of power generation in Africa. This in turn will make access to electricity more affordable. It is assumed that as Africa develops increased fuel exports of local reserves will be readily possible. Thus, at the prices assumed, utilization of local RE resources potentially frees up fossil fuels, most notably gas for export. Effectively the cost of moving to greater renewable electricity generation is outweighed by the monetary gains to be had by selling the freed up fossil fuel.

Two scenarios have been developed, based on high and low GDP projections to enable assessment of technology competitiveness at different power demand levels. High projections are based on country by country GDP projections used in the African Union's *Energy Outlook 2040* (Sofreco, 2011) – average annual growth over the period exceeds 6% – while the low projections are taken from projection for Africa in the IEA's *World Energy Outlook* – 3.8% average annual growth. In these scenarios, trade is allowed, as is investment in all technology options. We do not consider investments in projects which aim to export electricity outside Africa, though trade within the continent is allowed.[13] Such actions are likely to further increase the deployment of RE through the continent. Even without these measures, the share and absolute investment in RE increases dramatically, as shown by Figure 1. By 2030 roughly 42% and 55% of electricity generation is renewable, in the high and low GDP scenarios respectively.

3.1.1 – High GDP growth

The significant potentials for new RE investments are to be found in all the regions modelled. In particular, large investments in RE are projected in Central, East and North Africa over the study period. In Central Africa, where according to our region split the Democratic Republic of Congo (DRC) is situated, large hydro investments are likely, as DRC is home to large hydro reserves hydro potential in the Inga project on the Congo-river. Some of this potential is invested in during the period consid-

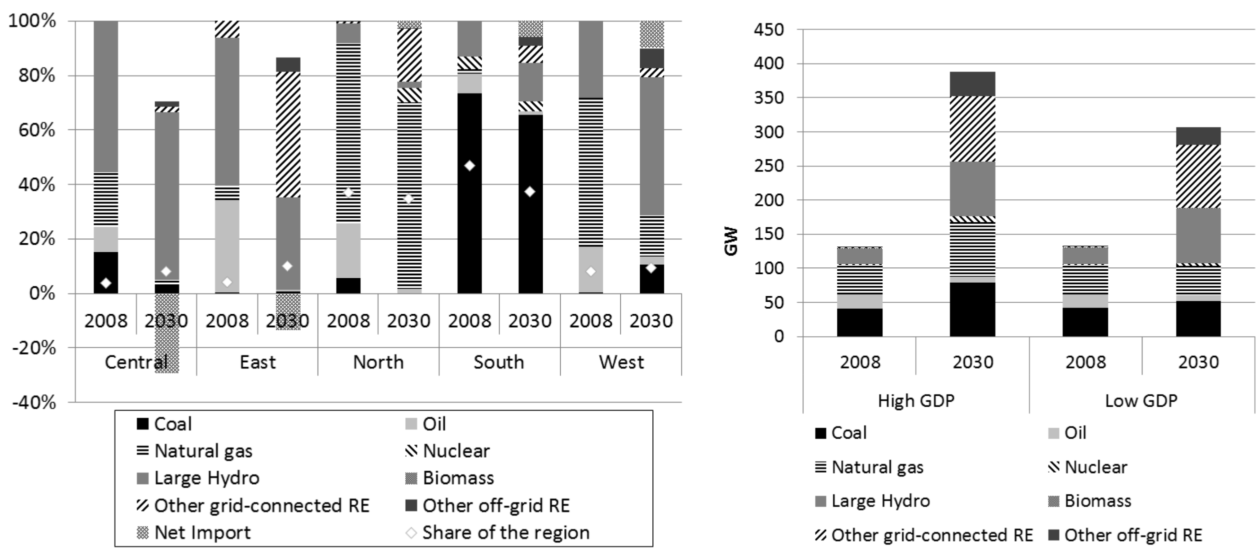

Figure 1: Share of each category in generation in the high GDP scenario (left) and development of generating capacity in both scenarios (right).

ered. Only around 13GW of over 40GW potential of the grand Inga project is assumed to be completed by 2030, limited by the maximum speed of project implementation according to analysis of project documents.

In the north and east, large quantities of wind energy is generated, at very high load factors. In the East, 22GW of new wind capacity is invested in as well as 13.5GW of new hydro. Over 45GW of wind with an average load factor above 40% is estimated to be available in this region. In the north, there is investment in 36GW of wind at estimated load factors of 30 to 40%. However, due to conservative maximum penetration rates assumed in the analysis, not all of the economic potential is realized by 2030.

A key issue relating to the high wind penetration will be integration in a robust and resilient manner; ensuring the balance between demand and intermittent supply. Related to this, much of the wind based generation potential is close to the coast in dry countries. These dry countries have high demands for desalinated water, which is relatively inexpensive to store. Thus, desalinated water can be produced during periods of high wind availability or during times of off-peak demand, so as to reduce electricity demand in other instances.

Despite the considerable increase in power generation by RE sources across the continent (Figure 2), none of the regions reach their full economic investment potential in RE in the timeframe of the scenarios investigated. In all regions, a greater rate of RE technologies deployment would be cost optimal. This does not occur, as the analysis assumes that their maximum annual penetration is limited.

In the scenarios modelled, limited electricity trade is allowed between regions. In order to estimate transmission costs required for trade, an average of 365$/kW investment is required for electricity to leave a region, according to existing IRENA assessments (Miketa and Merven, 2013a). The same is required for electricity to be imported into a region. Further, different transmission losses are assumed for the interregional linkages, due to variations in distances between the regions; primarily from major points of energy source to points of energy demand. To the north, large losses of around 20% are assumed, over 'normal' intrare-

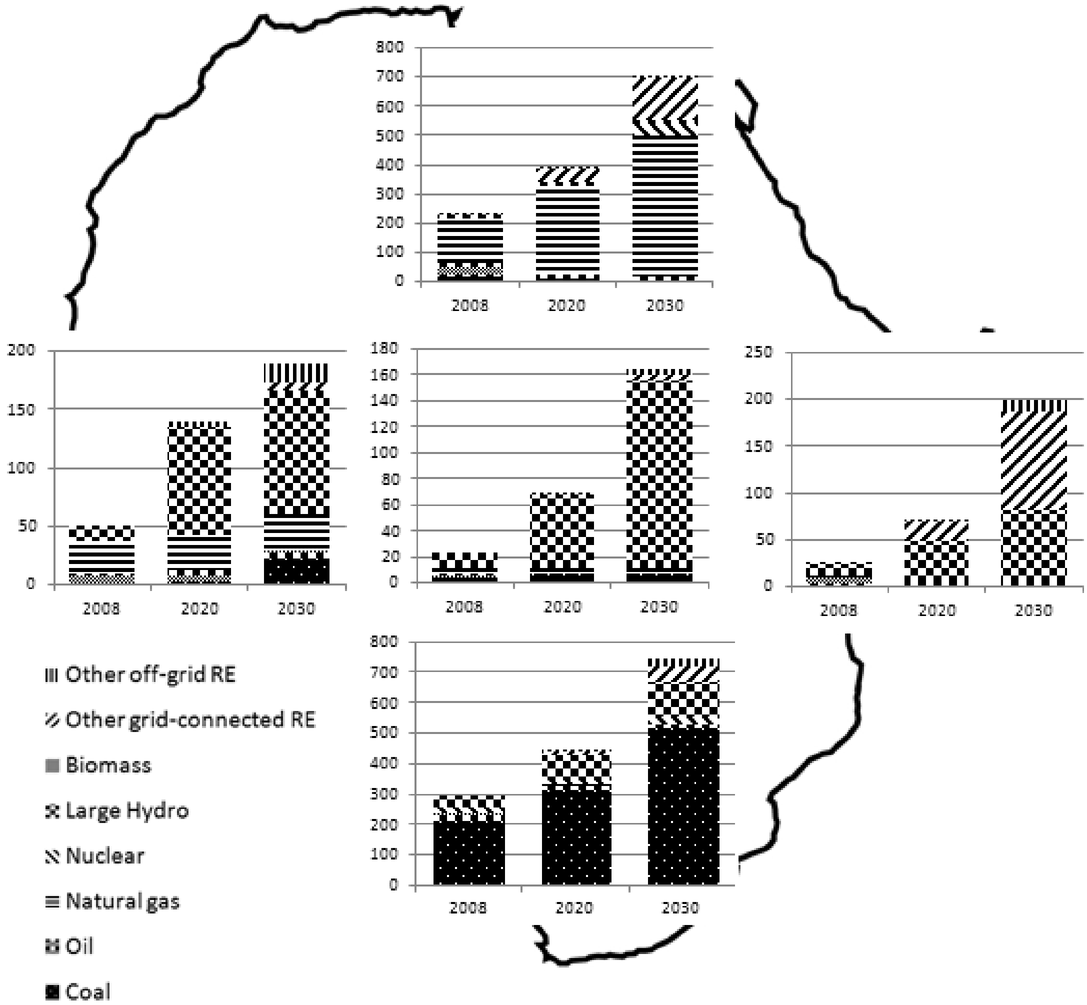

Figure 2: Generation (TWh) by fuel type in each of the regions in the high GDP scenario

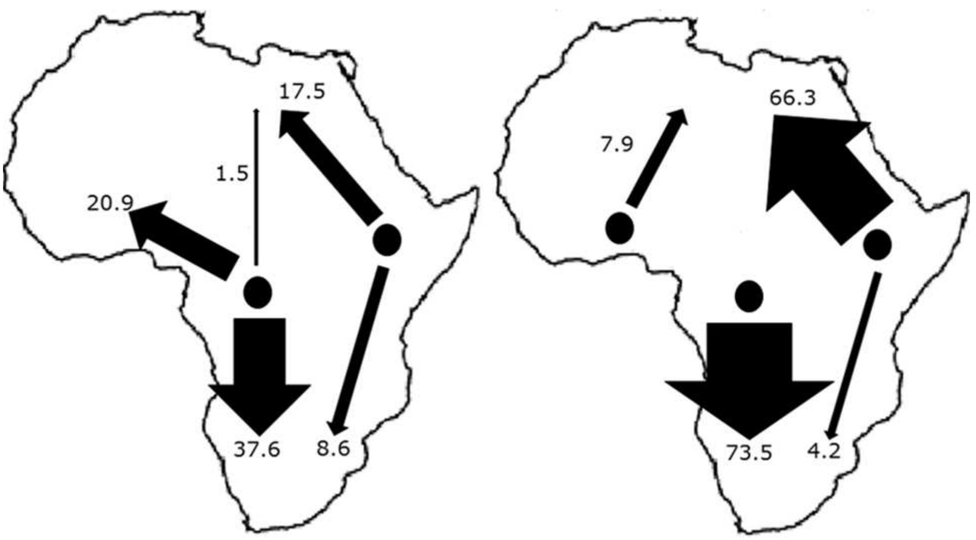

Figure 3: Indicative trade between regions in 2030 in the high (left) and low GDP (right) scenarios (TWh)

gional transmission losses of 7%, for both leaving and entering a region. Small losses between West and Central Africa are assumed, especially as the DRC is already included in current West African power pool planning. The result, even with these assumptions is that trade is economically viable. Figure 3, in which each arrow is in proportion to the level of trade, indicates the role trade plays in freeing up Central African hydro potential. Significant trade potential occurs from the east, where high load factor wind is available. The trade of 73.5 TWh to the South from Central Africa in the low GDP scenario is the largest trade flow in 2030. It accounts to about 12% of the electricity demanded in that region. It should be noted that trade occurs at a greater scale in the low GDP scenario, as there is lower demand in RES rich regions, such as East and Central Africa, thus freeing up electricity for trade.

Scenarios without non-hydro RE, without CO_2 tax and without trade have been modelled within the High GDP scenario. Differences in system costs with and without non-hydro RE are shown later on in this paper. Note that when non-hydro RE development is not constrained, it is chosen as part of the optimal solution. Africa will have a more expensive electricity system without RE, and it will result in greater emissions. During 2008-2030 the total undiscounted system costs in the scenario where RE investment is limited amount to $2.874 trillion, while in the scenario where RE investment is allowed, total undiscounted system costs for the same period amount to $2.834 trillion. For years 2008-2040, the respective figures are $6.025 and $5.467 trillion. At the same time, CO_2 emissions are 6.35% lower in the RE scenario for period 2008-2030, and 12.86% lower for period 2008-2040. It should be mentioned though that in the no RE case, large hydro is allowed to be part of the solution, while investments in other RE projects are allowed to occur only until 2015. This explains the relative similarity in CO_2 emissions in these two scenarios, indicated by the small difference in CO_2 costs, as shown in Figure 4 (overleaf).

3.1.2 – Low GDP growth

A lower GDP growth rate on the African continent is expected to have a corresponding effect on electricity demand. As internal demand for power remains low, the need for capacity additions subsequently follows at analogous levels. Countries with renewable energy resources at cost-competitive prices do not need to invest as much to meet their demand. Nonetheless, they still have a greater potential for electricity trade. As shown in Figure 5, the interregional trade outlook changes in the Low GDP scenario. The decrease in internal regional demand, allows low-cost power to be exported to points of greater demand. Central and East Africa export a greater share of their generated power, as a result of this. In comparison to the High GDP scenario, net exports from these two regions in this scenario increase from 68 and 31 TWh to 87 and 82 TWh respectively in 2030. Similarly, in the same year, West Africa becomes a net exporter of power, transmitting 10 TWh to Northern Africa.

Moreover, in a low GDP growth case, Southern Africa's net imports in 2030 increase from 46 to 77 TWh; these figures correspond to 5 and 12% of the total generation mix of the region. Finally, Northern Africa transforms into a major purchaser of power generated in Sub-Saharan Africa; primarily from Eastern and Western Africa. Whereas in the High GDP scenario Northern Africa's net imports amount 19 TWh in 2030, in this scenario this figure increases to 75 TWh. Such a development will assist in freeing up considerable volumes of fossil fuel reserves in this region for export purposes, instead

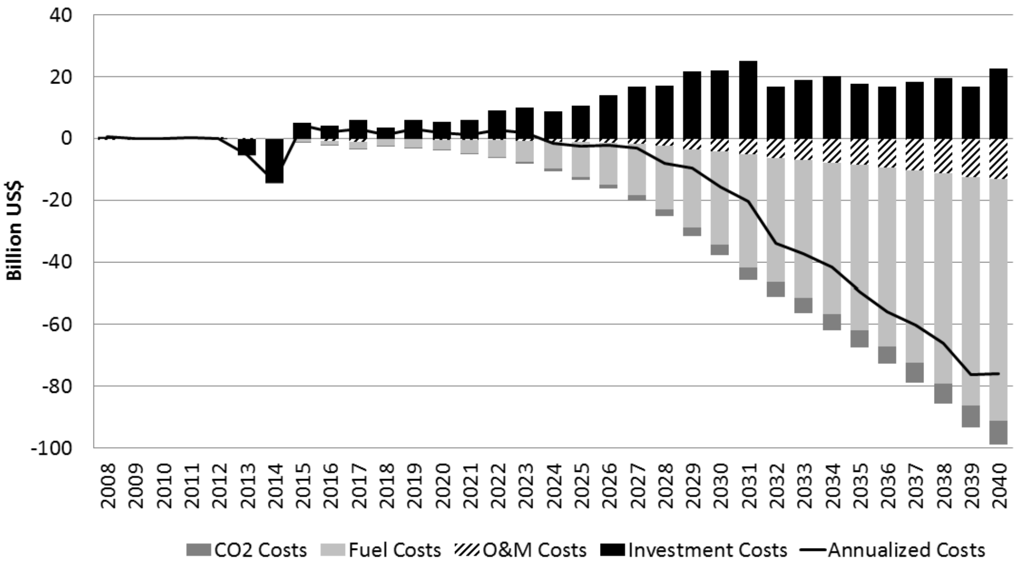

Figure 4: Difference in system costs (billion US$, undiscounted) in the high GDP scenarios with and without non-hydro RE. Net negative costs indicate lower costs in the scenario where RE technologies are not constrained, whereas net positive costs indicate higher costs for the same scenario

of consumption in domestic fossil-fired power plants. However, this scenario also implies that the target for universal access to electricity in Sub-Saharan Africa will be hindered to a great extent.

3.2 Sensitivity analysis

In this section a comparison is presented between the High GDP scenario and two scenarios, in which the carbon tax and interregional electricity trade links are separately disabled in the model. This sensitivity analysis is conducted to investigate the financial viability of investments in RE technologies without these conditions.

3.2.1 Carbon tax

In the scenarios presented, it is assumed that a carbon tax will gradually be implemented in Northern and Southern African regions after 2014. Without this option, the grid connected renewable options are less competitive against coal power in the South, while in the North nuclear power is not implemented. Without a carbon tax, in Southern Africa, coal fuelled power accounts for about 75% of the total electricity generation by 2030, while the share of renewable technologies declines accordingly; 20% instead of 25% (Figure 6). Installed capacity of non-hydro based renewable technologies in Africa is limited to about 100 GW, instead of 123 GW projected for 2030 in the scenario with carbon tax.

3.2.2 – Interregional trade

As mentioned, interregional trade of electricity allows cost competitive hydro options to be utilized

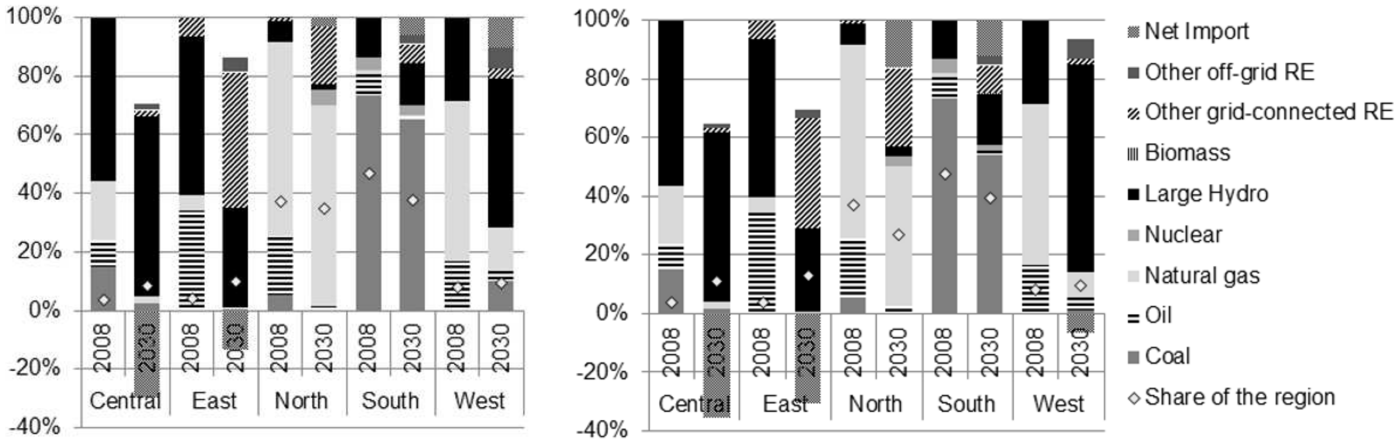

Figure 5: Electricity generation mix of the five regions in 2008 and 2030, in the high (left) and low (right) GDP scenarios

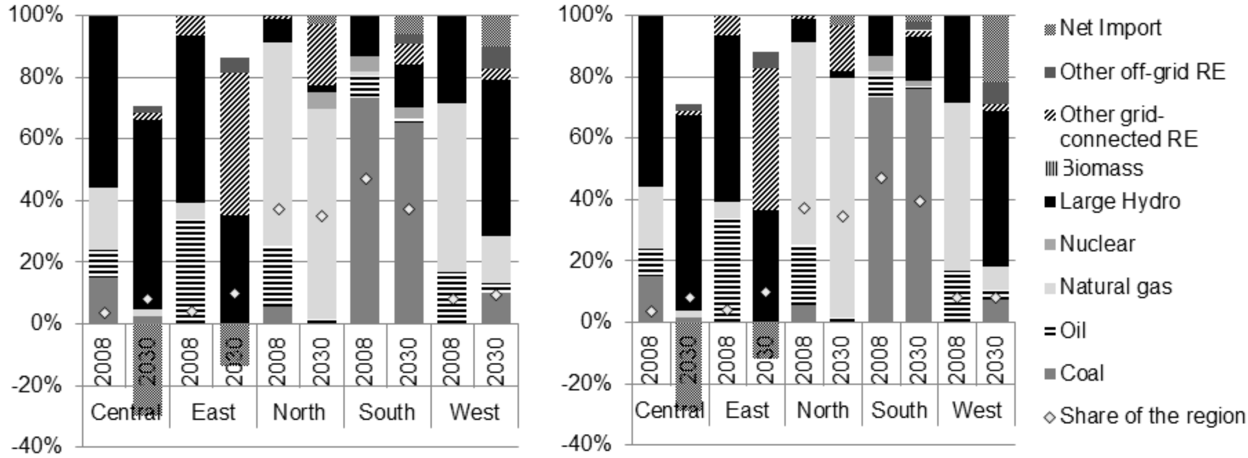

Figure 6: Electricity generation mix of the five regions in 2008 and 2030, in the high GDP scenarios with (left) and without (right) CO_2 pricing

by regions outside of where the potentials exist. Figure 7 shows how the electricity mix changes in each region with and without trade. Without trade, North, South and West regions need to meet their regional demand by expanding fossil-fuelled power plants, which reduce the share of all renewable at a continental level to 37% instead of 41%. Central Africa with vast hydro potential is the main exporter region when interregional trade is implemented. When the interregional trade is not allowed, full investment in the available hydro resources makes no economic sense, due to the low regional demand. As such, by 2030, this leads to an investment of 16.3 GW instead of 23.5 GW. Similarly, in East Africa, 13.6GW instead of 22.4 GW of wind farms are developed when trade is not allowed.

The difference in system costs between 2008 and 2030 in two scenarios with and without interregional trade is not so significant (Figure 8), amounting to 43 billion (undiscounted) which corresponds to cost savings of 1%. Since regions are not able to exploit readily available renewable energy resources beyond their boundaries, they have to use more fossil fuels, thus increasing the respective cost. The cost reduction is mainly related to the reduced fuel use. It should be noted that if we extend the assessment by 10 years up to 2040, the total system cost savings are approximately 2%. This low difference can be attributed to the high investment cost in technologies, which are only operated for a fraction of their lifetime during our projections; namely hydropower, solar and wind technologies.

Key areas, for which further sensitivity studies must be undertaken, include changing some of the following parameters, and relating them to the effect on RE penetration by region:

- Transmission costs and losses: With high levels of trade and variable intermittent generation, the coordinated development of a strong transmission system is important. The effects of varying costs and losses associated with transmission on the deployment of RE should be investigated.
- The cost of fossil fuels should be varied in order to determine the relationship between international gas prices, local coal as well as oil and RE deployment by region.

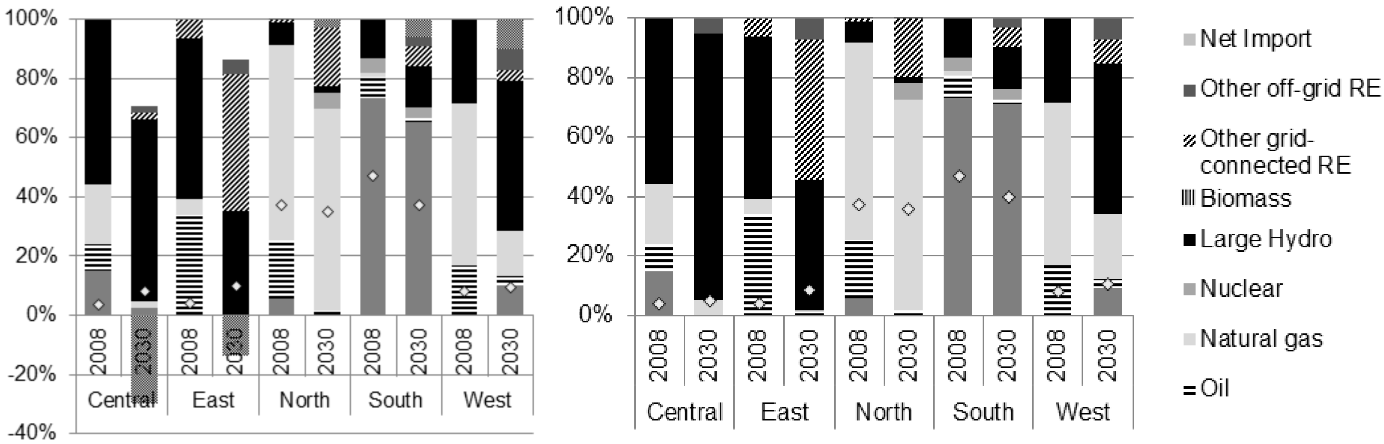

Figure 7: Electricity generation mix of the five regions in 2008 and 2030, in the high GDP scenarios with (left) and without (right) inter-regional trade

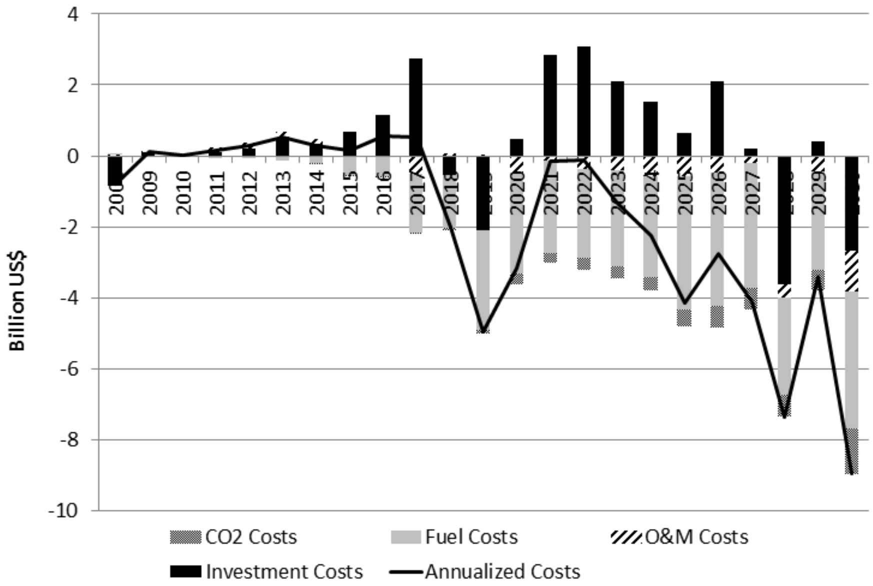

Figure 8: Differences in system costs (billion US$, undiscounted), in the high GDP scenarios with and without inter-regional trade. Net negative costs indicate lower costs in the scenario where RE technologies are not constrained, whereas net positive costs indicate higher costs for the same scenario

- The cost of key RE technologies should be investigated to determine at what price range they become cost optimal or not. This is particularly important as various costs are expected to go down with learning.

4. Conclusion

The potential for demand growth in Africa is large – due both to improving economic conditions and currently large levels of unmet demand. Additionally, the continent is mineral rich thus mining, which is energy intensive, is a growing and important electrical load. If large quantities of renewable energy sources are exploited, local reserves of fossil fuels will likely be freed up for export. To incorporate large quantities of variable generation, such as wind, the development of a strong interconnected grid is important. This will help allow balancing of intermittent generation, with significant balancing potential in the hydro system, as much of the wind potential is situated in dry countries. In this regard, there exists a large and unexplored potential role for desalination using electricity.

Future studies – beyond the scope of this analysis – should include, amongst others, the potential for system balancing, transmission development, smart grid investments (in the context of variable loads, such as desalination). Further – following this indicative study – an extensive parametric sensitivity and robustness analysis may be a useful complement. The goal of the latter would be to wide suite of macro factors that determine the economic robustness of these conclusions. These may include for hydro changes in water availability perhaps via climate change, or more generally the effect of rapid reductions in fossil prices with the possible onset of shale gas, etc. It would also be useful to develop a single African energy model with each national model represented. All of this is no longer a computational challenge, and it allows for a number of improvements over this work.

Acknowledgments and disclaimer

The guidance, patience and funding of IRENA for this and related work are gratefully acknowledged. Initial efforts undertaken by the World Bank (World Bank, 2011) as well as interactions with the project leader of that effort, Vivien Foster, are appreciatively recognized. The cited work provided a cornerstone for this effort.

The views and perspectives expressed in this paper are those of the authors and do not necessarily reflect the views of the IRENA and KTH or their senior management.

Notes

1. Including, for each country and region (as appropriate): electricity demand projections for each country based on GDP and population; existing power station performance data (fuels, outages, fixed and variable costs, vintage structure, all based on plant types); and data for new power stations (including costs, expected life times, and an estimation of performance improvements).
2. Further attributes of the GAMS model developed by Rosnes and Vennemo (Rosnes and Vennemo, 2012) include: Country by country model, covering the period 2005 to 2015 in one single step; considers two load blocks (off and on-peak demand) to estimate new investment requirements; the scope is limited to a detailed assessment of the electricity sector, without coverage of associated emissions and inter-linkages

with water demands; extends transmission between countries and estimate trade potentials within power pools; estimates optimal power trade and plant investments (and generation) based on cost and load factor assumptions to meet national demands.

3. Across Africa electricity demand differs by: week day (weekends – with different demand requirements – occur on different days in different countries); longitude (with peaks occurring at different times in East and West); as well as latitude, with North African summer occurring during the Southern African winter. If demands are high in one region and low in another, and regions are connected, there is potential for trade and 'sharing' generation infrastructure. This will influence the trade potential as well as investment requirements.
4. Historical power plant data was taken from Platts (Platts, 2012), specific renewable power plant data, including learning expectations were taken from IRENA (IRENA, 2012b), other data based on regional power pool information or IEA (OECD and Nuclear Energy Agency, 2010). The starting point for the work was the World Bank's Electricity Spending Needs Model (World Bank, 2011).
5. Data tables by country, later aggregated by region were developed for: Fossil fuels (U.S. Energy Information Administration (EIA), 2012), hydro and geothermal (IRENA, 2012a), wind and solar (Hermann *et al.*, 2012); Regional biomass estimates are taken from IRENA (IRENA, 2012b).
6. Angola; Botswana; Lesotho; Madagascar; Malawi; Mauritius; Mozambique; Namibia;, Seychelles; South Africa; Swaziland; Zambia; Zimbabwe
7. Benin, Burkina Faso, Cabo Verde, Cote d`Ivoire, Gambia, Ghana, Guinee, Guinee Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, Togo
8. Cameroon; Central African Republic; Chad; Congo (Brazzaville); Democratic Republic of Congo; Equatorial Guinea; Gabon; Sao Tome et Principe
9. Burundi; Kenya; Rwanda; Tanzania; Uganda (all EAC); Djibouti; Eritrea; Ethiopia; Somalia; Sudan
10. Algeria; Egypt; Lybia; Mauritania; Morocco; Tunisia; Western Sahara (disputed territory)
11. Each year subdivided into 24 slices – 3 seasons: captures rainfall variations by region. One season period for peak usage (winter in the South and summer in the North). Each weekday is sub divided into 5 time-slices, and each weekend day into 3.
12. Important caveats of the study include: (1) System balancing is not undertaken (this will be important especially as the intermittent wind and hydro with storage may interact in a manner that effects the investment profiles of each, as well as the level of storage required. (2) Macro data is assembled from available sources and de-rated in order to attempt to gain renewable energy potential data. In the absence of project level data, such estimates will be indicative, rather than conclusive. (3) Certain data, such as transmission costs, are purely suggestive. (4) The normal uncertainties apply, associated with scenario projections, including: technology learning rates which may vary especially with developing technologies, such as solar and nuclear; demand projections which relate to lifestyle changes, global economic conditions (especially where high growth will demand high commodity and resource extraction. The latter may strongly affect the demand for energy intensive mining, in resource rich Africa, etc.) (5) Energy trade is assumed to be relatively unconstrained by political considerations.
13. Trade is limited and allowed to grow over time. The penetration of new power plants is limited in the short term. Where project data is available, this is used. For example grand Inga is allowed into the solution in 2020. Otherwise, limited penetrations are used to approximate limited deployment rates of new build programs.

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Impact of thermoelectric cooling modules on the efficiency of a single-phase asynchronous machine

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Abstract
In this paper, the authors present the impact of thermoelectric cooling modules (TECMs) on the efficiency of a single-phase asynchronous machine. TECMs are used to lower the stator winding temperature and core temperature of the single-phase asynchronous machine. A similar effect might be possible by operating the asynchronous machine in a controlled lower temperature environment or by using other means of improved controlled cooling. An overview on the materials and method used during the experimental setup of the single-phase asynchronous machine with the TECMs is provided. Experimental results on the efficiency analysis, temperature analysis and equivalent circuit parameter analysis are provided. It is shown that the efficiency of the single-phase asynchronous machine can be increased by 4.44% when cooled by TECMs.

Keywords: asynchronous machine, thermoelectric cooling modules, efficiency temperature analysis

1. Introduction

Globally around 40% of the electricity supplied to the industrial (mining) sector is consumed by electric motorised systems and for South Africa around 60% of the electricity supplied to the industrial (mining) sector is consumed by asynchronous machines (DME, 1998; Mthombeni, 2007). It should be noted that these asynchronous machines also include larger three phase machines, some of them starting out at higher efficiencies, and essentially operate on different principles.

It is therefore important to invest in projects to lower the energy consumption (or improve the efficiency) of electric motorised systems and specifically asynchronous machines. In this paper, the efficiency of a single-phase asynchronous machine is improved by the use of thermoelectric cooling modules (TECMs). The TECMs are used to lower the stator winding and core temperature of the single-phase asynchronous machine. The materials and method used during this project is detailed in section 2 and the efficiency analysis results obtained from the experimental setup of the single-phase asynchronous machine is presented in section 3. In this paper, a single phase asynchronous machine is cooled by means of TECMs, the same method of cooling can also be applied to three phase motors and other electric motorised systems. The size and radically different operating point of the three phase motors may, however, present some difficulty in the design and placement of the cooling system.

The following are only a few methods that exist to effectively determine the efficiency of an asynchronous machine: 1) the segregated losses method, 2) the equivalent circuit method, 3) the slip analysis method, 4) the air gap analysis method, and 5) the current analysis method (Dlamini et al., 2010). It should be noted that in industrial terms efficiency is normally the ratio of the shaft output power to the input power. For this study, we are only interested in the impact of the cooling caused by the TECMs on the efficiency of the asynchronous machine, therefore, we decided to use the equivalent circuit method to determine the efficiency of the asynchronous machine. Gouliaev et al., (1999) provide more detail on high reliability thermoelectric cooling modules and a TECM manufacturing process developed specifically to reduce internal mechanical stresses and to increase system reliability (Gouliaev and Holopkin, 1999). The precise methods and equipment for thermoelectric

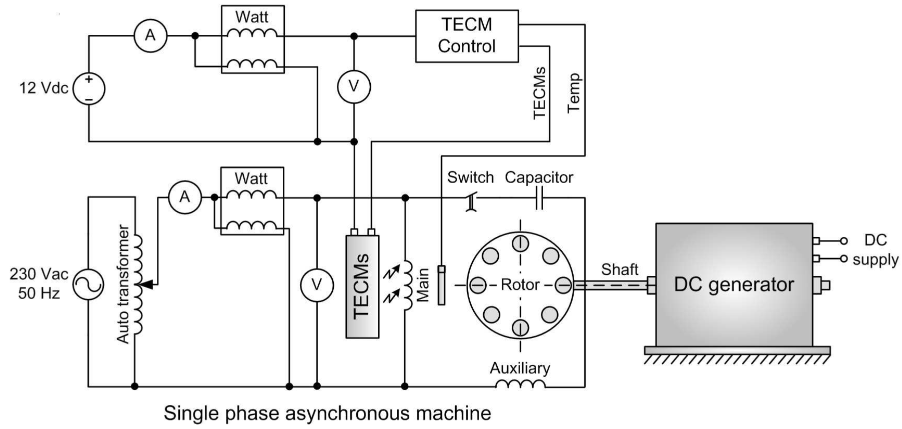

Figure 1: Experimental setup of the asynchronous machine with the TECMs

cooling modules parameters measurement is presented by Anatychuk et al., (1997). Zhang *et al.* (2010) provide detail on the analysis of thermoelectric cooler performance for high power electronic packages such as processors.

This study specifically focussed on the impact of the TECMs on the efficiency of the single phase asynchronous machine. Further study is, however, required to quantify the economics. The exact savings (return or payback) in energy needs to be quantified against the cost of the TECMs, in order to calculate the economical viability of the project.

2. Materials and method

This section provides an overview on the single-phase asynchronous machine and the method used to perform cooling. Figure 1 shows an overview diagram of the experimental setup of the single-phase asynchronous machine with a dc generator connected to the shaft. The dc generator was used as a load on the single-phase asynchronous machine. The output of the dc generator can also be used to power the TECMs.

The single-phase asynchronous machine is capacitor started by means of an auxiliary winding. The main winding is used for continuous (running) operating conditions. The temperature of the main winding (stator winding) of the single phase asynchronous machine is lowered by means of TECMs. The TECMs is supplied with a 12 V_{DC} source and is controlled according to the temperature of the main winding. The single-phase asynchronous machine is supplied with a 230 VAC, 50 Hz source.

A digital wattmeter, ammeter and voltmeter connected to the terminals of the single-phase asynchronous machine are used to measure the power consumption and determine the parameter of the equivalent circuit. The no-load test and blocked rotor test (or locked rotor test) are performed on the asynchronous machine to determine the parameters of the equivalent circuit. The autotransformer is included in the figure as it forms part of the blocked rotor test. Guru and Hiziroglu (2001) provide more detail on single-phase asynchronous machines and equivalent circuits.

The power consumption of the TECMs is measured separately with another digital wattmeter. The sum of the two digital watt-meters represents the total energy consumption of the single phase asynchronous machine with the TECMs. The power to drive the cooling devices is therefore included in the saving factor. Gouws (2011) provides more detail on the efficiency calculation (analysis) of an asynchronous motor at an industrial plant in South Africa and the simulation model development of an asynchronous motor. More detail on the simulation model of the single phase asynchronous machine in SolidWorks® and the thermal analysis performed on the single phase asynchronous machine by means of the SolidWorks® Flow-Simulation software is presented by van Jaarsveldt (2011).

Figure 2 provides a photo of the single-phase asynchronous machine that was used for this project. From this photo, the stator windings, core and closure can be clearly seen. The single-phase asyn-

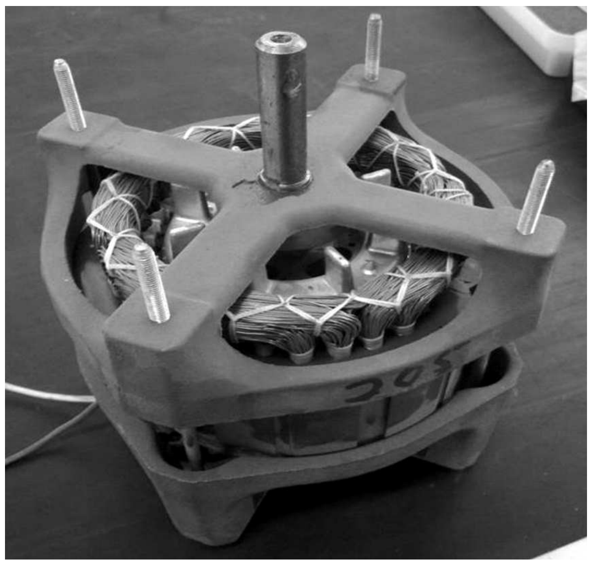

Figure 2: Photo of the single-phase asynchronous machine

chronous machine has a squirrel cage rotor design, rated output power of 0.22 kW (or 0.3 Hp), 4 poles and a rated speed of 1740 rpm. The single-phase asynchronous machine further has a slip of 3.33%, a rated torque of 1.12 Nm and a counter clockwise rotation.

Figure 3 shows a SolidWorks® drawing of the stator assembly with the exact placement of the TECMs onto the stator winding. The grey square blocks represent the TECM modules. In this figure, the stator windings and core of the single-phase asynchronous machine is clearly visible. Four TECMs are on the front-end side of the stator assembly. It was possible to only place two TECMs at the back end side of the stator assembly due to a limitation in the available space. A thermal analysis was done in SolidWorks® to determine the exact placement of the TECMs. Van Jaarsveldt (2011) provides more detail on the thermal analysis.

Figure 4 provides a SolidWorks® drawing and a photo of the housing structure for the TECMs. Four TECMs was installed on the front-end side of the single-phase asynchronous machine. The metal plate, seen in these figures is bolted directly to the structure of the single-phase asynchronous machine. The TECMs are placed onto the heat sinks by means of thermal paste. The thermal paste services as a medium between the heat sink and the TECM module and improves the dissipation of heat.

Figure 5 shows a photo of the single-phase asynchronous machine with the installed TECM housing structure. The single-phase asynchronous machine is cooled by the TECMs on the front end and back end side. The designs done by means of the SolidWorks® Flow-Simulation were used to fabricate and construct the various parts for the final design. The complete system shown in Figure 5 was used as basis to perform the efficiency analysis, temperature analysis, and equivalent circuit analysis. The results obtained from each of these tests are provided in section 3. More detail on the simulation model development of the single phase asynchronous machine done by means of the SolidWorks® Flow Simulation software is presented by van Jaarsveldt (2011).

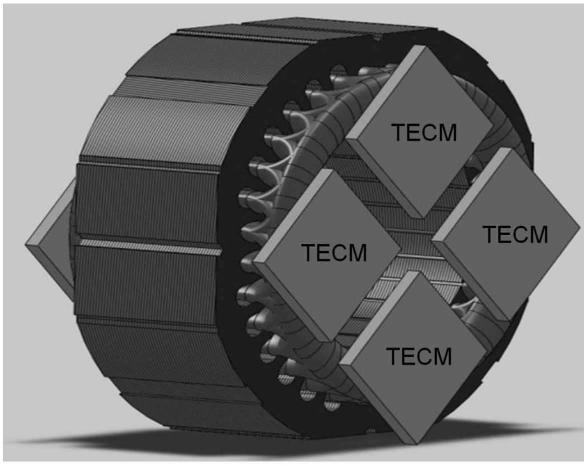

Figure 3: SolidWorks® drawing of the stator assembly with the TECMs

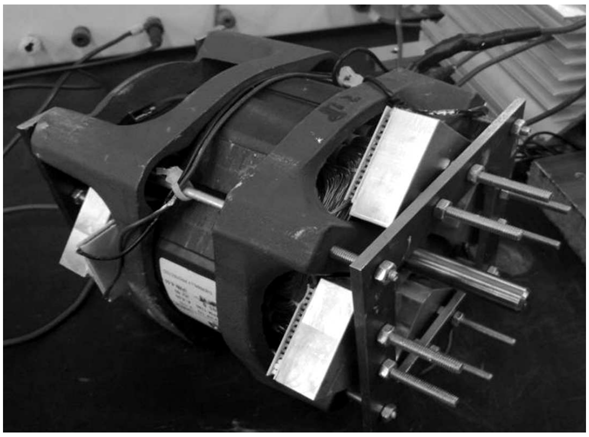

Figure 5: Photo of the single-phase asynchronous machine with the TECM housing structure

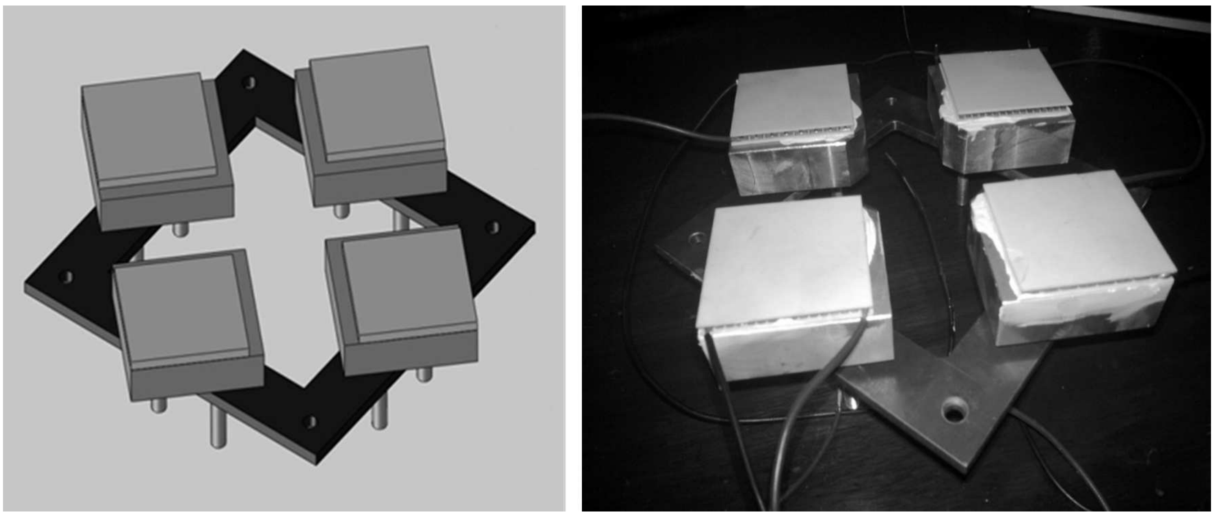

Figure 4: SolidWorks® drawing and photo of the housing structure for the TECMs

3. Results and discussion

This section provides the experimental results obtained from the single-phase asynchronous machine with the installation of the TECMs. Table 1 provides the results on the stator temperature and stator resistance test. From this table, it can be seen that the initial stator temperature and initial stator resistance is 24.6°C and 3.12 Ω, respectively. The readings are recorded in 5-minute intervals and after an hour, the stator temperature and stator resistance has increased to 68.7°C and 4.98Ω, respectively. The temperature increased by 44.1°C over a period of an hour and the stator resistance increased by 1.86 Ω over the same period.

Table 1: Stator temperature and stator resistance test results

Time (minutes)	*Stator temperature (°C)*	*Stator resistance (Ω)*
Initial	24.6	3.12
5	31.7	3.18
10	38.4	3.32
15	44.6	3.48
20	49.3	3.62
25	52.8	3.94
30	55.3	4.08
35	58.8	4.16
40	60.2	4.32
45	61.4	4.54
50	63.8	4.73
55	65.9	4.86
60	68.7	4.98

Figure 6 provides a graph of the stator resistance against the stator temperature. From this graph, it can be seen that the data follows a second order polynomial of $y = 0.0011x^2 - 0.0565x + 3.8637$, with a R^2 value of 0.9889. The R^2 value obtained for the fit between the measured data and the second order polynomial represents a very good fit. Griffiths (2005) provide more detail on second order polynomial line fittings (or trend-lines) and the coefficient of determination (R^2). It can further be seen from this figure that when the stator temperature decreased, the stator resistance also decreased.

Table 2 provides the experimental results for the no-load test. From this table, it can be seen that at an average temperature of 30°C, the voltage was 100.4 V, the current was 5.80 A, the power factor was 0.22387 and the active power was 130.36 W. When the temperature reached 68.8°C, the voltage was measured at 100.1 V, the current was 5.75 A, the power factor was 0.24772 and the active power was recorded at 142.58 W.

Table 2: Experimental results for the no-load test

Temperature (°C)	*Voltage (V)*	*Current (A)*	*Power factor (θ)*	*Power (W)*
30	100.4	5.80	0.22387	130.36
40	100.6	5.83	0.23039	135.12
50	100.0	5.74	0.23906	137.22
60	100.5	5.81	0.24339	142.12
68.8	100.1	5.75	0.24772	142.58

Table 3 provides the experimental results for the blocked-rotor test. From this table, it can be seen that at an average temperature of 30°C, the voltage was only 19.60 V, the current was 6.17 A, the power factor was 0.71691 and the active power was 86.70 W. When the temperature reached 68.8°C, the voltage was measured at 20.67 V, the current was 6.03 A, the power factor was 0.74111 and the active power was recorded at 92.37 W.

Table 4 provides the parameter calculation results for the blocked rotor test. From this table, it can be seen that the leakage reactance's (X_1 and X_2) and rotor resistance (R_2) was calculated at 1.151 Ω

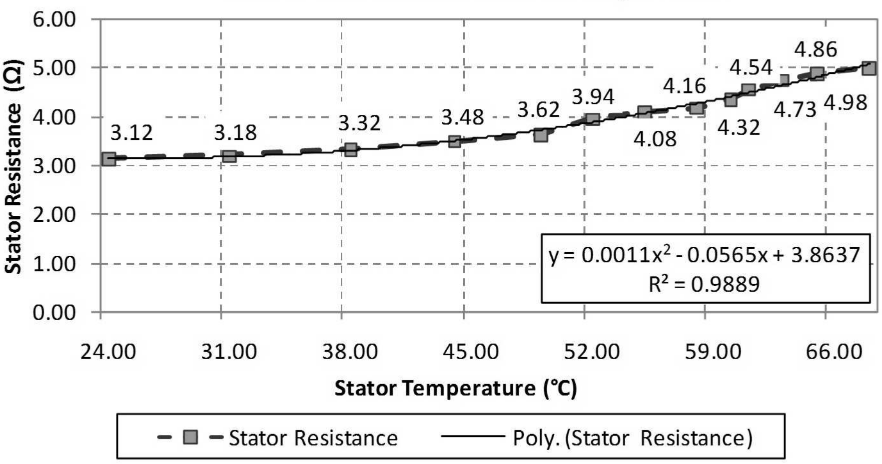

Figure 6: Plot of the stator resistance against the stator temperature

and 0.170 Ω, respectively. The input impedance, total resistance and total reactance for the blocked rotor test were calculated at 3.428 Ω, 2.540 Ω and 2.301 Ω, respectively.

Table 3: Experimental results for the blocked rotor test

Temperature (°C)	*Voltage (V)*	*Current (A)*	*Power factor (θ)*	*Power (W)*
30	19.60	6.17	0.71691	86.70
50	20.31	6.15	0.72901	91.06
60	20.47	6.08	0.73509	91.49
68.8	20.67	6.03	0.74111	92.37

Table 4: Parameter calculation results – Blocked rotor test

Parameter	*Description*	*Value (Ω)*
Z_{bm}	Input impedance	3.428
R_{bm}	Total resistance	2.540
X_{bm}	Total reactance	2.301
$X_1 = X_2$	Leakage reactance	1.151
R_2	Rotor resistance	0.170

Table 5 provides the parameter calculation results for the no-load test. From this table, it can be seen that the magnetization reactance (X_m) and the rotational loss (P_r) was calculated at 30.280 Ω and 62.814 W, respectively. The impedance, resistance and reactance for the no-load test were calculated at 17.409 Ω, 4.312 Ω, and 16.866 Ω, respectively.

Table 6 provides the results on the efficiency analysis of the single-phase asynchronous machine. From this table, it can be seen that when the stator winding temperature is 30°C, the efficiency of the asynchronous machine is 47.05%. When the temperature rises to 68.8°C, the efficiency drops to 42.61%. The efficiency therefore increased by 4.44% when the stator temperature decreased by 38.8°C over the provided period.

Table 5: Parameters calculation results – no-load test

Parameter	*Description*	*Value*
Z_{nl}	No-load impedance	17.409
R_{nl}	No-load resistance	4.312
X_{nl}	No-load reactance	16.866
X_m	Magnetization reactance	30.280
P_r	Rotational loss	62.814

Figure 7 provides a graph on the machine efficiency against the stator temperature. From this graph, it can be seen that the data follows a second order polynomial of $y = -0.0009x^2 - 0.0306x + 48.773$, with a R^2 value of 0.9987. The R^2 value of 0.9987 obtained from the fit between the measured data and the second order polynomial represents a very good fit. It can further be seen from this figure that the motor efficiency increased when the stator temperature decreased.

Table 6: Efficiency analysis of the single-phase asynchronous machine

Stator winding temperature (°C)	*Efficiency (%)*
30	47.05
36.3	46.62
40	46.04
50	45.06
60	43.79
68.8	42.61

Table 7 provides an efficiency comparison of the single-phase asynchronous machine. From this table, it can be seen that the efficiency of the asynchronous machine was increased from 42.61% under normal operating condition to 47.05% under cooled operating condition. The stator temperature under normal operating conditions was calculated at 68.8°C and the stator temperature under cooled operating conditions was calculated at 30°C.

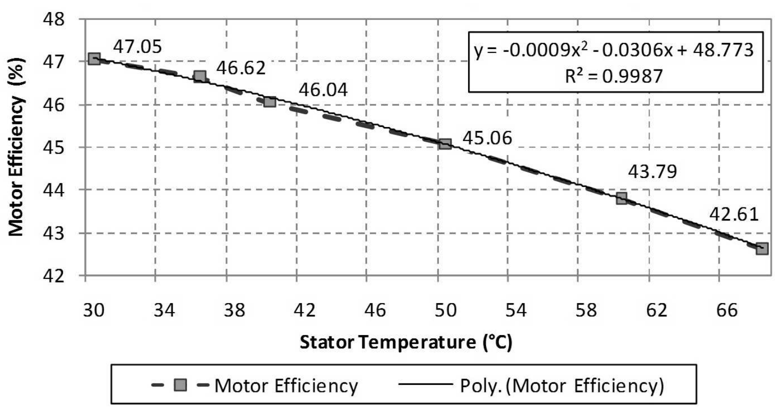

Figure 7: Plot of the asynchronous machine efficiency against the stator temperature

Table 7: Efficiency comparison of the single-phase asynchronous machine

Normal operating condition		*TECM cooled operating condition*	
Stator temperature (°C)	*Efficiency (%)*	*Stator temperature (°C)*	*Efficiency (%)*
68.8	42.61	30	47.05

4. Conclusion

In this paper, the stator and core temperature of a single-phase asynchronous machine is lowered by means of TECMs. The impact of the cooling (by means of the TECMs) on the efficiency of the single-phase asynchronous machine was presented. The experimental results included an efficiency analysis, temperature analysis and equivalent circuit analysis. It is shown that when the stator temperature increased, the stator resistance increased, but the machine efficiency decreased. When the stator temperature was decreased by the TECMs the stator resistance decreased, which in turn, increased the efficiency of the single phase asynchronous machine. The TECMs also has an influence on the core temperature of the single-phase asynchronous machine. The efficiency of the single-phase asynchronous machine was increased from 42.61% under normal operating condition to 47.05% under cooled operating condition (by means of the TECMs). The efficiency of this specific single-phase asynchronous machine was therefore increased by 4.44%.

It should be noted that the class of machine selected for this study is normally used because they are cheap, reliable, and small and generally only drive small loads. The efficiency of these types of single-phase asynchronous machines is generally not a selection criterion. A larger percentage efficiency increase is required to justify the cost of the TECMs and to make the system economically viable. Further study is required to calculate the exact impact of the TECMs (and cooling in general) on larger three-phase machines, which are normally more efficient to start with. The impact of TECMs (and cooling) on three phase machines working in closed environments where other means of cooling (typically air) is not available will also provide an interesting study.

Van Jaarsveldt (2011) presents more detail on the efficiency analysis of the asynchronous machine. Huai *et al.*, (2003) provide detail on the computational analysis of the temperature rise phenomena in electric asynchronous motors and Wang *et al.*, (2010) provide detail on a single-phase asynchronous motor with series connected windings and capacitors.

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Evaluation of noise levels of two micro-wind turbines using a randomised experiment

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Abstract
One of the more contentious environmental concerns of wind turbines is the wind turbine noise. This study assesses the noise impacts of two micro-wind turbines on the environment by comparing the noise generated by these turbines to traditionally accepted surrounding sounds. The sound level data was collected using a randomised experiment and fitted using a general linear model (GLM). The GLM was used to determine the relationship between the sound level generated at a given site to the time of day, the wind speed, the wind direction and a fixed predetermined distance from the sound source.

Keywords: general linear model, micro-wind turbine sound levels, sound pressure levels.

1. Introduction

Energy is an important aspect of social and economic development in South Africa. The demand for electricity has increased over the years and the challenge is to promote renewable energy in South Africa (Winkler, 2005).

Eskom, the predominate supplier of electricity in South Africa, has implemented a number of price increases over the past few years, causing a growing concern in the country. In light of the current electricity shortage, there is a need to consider alternative energy sources. Solar, water, wind and nuclear power are generating interest as future sustainable sources of power.

One of the most developed and cost effective renewable energy source has been shown to be wind energy (Prospathopoulos and Voutsinas, 2007). Wind turbines are one of the cleanest energy production machines (Islam, 2010). Tommaso, Miceli and Rando (2010) refer to a study conducted by Greenpeace where it was estimated that in the year 2020, 12% of the world's energy will be by means of wind energy.

One of the biggest environmental concerns of wind turbines is the noise emission (Prospathopoulos and Voutsinas, 2007). Excessive exposure to noise has been shown to cause several health problems. The most common health problems are hearing loss, headaches, and fatigue (caused by sleep disturbance) (Alberts, 2006). Extremely high noise exposure may even cause constricted arteries and a weakened immune system (Alberts, 2006). This paper assesses the noise impacts of wind turbines on the environment by comparing the wind turbine noise to traditional accepted surrounding sounds.

Most studies conducted internationally on the noise emission of wind turbines have been survey type studies. These studies deal with the perception of noise and focus on large scale wind turbine farms near residential areas. At the time of the study, there were no operational wind turbine farms near residential areas in South Africa and thus a survey study was not possible. However, micro-wind turbines are a growing area of interest in the Port Elizabeth (PE) region. There has been an increase in the installation of micro-wind turbines and solar panels in households. As such, this paper evaluates actual noise measurements from operational micro-wind turbines in PE.

1.1 Noise and sound fundamentals

Sound is a travelling wave which is characterised by its frequency and magnitude. The loudness is related to a physically measurable quantity, namely the intensity of the wave. The intensity is defined as the energy transported by the wave per unit time across unit area and is proportional to the square of the wave amplitude. Sound in this paper was measured on a logarithmic scale, using the Sound Pressure Level (SPL) in units known as decibels (dB). SPL is defined as the instantaneous difference between the actual pressure created by the wave and the average pressure given at a point in space.

A-weighting, denoted by dBA, is a filter that is often related to SPL. It decreases or amplifies certain frequencies. This is in accordance with the international standards to approximate the frequency dependence of average human hearing. A-weighting readings are intended for measurements of low-level sounds (e.g. environmental noise and industrial noise) (Howe, Gastmeier and McCabe, 2007).

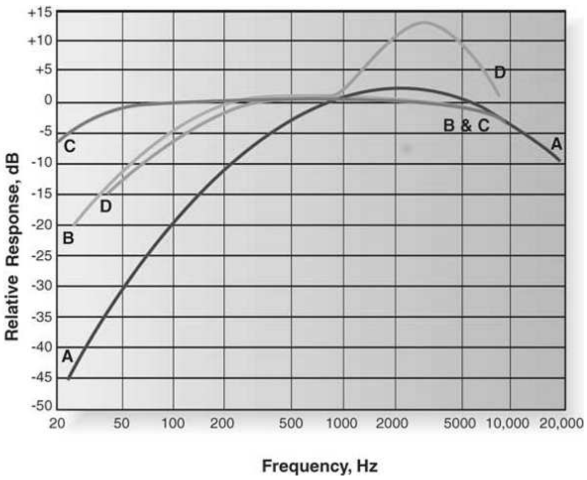

Figure 1: Acoustic weighting curve
Source: www.extron.com (Retrieved on 13 November 2011)

Noise is defined as unwanted sound and does not need to be excessively loud to cause annoyance. For sound to be perceived as noise it depends on the duration and amplitude of the sound (Kamperman and James, 2008). Noise annoyance is a feeling of displeasure that is created by noise. Noise annoyance is related to sound properties and as well as individual, situational and noise source related factors (Pederson and Waye, 2007).

1.1.1 Sounds from wind turbines

Sounds from wind turbines can be divided into two groups: mechanical sounds and aerodynamic sounds.

Mechanical sounds are described as sounds that are related to the interaction of wind turbine components. The source of this sound comes from the gearbox, generator, yaw drives, cooling fans and auxiliary equipment (Rogers *et al*, 2006). According to Rogers *et al.* (2006) small (or micro) wind turbines are more likely to produce more noticeable mechanical noise.

Aerodynamic sounds are generated by the interaction between the wind flow and the wind turbine components, namely the blades of the wind turbine and the wind turbine tower. Depending on the wind turbine and the wind speed, aerodynamic noise has been described as a buzzing, whooshing, pulsing and even a sizzling sound (Alberts, 2006). When the wind turbines blades are downwind of the tower, it is known to make a thumping sound as each blade passes the tower.

1.1.2 Previous studies

Other researchers (Pederson and Waye, 2007) claim that excessive noise associated with wind turbines may just be a perception. Factors that add to this perception are visibility, economic benefit from wind turbine farms and place of residence. Pederson and Waye (2007) showed that there is an increase in the irritability of noise when residents can see the wind turbines. Furthermore, Pederson and Waye (2007) showed that one in two respondents was positive towards wind turbines, but only one in every five was positive towards their impact on the landscape scenery. The conclusion of their study was that there was a significant decrease in noise annoyance when people benefitted economically from the wind turbines.

Bolin, Nilsson and Khan (2010) investigated whether natural sounds are able to mask wind turbine noise. Their results showed that there was a reduction in the perceived loudness of wind turbines due to the masking of natural sounds. Wind turbine farms are normally placed in rural areas with low ambient noise. This may contribute to the perception that wind turbines are noisy. The research of Bolin *et a*l. (2010) impacts this study as it provides evidence that placing a wind turbine in an environment with high ambient noise levels may have the ability to mask the wind turbine noise.

1.2 Objectives

This study has the following objectives:

- To design an experiment to collect sound level data from different sites in the Summerstrand, PE region.
- To propose a method for comparison of wind turbine noise to traditional surrounding sounds.
- To identify the factors influencing the sound levels of micro-wind turbines by comparing the sound levels at different sites.

2. Research methodology

A randomised experiment was designed to collect sound level data from several sites in the PE region. Sound level data was collected via an MT975 sound level meter. Readings were taken over a 70 day period. The site and time for each reading were selected randomly and four measurements were taken at each site and time. The reason that only four sets of measurements were taken at each site and time was due to the time constraint. The randomised selection process of each site and time was created in GNU R 2.11.1 (R Development Core Team, 2010).

The sites selected for the experiment are given in Table 1. The seventh site was the ambient measurement for the vertical axis micro-wind turbine. The ambient measurement for the horizontal micro-wind turbine was not possible as the horizontal wind turbine could not be switched off during the experiment.

Measurements were taken at 08h00, 12h00, 17h00 and 22h00. The reasons for these four times were that they were believed to include a typical day's activity. The 08h00 and 17h00 times represent periods of busy community activity, the 12h00 time represents a period of midday relaxation, while the 22h00 time represents a quiet period with little community activity.

For each treatment level two separate readings were taken. These recordings were related to the distance from the sound source. The first measurement was taken close to the sound source. The second measurement was taken approximately 10m from the source sound. This 10 m distance was chosen as it was believed to be the approximate distance that a micro-axis wind turbine would be between two residential households.

Sound measurements were recorded in decibels with an A-weighting over a period of two minutes. In the two minute period, decibel measurements were recorded every half a second making a sample size of 240. This was assumed to be a large enough sample to obtain an accurate decibel recording for each measurement. According to the IEC (International standards: Wind turbine generator systems Part 11: Acoustic noise measurement techniques) document at least 30 measurements are required in a one minute period to determine an accurate average sound level for a wind turbine evaluation. Once the sound data was collected the average decibel level over the 240 measurements was calculated in MS Excel 2007.

A WSD-100 Wind Speed and Direction Sensor was used to record the average wind speed in m/s and the average wind direction for each measurement. The WSD-100 Wind Speed and Direction Sensor was set up at the Centre of Energy Research (CER) on the Nelson Mandela Metropolitan University South Campus. It was assumed that the measurement recorded at the CER was an accurate average measurement for wind speed and direction for the Summerstrand region in PE, where all measurements were taken. Wind speeds and wind directions were logged instantaneously every 5 minutes. The average wind speed and wind direction were calculated over a 15 minute period during the time that the sound measurements were taken. The wind direction was defined as a qualitative variable and was grouped into four categories, North, South, East and West.

3. Results and discussion

The descriptive statistical analysis of the sound level data is given in Section 3.1 with results presented in tabular and graphical form followed by discussion. The fitted General Linear Model is given and discussed in Section 3.2.

3.1 Descriptive statistics

A basic descriptive analysis of the quantitative variables was done in STATISTICA v10. Presented in Table 2 are the descriptive analysis results of decibel measurements at the seven sites at the distance closest to the turbine. Similar results were observed for distance 10m away.

The data set had one missing observation. This is seen in Table 2, under the vertical axis wind turbine column. The missing sample measurement occurred at 08h00. The reason a measurement was not obtained was a malfunction of the vertical axis wind turbine.

The results in Table 2 indicate that the street had the highest average decibel reading of 66.0 dBA. The sound levels at the site were influenced by vehicles travelling in the vicinity and the change in vehicle speeds for traffic lights, hills and intersecting roads. This street is used by vehicles during the day and has a busy traffic intersection with traffic lights. These factors influence the average sound levels present at the site.

The horizontal axis wind turbine had an average decibel reading of 62.4 dBA. This was the second

Table 1: Site description

Site	*Location*	*Geographical co-ordinates*
Horizontal axis wind turbine e300[1] (1kW)	Hobie Beach, Port Elizabeth	33° 58.881'S, 25° 39.530'E
Vertical Axis Wind Turbine (1kW)	NMMU South Campus, Port Elizabeth	34° 0.523'S, 25° 39.908'E
Residential area	Cathcart Road, Port Elizabeth	33° 58.801'S, 25° 38.441'E
Beach front	Pollock Beach,Port Elizabeth	33° 59.065'S, 25° 40.279'E
Rural environment	NMMU South Campus, Port Elizabeth	34° 0.509'S, 25° 39.744'E
Street	Beach Road,Port Elizabeth	33° 58.607'S, 25° 38.870'E

Table 2: Descriptive statistics

	Street	*Horizontal wind turbine*	*Beach front*	*Residential area*	*Rural*	*Vertical wind turbine*	*Ambient site of the vertical turbine*
Mean (dBA)	66.0	62.4	60.5	51.0	48.4	46.1	43.8
Standard deviation (dBA)	3.8	4.2	5.1	4.2	7.8	6.0	4.8
Sample size (n)	16	16	16	16	16	15	16

highest average sound level found across the sites. Although the microphone was in close proximity to the wind turbine, the surrounding sounds of traffic, pedestrians and beach activity could have contributed to the readings. However it was noted that the wind turbine made sounds that can be described as a 'whoosing' and 'swishing' sound. This type of sound can be characterised as aerodynamic sounds produced by the interaction between the blades of the wind turbine and the air flow around the blades. These sounds would have also been captured when taking the measurements.

The lowest average decibel reading was the ambient sound level at the vertical axis wind turbine site. This result was surprising as the rural site was expected to have the lowest sound level readings. However, the rural site measurement position was situated near several trees and bushes. An increase in wind speeds could have increased the noise levels due to the moving of the leaves of the trees and bushes. Also the ambient measurement for the vertical axis wind turbine was situated at the CER which consists of buildings and other structures. These buildings and structures would have influenced noise propagation paths and most likely dampened the sound levels recorded.

The second lowest average decibel reading was found at the vertical axis wind turbine with an estimated sound level of 46.1 dBA. The vertical axis wind turbine mean estimate of 46.1 dBA indicates a 2.3 dBA increase in sound levels at this site.

For most of the sites, the standard deviation of the sound levels was fairly low. This indicates that the sounds levels did not vary much from their mean values. The exceptions to this were the rural and the vertical wind turbine sites, which had considerably higher standard deviations. This could be due to the low ambient noise levels at these sites.

Figure 2 is a graphical representation of the mean decibel recordings for the seven sites at the four different times. The graph indicates that the sound levels at the residential site, ambient site of the vertical axis wind turbine, the vertical axis wind turbine site and the rural environment are lower than the other three sites. Worth noting is that the average sound levels at the vertical axis wind turbine were lower than the residential area. This is a very interesting result. This indicates that the existing noise in the residential areas is sufficiently noisy to potentially mask noise created by the vertical axis wind turbine. This means installing a vertical axis wind turbine in a residential area may not increase the noise pollution, as is often argued.

As concluded by Bolin *et al* (2010), environments with high sound levels may have the ability to mask wind turbine noise. This masking may decrease the perception of noise irritability of wind turbines. The sites with the highest sound levels are the street and the beachfront. This suggests these sites are potential environments in which to place horizontal axis micro-wind turbines.

3.2 General linear model

To assess the noise level of wind turbines, a general linear model was used. The model compared the response variable, the average sound measurement

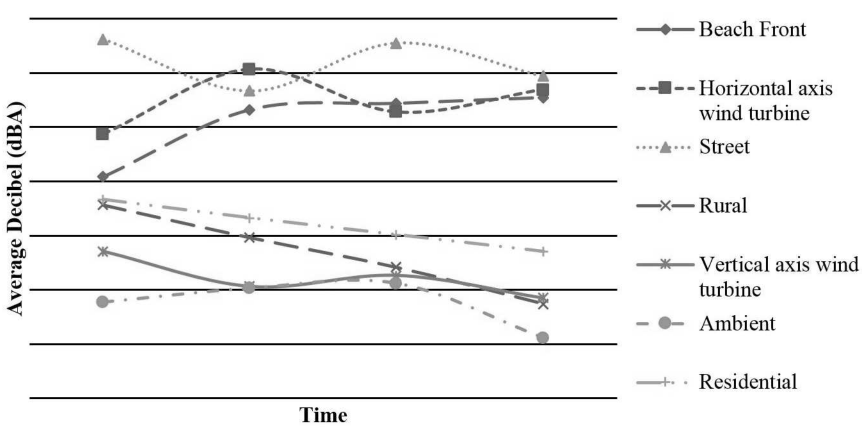

Figure 2: The average decibel recordings for each site across the four different times

at the different sites, and the results are interpreted as noise comparisons. The linear model was also used to identify which variables influence the sound levels.

The following model was fitted to the sound level data:

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site}$$
$$+ \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{11} x_{11}}_{distance}$$
$$+ \underbrace{\beta_{12} x_{12} + \ldots + \beta_{14} x_{14}}_{direction}$$

where y, the response variable, is the average sound level (dBA). The independent variable, x_1 = wind speed (m/s) is quantitative, and the independent variables site, time, wind direction and distance, coded as binary response variables, are qualitative. The seven sites are coded as

$$x_2 = \begin{cases} 1 & if \ \ Beach\ Front \\ 0 & otherwise \end{cases},$$

$$x_3 = \begin{cases} 1 & if \ \ Horizontal\ \ axis\ \ wind\ \ turbine \\ 0 & otherwise \end{cases},$$

$$x_4 = \begin{cases} 1 & if \ \ Ambient\ site \\ 0 & otherwise \end{cases},$$

$$x_5 = \begin{cases} 1 & if \ \ Vertical\ \ axis\ \ wind\ \ turbine \\ 0 & otherwise \end{cases},$$

$$x_6 = \begin{cases} 1 & if \ \ Rural\ site \\ 0 & otherwise \end{cases}, \text{ and}$$

$$x_7 = \begin{cases} 1 & if \ \ Street \\ 0 & otherwise \end{cases}$$

with the residential site used as the base level.

The four time periods are coded as

$$x_8 = \begin{cases} 1 & if \ \ 08h00 \\ 0 & otherwise \end{cases}, \ x_9 = \begin{cases} 1 & if \ \ 12h00 \\ 0 & otherwise \end{cases}, \text{ and}$$

$$x_{10} = \begin{cases} 1 & if \ \ 17h00 \\ 0 & otherwise \end{cases}$$

with 22h00 used as the base level.

The two distance measures are coded as

$$x_{11} = \begin{cases} 1 & if \ \ Distance\ one \\ 0 & otherwise \end{cases}$$

with distance two used as the base level.

The four directions are coded as

$$x_{12} = \begin{cases} 1 & if \ \ West \\ 0 & otherwise \end{cases}, \ x_{13} = \begin{cases} 1 & if \ \ North \\ 0 & otherwise \end{cases}, \text{ and}$$

$$x_{14} = \begin{cases} 1 & if \ \ South \\ 0 & otherwise \end{cases}$$

with East used as the base level.

This model was fitted to 222 data points using the statistical software package STATISTICA 10. The goodness-of-fit measures of the model, as well as the significance level of the models' overall fit are presented in Table 3.

Table 3: Goodness-of-fit statistics for the GLM

Multiple R	*Multiple R^2*	*Adjusted R^2_a*	*p*
0.8707	0.7582	0.7418	0.0000

The coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a) are 0.8707, 0.7582 and 0.7418 respectively. These statistics all indicated a good fit for the model. The *F*-test to determine the utility of the model had a statistically significant *p*-value of 0.00. This small *p*-value indicated that the model was useful for predicting the average sound level based on the independent variables used.

The effects of the individual factors are shown in Table 4. The significance of the factor is indicated by the *p*-value in the table. Commonly used levels of significance are 1%, 5% and 10%. These are typically referred to as strongly significant, significant and weakly significant respectively. The results in Table 4 indicate that wind speed, site and wind direction are statistically significant at the 1% level, whilst time and distance at 10 m from the sound source are statistically insignificant at the 10% level.

Table 4: Effects of individual factors for the GLM

Effect	*p*
Intercept	0.0000
Wind speed (m/s)	0.0000
Site	0.0000
Time	0.2511
Distance	0.2145
Wind direction	0.0024

We use these results to reduce the size of the model by omitting the insignificant factors whilst simultaneously cautioning researchers to the fact that the model used did not contain interaction terms. Interaction terms can influence factor levels in such a way that a factor appears to be statistically significant yet it is the interaction between factors that creates the significance. Likewise it is also possible that a factor appears to be statistically insignificant yet it is an important predictor of a response variable. The reason for not including interaction terms at this stage is that the variable, wind direction is uncontrolled, which resulted in an incomplete data set hence estimation problems occurred.

The reduced model estimated for the 222 data points is given by the equation

$$y=\beta_0+\underbrace{\beta_1 x_1}_{windspeed}+\underbrace{\beta_2 x_2+\ldots+\beta_7 x_7}_{site}$$
$$+\underbrace{\beta_{12} x_{12}+\ldots+\beta_{14} x_{14}}_{direction},$$

with variables as previously defined.

In Table 5 is the summary of goodness-of-fit measures of the reduced model, as well as the significance level of the overall models' fit.

Table 5: Goodness-of-fit statistics for reduced model

Multiple R	*Multiple R^2*	*Adjusted R^2_a*	*p*
0.8669	0.7515	0.7398	0.0000

Although there was a slight decrease in the R, R^2 and R^2_a the model still had a good fit to the average sound level data. This decrease was due to the decrease in the number of variables used in the estimated model. The *F*-test had a statistically significant *p*-value of 0.00 which indicated a good fit for the model. This small *p*-value indicated that the model was useful in predicting the average sound level based on the independent variables used.

Table 6: Effects of individual factors for reduced model

Effect	*p*
Intercept	0.0000
Wind speed (m/s)	0.0000
Site	0.0000
Wind direction	0.0017

The effects of the individual factors are shown in Table 6. The results in Table 6 indicate that wind speed, site and wind direction are all statistically significant at the 1% level.

Given we have reduced our model to the most parsimonious case and that no outliers were detected it is important to consider the parameter estimation for each variable. The individual parameter estimates for the reduced model are given in Table 7.

Table 7: Parameters estimates for the reduced model

	Parameter estimates	*Std error*	*p*
Intercept	49.27	0.66	0.0000
x_1 Wind speed	1.21	0.15	0.0000
x_2 Beach front	7.45	0.79	0.0000
x_3 Horizontal axis wind turbine	7.39	0.79	0.0000
x_4 Ambient site	-8.18	0.79	0.0000
x_5 Vertical axis wind turbine	-7.45	0.81	0.0000
x_6 Rural site	-5.51	0.78	0.0000
x_7 Street	9.83	0.78	0.0000
x_{12} West	-1.55	0.53	0.0037
x_{13} North	1.26	0.667	*0.0607*
x_{14} South	-1.38	0.61	0.0254

The intercept represents the average sound level response for the base level variables. The estimated parameter for wind speed indicates that for every 1 m/s increase in wind speed there will be 1.21 increase in the average sound level if all other variables are fixed. To interpret the parameter estimates a single case is discussed.

The parameter estimate for variable is -8.18. This is the lowest value of all the parameter estimates. This estimate represents the difference between the estimated mean sound level for the ambient site and the mean base level when all other factors are fixed. The negative value indicates a site of low sound levels. This estimate (-8.18) is interpreted as follows: the mean sound level recording at the ambient site is 8.18 dBA less than the residential site when all other factors are fixed. This mean response for the ambient measurement for the vertical axis micro-wind turbine site confirms what has already been shown in section 3.1; that the site has very low sound levels compared to the other six sites.

The *p*-values for the parameter estimates indicated that all but one of the variables in the model are statistically significant at the 5% level. Variable has a *p*-value slightly higher than 0.05. However the overall factor contribution was statistically significant and wind direction was found to be a useful predictor.

The conclusion of the statistical analysis is that the reduced model is preferred to the complete model. The factors wind speed, site and wind direction were found to be significant predictors of the average sound level. Surprisingly, the factors time and distance were found to be statistically insignificant, however as discussed earlier this could be a result of interaction effects.

4. Conclusions and recommendations

The aim of the paper was to provide a comparison between wind turbine noise and traditionally accepted surrounding sounds. The collection of sound level data was done using a randomised experiment. Seven sites and four different times were selected. A GLM was used to determine the relationship between the noise generated at a given site and the time of day, wind speed, wind direction and distance.

The statistical analysis summary showed that the reduced model was preferred to the complete model. The reduced model fitted the data well according to the coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a). The factors wind speed, site and wind direction were found to be significant predictors of the average sound level. The factors time and distance of 10 m away from the sound source was found to be statistically insignificant. That being said, the model shows that several factors are important predictors of the response variable. As this study is the first attempt at investigating the noise of wind turbines, it provides a useful starting point for future evaluations.

Table 7 shows that when all other factors are fixed the horizontal axis micro-wind evaluated in this study turbine increases the sound level by 7.39 dBA when compared to the sound level of a typical residential area (the base site in this study).

Improvements into the study the model would be to increase the sample size and increase the distance at which the second measurement is taken from the sound source. Distance showed to be an insignificant predictor for the average sound level. Increasing the distance from the wind turbine may show the relationship between distance and average sound level in the model. Also, the inability to assess the ambient noise measurement of the horizontal axis micro-wind turbine can be addressed. This would add more information to the change in sound levels attributed to wind turbine noise.

Adding more variables such as rainfall, topography, height, ambient noise, temperature and other distance measures to the randomised experiment may allow for a more accurate and informative model to be developed. Increasing the number of micro-wind turbine models in the experiment may also provide more information about the wind turbine acoustics.

In conclusion, a methodology for collecting of sound level data was developed. This methodology allowed for accurate modelling of sound level data. Site, wind speed and wind direction were identified as factors influencing the sound levels in an environment. Investigation into this area has the potential for extensive future research, both in the field of wind turbine acoustics and experimental design

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SADC's response to climate change – the role of harmonised law and policy on mitigation in the energy sector

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Abstract

The negligible levels of energy-related GHG emissions attributable to the Southern African sub-region translates into the sub-region contributing relatively little towards global climate change. Notwithstanding, the member states comprising the Southern African Development Community (SADC) are among the most vulnerable to the trans boundary effects of global climate change. Existing SADC climate change policy documents highlight the important role of the energy sector in climate change mitigation. Furthermore, various international, African Union and SADC legal instruments stress the crucial role of harmonised law and policy as climate change adaptive measure. It is the central hypothesis of this paper that harmonised sub-regional law and policy aimed at regulating SADC member states' mitigation efforts in the energy sector is a crucial climate change adaptive strategy. This hypothesis is based on the mandates for the formulation of a SADC climate change action plan and for mitigation in the energy sector. These mandates are contained in the texts of the SADC-CNGO Climate Change Agenda, 2012 and the Southern Africa Sub - Regional Framework on Climate Change, 2010 respectively. It is the main aim of this paper to investigate recent developments in the formulation of harmonised SADC law and policy on climate change in general and law and policy pertaining to mitigation in the energy sector specifically. In achieving the stated aim, themes to be investigated by means of a literature study are those of energy-related greenhouse gas emissions and global climate change and harmonised sub-regional policy on mitigation in the energy sector as adaptive measure in the SADC.

Keywords: energy-related GHG emissions, climate change, sub-regional policy, adaptation, mitigation

1. Introduction

According to the 2007 Report of the Inter-governmental Panel on Climate Change (IPCC) the largest growth in greenhouse gas (GHG) emissions between 1970 and 2004 has come from the energy supply sector, transport and industry (IPCC, 2007). In its 2008 *World Energy Outlook*, the International Energy Agency (IEA) warns that:

> Current global trends in energy supply and consumption are patently unsustainable – environmentally, economically and socially. It is not an exaggeration to claim that the future of human prosperity depends on how successfully we tackle the two central energy challenges facing us today: securing the supply of reliable and affordable energy; and effecting a rapid transformation to a low-carbon, efficient and environmentally benign system of energy supply. (IEA WEO 2008)

While industrialised countries and rapidly developing economies are the largest emitters of energy-related carbon dioxide (CO_2) and other GHGs, the impacts of climate change will be most evident in developing countries and regions (Modi, McDade, Lallement & Saghir, 2006; IPCC, 2007). African countries are particularly vulnerable to climate change because most states have fewer resources to cope with climate change and have low adaptive capacity (Pressend, 2011). The concept of vulnerability is important for understanding climate change in the context of social and human development as it refers to the expected magnitude of adverse effects climate change poses to SADC. In the first instance, human vulnerability will increase as a result of both extreme weather events and long-term environmental degradation resulting from climate change (Füssel & Klein, 2006). Secondly, vulnerability draws on the various manifestations of social and human deprivation, such as: social exclusion, gender discrimination, migration, employment, health and education, as well as resilience of those affected. In short, climate change will have the effect of adversely affecting the vulnerable status of the region by impacting negatively on the general development of member states and individuals alike. The impacts generally foreseen include, but are not restricted to: reduced agricultural production; reduced fresh water availability; loss of biodiversity; increased food insecurity, increased health problems; and increased migration (ADF, 2010).

Addressing the challenge of climate change clearly requires more than technical and environmental solutions. The trans boundary nature of the effects of climate change warrants comprehensive strategies based on intense cooperation which link climate change with the broad socio-economic and political development frameworks of SADC member states (SADC-CNGO Regional Policy Paper 7 2012). The southern African sub-region comprises the total geographical area occupied by member states of the Southern African Development Community (SADC) which includes: Angola, Botswana, the Democratic Republic of Congo, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe (www.sadc.org). SADC has a combined population of over 228 million people and an aggregate Gross Domestic Product (GDP) of $226.1 billion (SADC, 2003; ISS, 2006). Despite its relatively high aggregate GDP, individual countries' social and economic growth and development vary considerably. The national economic development status of the sub-region is a combination of advanced developing countries like South Africa, developing countries like Zimbabwe, and least developed countries like Malawi. The general characteristic of the sub-region's aggregate economy, however, is that of a developing sub-region (Pressend, 2011).

The main sources of CO_2 emission in Southern Africa relate directly to the generation and consumption of energy, namely fossil fuel burning (liquid fuels and especially coal in the thermal power stations of South Africa) and deforestation due to the use of traditional source of biomass as primary energy source (Kandji *et al* 2006; Chishakwe, 2010, Pressend, 2011). Therefore, while the sub-region's contribution to global energy-related GHG emissions is low, the SADC energy sector is the highest contributor to GHG emissions in the sub-region itself. Deforestation in the sub-region is characterised by a combination of forests cleared for agriculture or for commercial purposes and the increasing demand for biomass as an energy source. The decimation of forest-areas resulting from the fulfilment of energy needs inevitably leads to deforestation which in turn impacts negatively on global climate change (Goldemberg & Coelho, 2004; Agyei, 1998; Olander ea, 2009).

For SADC member states, the priority is on mitigation and also on adapting to increased climate variability and climate change (Lesolle, 2012). With reference to the areas of mitigation, the Southern Africa Sub-Regional Framework on Climate Change 2010 (Framework) specifically highlights the energy sector (Chishakwe, 2010). In conjunction hereto the SADC-CNGO Climate Change Agenda (Agenda) prescribes the formulation of a

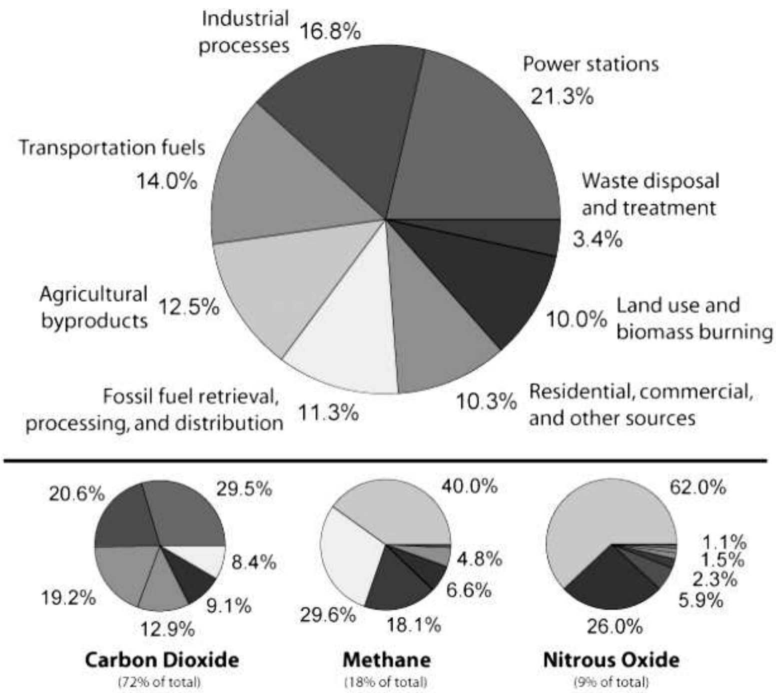

Figure 1: SADC GHG emissions per sector in 2012
Source:http://timeforchange.org/cause-and-effect-for-global-warming

SADC Climate Change Action Plan which should contain and reflect the SADC common position on climate change. In plain terms, the Agenda mandates the formulation of a single, coherent SADC policy document on climate change reflective of SADC member states' common position on climate change. This article is written from the central hypothesis that harmonised sub-regional policy responses aimed at regulating mitigation efforts in the sub-region's energy sector qualifies as climate change adaptation measure. Energy-related GHG emissions as factor contributing to global climate change and SADC law and policy on mitigation in the energy sector are themes related to this hypothesis. In addressing these themes, a series of interrelated topics will be discussed, most notably: energy-related GHG emissions and global climate change; energy-related GHG emissions and climate change in the Southern African sub-regional context; the energy sector as climate change mitigation area in SADC; and SADC climate change policy and programmes as adaptive measure. Recommendations as to the content of future SADC climate change policy and programmes pertaining to mitigation via energy sector reform will be made in the final instance.

2. Energy-related GHG emissions and climate change as global environmental challenge

2.1 Energy and climate change

Climate change has been labelled as the defining human development challenge of the 21st Century (UNDR 2007/2008). The rapid increase in energy-related GHG emissions is a topic central to the global climate change debate and is cause for major environmental concern. According to the International Energy Agency (IEA), the direct combustion of fossil fuels represents by far the largest source of energy-related CO_2 emissions comprising more than 80% of anthropogenic emissions (IEA, 2011). In 2009 electricity and heat generated from the direct combustion of fossil fuels contributed 41% towards global CO_2 emissions, with coal, oil and gas being the major contributors. While coal represented only one-quarter of the total primary energy supply, it accounted for 43% of global CO_2 emissions due to its heavy carbon content per unit of energy released (IEA 2011). These figures become even more alarming considering that coal is filling much of the growing energy demand of rapidly developing economies and, with projections showing that, without additional measures, intensified use of coal will radically increase CO_2 emissions by 2035 (IEA WEO, 2009). In fact, if the next decade of energy-related CO_2 emissions follow the linear trend of the previous decade, dangerous climate change will be unavoidable (IEA, 2012). Projections for energy use point precisely in this direction as current investment patterns are putting in place a carbon intensive energy infrastructure with coal playing a dominant role.

2.2 Energy-related GHG emissions and climate change in the African context

The IEA states that the situation surrounding energy in Least Developed Countries (LDC) situated in the SADC region is one characterised by almost non-existent levels of access to modern energy services (IEA WEO, 2010). Seven of the fourteen member states comprising SADC are currently listed by the United Nations as LDCs (Angola, the Democratic Republic of Congo, Lesotho, Malawi, Mozambique, Tanzania and Zambia) (www.unc-

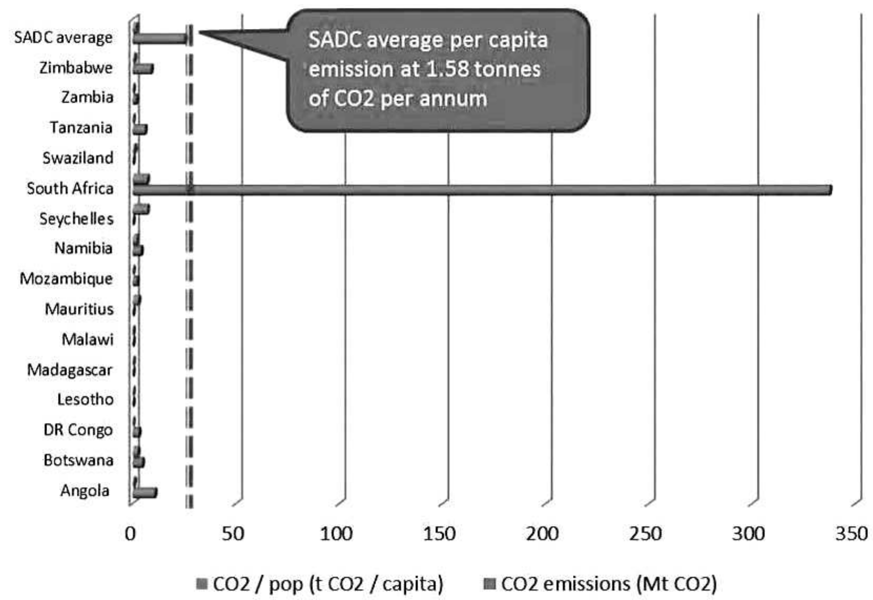

Figure 2: GHG emissions indicators of SADC member states
Source: 2010 Key World Energy Statistics

tad.org). In SADC, energy consumption and, as a result, GHG emissions are low both per capita and on aggregate and the primary concern is not necessarily curbing emissions but rather the conservation of the local environment and natural resources (Lesolle 2012; Modi *et al.,* 2006).

On account of its low per capita energy consumption, the SADC region contributes relatively little towards over-all energy related GHG emissions globally (IEA WEO, 2010). Current fossil fuel consumption levels in SADC are so low that even if these countries increased consumption at an annual rate of 10% per year, from 2010 to 2015, the associated per capita GHG emissions will remain at levels that are less than five percent of current levels in industrialised countries (IEA, 2011). Increased GHG emissions from SADC should therefore not likely have any significant impact on the climate, both local or globally. The foregoing statement should, however, be taken against the backdrop of population growth and accompanying human needs and the effect thereof on energy-related GHG emissions in Africa. The current African population of 954 million people – 14% of global population, will grow to 17% by 2025 and by 2050 a quarter of the world's population will live in Africa. While this population explosion sets the scene for future economic growth, the growing demand for food and energy it brings about will undoubtedly contribute toward increasing anthropogenic GHG emissions and ultimately climate change (Cilliers, 2009). Naturally, this is true only if the *status quo* pertaining to the fossil fuel intensive nature of energy generation in Africa prevails. In short, population growth in Africa will result in an increased demand for energy, leading to higher levels of energy-related GHG emissions and ultimately culminating in heightening the continent's vulnerability to climate change. The energy sector and in particular the provision of electricity for southern Africa's population and industries comprise a complex issue without even adding climate change to the equation. If energy needs throughout the sub-region increases incrementally with population growth and SADC intends on reducing its energy-related GHG emissions a transition to more climate-friendly sources of energy is inevitable. This requires redefining SADC's competitive advantage from attracting energy–intensive sectors on the basis of non-renewable energy, such as coal, to building a new advantage around low carbon technology and energy (Ruppel, 2012). This shift to a low carbon energy future for the sub-region will need to be regulated in terms of sub-regional law and policy responses.

3. Regional policy as climate change adaptation measure

Climate change is an environmental challenge without borders or geographical limits. While climate change is globally caused, its impacts are locally felt and nowhere more so than in vulnerable regions such as Southern Africa. The trans boundary nature of climate change and its impacts necessitates harmonised solutions.

At the African Union (AU) level, the *AU-NEPAD African Action Plan 2008* expressly states the important role harmonised regional policies will play in adapting to climate change. At the international level, the development of law and policy related to climate change originated from the establishment of the United Nations Intergovernmental Negotiating Committee in 1990 and the subsequent drafting of the *United Nations Framework Convention on Climate Change* (UNFCCC) and the *Kyoto Protocol*.

These two documents stress the importance of climate change mitigation and identify the implementation measures needed for the mitigation envisaged. Mitigation refers to efforts to reduce or prevent emission of GHGs and, according to the text of the UNFCCC, should take the form of reducing GHG emissions in terms of cooperative action. The emission reduction-based climate change mitigation intended by the UNFCCC was to have the so-called Annex I countries reduce their GHG emissions to 1990 levels by the year 2000 (Article 4(2) of the UNFCCC). The measures needed to achieve the proposed mitigation is listed in the Kyoto Protocol and includes emissions trading, the clean development mechanism (CDM), and joint implementation (Articles 17,12 and 6 of the Kyoto Protocol).

Equally as important as mitigation is the process of adapting to climate change. Adaptation in the field of climate change refers to changes in processes, practices and structures to moderate potential threats associated with climate change (McDonald, 2011, Leary, Dokken & White, 2001). This definition should be seen to include adaptive action at the regional level – a viewpoint underpinned by the UNFCCC's reference to the important role of regional law in facilitating adaptation to climate change (Article 4(1) of the UNFCCC). The author submits that adaptation should therefore be seen to include the formulation of harmonised sub-regional law geared towards collective action relating to climate change mitigation and adaptation (Lubbe & Barnard, 2012).

3.1 SADC mandate for harmonised sub-regional responses to climate change

At the SADC level, the important adaptive role of harmonised regional policies is recognised by a number of provisions contained in various regional instruments. Article 5(2)(a) of the *Treaty of the Southern African Development Community*, 1992 (SADC Treaty) states that in order for the region to attain the objective of sustainable development, the harmonisation of political and socio-economic policies is necessary. With reference to energy policies specifically, article 3(1) and article 4 of the *SADC Protocol on Energy*, 1996 (Energy Protocol) states as one of its objectives, the harmonisation of national and regional energy policies on matters of common interest in order to provide sustainable energy services (Ruppel, 2012).

3.1.1 The SADC Energy Action Plan, 1997 and the Energy Sector Activity Plan, 1999

The *SADC Energy Action Plan* (Action Plan) was established in terms of the provisions of the SADC Energy Protocol and encompasses a comprehensive action plan for harmonised regional energy activities. The provisions contained in both the Action Plan and the *Energy Co-operation Policy and Strategy Document*, 1996 were the impetus for drafting the SADC Energy Sector Activity Plan in 1999 (Activity Plan) which sets out the activities and time-frame related to proposed regional energy activities.

Activities regulated by the Activity Plan are grouped under four focus areas, namely: energy trading; investment and finance; training and organisational capacity building; and information and experience exchange. The Activity Plan and its related activities ultimately revolve around the objective of increasing levels of access to modern energy sources in the region. It should be noted that the Activity Plan indeed refers specifically to climate change and the concerns and challenges it poses to the SADC energy sector. In this regard, the Activity Plan states that mobilising climate change funding will play an important role in facilitating adaptation of the energy sector to the impacts climate change is set to have (AECOM, 2009).

3.1.2 The Regional Indicative Strategic Development Plan, 2003

The Regional Indicative Strategic Development Plan (RISDP) acknowledges climate change as an environmental challenge resulting from and contributing towards the current developmental status of the region and refers to the important role of harmonised regional environmental policies as adaptive measure. The overall goal of the regional environmental intervention envisaged by the RISDP is to ensure the equitable and sustainable use of the environment and natural resources for the benefit of present and future generations.

In order to attain this goal, the RISDP identifies harmonised legal and regulatory frameworks focused on the promotion of regional cooperation on environmental issues as focus area. As mechanism of implementation, the RISDP proposes regional environmental policies embodied in multilateral environmental agreements concluded in terms of existing international climate change policy. The RISDP furthermore sets time-bound targets for the implementation of the regional environmental policies envisaged by its provisions. These include the finalisation of legal instruments for regional cooperation in environment and resources by 2006 and the development and implementation of environmental standards and guidelines by 2008.

3.1.3 Southern Africa Climate Change Framework, 2010

The path towards a SADC common position on climate change starts prior to the 17th Conference of Parties on Climate Change (COP 17), with the SADC Council of Non-Governmental Organisations (SADC-CNGO Regional Policy Paper 7 2012). The SADC-CNGOs was formed in 1998 to facilitate meaningful engagement of the people of the region with SADC Secretariat at regional level, and with the Member States at national level through national NGO umbrella bodies (http://www.sadccngo.org/). Following an intensive consultation process with its members and stakeholders, the SADC-CNGO commissioned a background research which was later transformed into a policy paper on climate change. The policy paper outlined the following as the key SADC positions to be taken to COP 17: legally binding emissions reduction targets; funding support for climate change; rejection of private market mechanisms; women focussed interventions; adaptation; mitigation; technology transfer; just transition; national policies and strategies; and ecological debt (Pressend, 2011). It paved the way for further consultation among SADC Member States on their shared position on climate change for C0P17, which resulted in the drafting of a Southern Africa Sub-Regional Framework on Climate Change in 2010.

While the Framework is only an indicative framework and therefore not legally binding among SADC member states, it is, however, a good start in that it makes recommendations to SADC countries to streamline climate change responses at the sub-regional level. The Framework not only reviews responses by member states to the climate crisis in terms of adaptation, mitigation, financing and technology transfer, it also flags out the priorities for the region. Adaptation was identified as the most pressing issue to be prioritized in the regional response framework. Within the Framework, proposed adaptation programmes include the following: disaster risk reduction and management; sectorial planning and implementation and building economic and social resilience (SADC-CNGO Policy Paper 7, 2012).

The four identified mitigation areas are: the energy sector; Reduced Emissions from Deforestation and Degradation (REDD) and REDD plus mechanisms; Land Use, Land Use Change and

Forestry (LULUCF); and International Carbon Markets (SADC-CNGO Policy Paper 7, 2012). Mitigation by the energy sector is seen to be the domain of those countries that are huge carbon emitters, most notably South Africa with its carbon intensive energy sector (Pressend, 2011).

The Framework describes energy sector mitigation as policies, programmes, and projects aimed at: scaling up investments for increased access to affordable and cleaner energy sources; developing appropriate alternative energy sources; increase energy efficiency; applying the precautionary approach to the development of alternative renewable energy sources; develop appropriate transport plans; develop standards and regulations to engender mitigation; and promote cleaner production and infrastructural development (Southern Africa Climate Change Framework, 2010). In conjunction with the provisions of the Framework, COP 17 also introduced voluntary mitigation actions on developing countries which, in the context of energy sector reform, refer to a transition to a low carbon economy (Lesolles, 2012).

Mitigation actions by means of energy reforms in the Southern African sub-region should therefore be seen to relate to decreasing fossil fuel reliance and shifting to more renewable energy options (Ruppel, 2012). This will have the result of reducing energy-related GHG emissions thereby reducing the extent of global warming and the effects of climate change. With specific reference to mitigation in the energy sector, the Programme for Basic Energy and Conservation (ProBEC) is a SADC climate change project geared towards basic energy conservation. Currently, ProBEC is actively involved in Malawi, Lesotho, Mozambique, Tanzania, Swaziland, Zambia, Botswana, Namibia and South Africa. ProBEC aims to ensure that low-income population groups satisfy their energy requirements in a socially and environmentally sustainable manner with a specific target on biomass energy. One of the foreseeable results of ProBEC interventions (specifically shifting from fossil fuels to biofuels) undertaken thus far is climate change mitigation in the form of reduced energy-related GHG emissions (http://www.probec.net).

3.1.3 SADC climate change agenda

After its success in drafting the Southern Africa Sub-Regional Framework on Climate Change, the SADC-CNGO convened a Regional Policy Dialogue session under the theme 'Beyond Durban - What is the regional climate change and sustainable development agenda' in 2012. One of the specific objectives of the dialogue session was to discuss the Southern Africa Common Position regarding COP17 and priority issues for SADC. The dialogue session resulted in the drafting of a regional policy paper named for the dialogue itself and contains an Agenda for SADC beyond C0P17. The Agenda is not intended as a comprehensive roadmap for SADC and is described by its drafters as 'deliberately minimalist for it to be doable'. It does, however, lay the groundwork for future sub-regional dialogue, policy formulation and implementation.

Due to its minimalist content, the Agenda itself does not contain any specific reference to energy or the role of energy sector reform in climate change mitigation. It does, however, refer specifically to the need for harmonised sub-regional climate change responses. With specific reference to the importance of a harmonised sub-regional climate change strategy, the agenda proposes that SADC should put in place and implement a Regional Climate Change Programme of Action. The programme of action should include priority interventions for the region such as adaptation as spelt out in Cancun, Durban and in Rio Declarations (SADC-CNGO Policy Paper 7, 2012). Further key components of the Agenda are: research and analysis; national climate change policies and strategies; implementation of the Durban Platform Action; regional and domestic resource mobilisation; adaptation; mitigation and climate governance (SADC-CNGO Policy Paper 7, 2012). At the time of writing, no progress towards the formulation of a SADC Climate Change Programme of Action had been made.

4. Conclusion and recommendations

Climate change resulting from energy-related GHG emissions is a global challenge without physical or geographical borders which pose various threats to vulnerable regions such as SADC. The trans boundary nature of climate change and its effects necessitates regulatory action in the form harmonised law and policy responses among SADC member states. Although a number of climate-related programmes and initiatives exist in SADC, much still needs to be done in terms of SADC climate law and policy. The current SADC climate change law and policy framework comprises the Southern African Sub-regional Climate Change Framework and the SADC-CNGO Climate Change Agenda. One of the areas of climate change mitigation identified by the SADC climate change framework is the energy sector and it furthermore specifies the mitigation actions to be taken by the energy sector. These provisions echo the voluntary mitigation measures prescribed to developing regions via COP 17, which mandates developing regions with a 'transition to a low carbon economy'. It is submitted that the role of the energy sector in climate change mitigation in developing regions such as SADC pertains to a shift from overtly fossil fuel-based energy sectors to more renewable energy sources. It is furthermore submitted that the energy sector reforms needed to achieve this transition to a low carbon economy based on less carbon-intensive energy sources should be regulated in terms of harmonised sub-regional law and policy.

The SADC Climate Change Framework and Agenda are steps in the right direction for harmonised sub-regional responses to climate change but they do not remedy the lack of a single, coherent sub-regional climate change policy document. This legal lacuna, in the mind of the author, can only be addressed with the formulation of a SADC Climate Change Programme of Action with sector-specific action plans. These sector-specific action plans must set out detailed policies and programmes of action on the mitigation areas of implementation as identified by the SADC Climate Change Framework. These should include: the development of appropriate alternative low carbon energy sources; increasing energy efficiency and the application of the precautionary approach to the development of low carbon renewable energy in the sub-region. A sub-regional energy sector action plan outlining SADC's common position on energy sector climate change mitigation is accordingly proposed. An energy sector action plan as sector-specific area of the overall SADC Climate Change Programme of Action will be crucial in aligning and then guiding the energy activities of member states towards improving climate change mitigation. It will ensure that shared climate change policy objectives are clearly defined and pursued through commonly agreed energy strategies among member states.

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Considerations for a sustainable hybrid mini-grid system: A case for Wanale village, Uganda

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Abstract
The extension of modern energy services to rural sub-Saharan Africa has continuously provided a challenge to energy utilities. The continued reliance on diesel generators for rural electrification is increasingly becoming unsustainable, due to a number of factors, among which includes their high fuel dependency, and the uncertainty surrounding the price and availability of fossil fuels. While the influx of renewable energy technologies has provided a means for providing off-grid electrification services, the intermittent nature of renewable resources poses a challenge, as energy generation does not always coincide with usage. Through a combination of renewable energy technologies, energy storage, and conventional diesel generation, a hybrid mini-grid system is able to achieve synergy in operation, hence providing a reliable means of extending electricity services to rural consumers. In this paper, a hybrid mini-grid system is proposed for the supply of electricity to a remote village in Uganda. Renewable energy resources are identified, an estimation of the projected village short-term electricity demand is modelled, and using HOMER software, a hybrid mini-grid system is designed, components sized, and the system optimized for efficient and reliable operation to meet the village demand at an affordable cost. A well designed and operated hybrid mini-grid system offers a viable tool for the electrification of even the remotest of areas.

Keywords: rural electrification, renewable energy, hybrid mini-grid system

1. Introduction

The absence of electricity greatly impacts on the lives of many people in Uganda. The government faces the challenge of providing reliable electricity to most of its population. The share of people connected to the national grid in Uganda is currently at 15%, of which, only 5% of the rural population has access to electricity (MEMD, 2012). This is despite the fact that 85 % of the population live in rural areas, and mainly engage in subsistence agriculture for food and a livelihood (Okure, 2009). The fact that Uganda is a developing country with a large rural population presents the energy utility and regulators with a number of challenges in their search for rural electrification options (Ezor *et al*., 2009):

- First and foremost, there is currently insufficient generation capacity to meet the growing electricity demand in Uganda. Therefore, the electricity transmission and distribution utilities concentrate most of the supply to the more reliable customers in urban and developed areas.
- Secondly, the cost of transmitting and distributing electricity to rural areas is high; this coupled with the difficulty of the terrain to most rural areas, low demand, and sparsely populated areas, makes grid extension unfavourable to energy utilities.
- Also, in Uganda, the location of rural areas poses a greater risk to energy losses due to theft (of power and equipment). This also results in difficulties in the monitoring and maintenance of the transmission and distribution network in these remote areas. This increases revenue loss-

es, making it more difficult to justify rural electrification.
- High electricity tariffs also constrain the affordability of rural consumers. This is coupled with their unwillingness to pay for the extension of the service. Thus, there's usually a necessity for government intervention when extending electricity services to poor consumers hundreds of kilometres from the nearest power plant.

Thus, without electricity, many rural communities struggle to obtain the resources necessary to lift them out of a static state.

Wanale village in Eastern Uganda faces these same challenges. Many of the members in this community are subsistence farmers who rely on their produce for food and a source of income. Energy services are provided through local resources such as kerosene for lighting, and fuel wood for cooking, with the nearest access to a 'posho' (maize flour meal) shop a two hour walk from the village. For such a community, electrification can act as a catalyst for the social and economic development of the area, allowing the members access to modernized health care, modern communication services, increased availability of light to extend work and engage in income generating activities (MPG, 2010). But in spite of their justifiably low energy needs, the road to achieving electrification can be unfortunately complex and costly.

2. Hybrid mini-grid systems

Due to the current global concern over carbon emissions from conventional fossil fuelled power generation sources, many countries are pushing for the integration of renewable resources into the power generation mix. In the past, diesel-powered generators have been the go-to supply option for mini-grid electrification. But factors such as their high maintenance and lifecycle costs (due to their daily fuel needs), high carbon emissions, fluctuating price and availability of diesel fuel, have led to a push for a more sustainable and reliable solution (Moner, 2008). Renewable energy technologies have in recent years become a popular choice for application in remote electrification projects. Among the renewable resources, mini-hydro, biomass, wind and solar have been the standout participants for mini-grid applications. These offer a relatively free and widely available energy resource (Dali, *et al.,* 2010). Resources such as geothermal, hydro and bio-energy are able to provide stability, reliability, and low-cost power generation. However, this is not the case for others such as wind and solar. Implementing these comes with some challenges (Lhendup, 2008):

- Solar and wind resources have daily and seasonal variations. This presents a challenge in matching the available resource with the fluctuating demand, adding to the complexity of deploying them.
- Furthermore, solar and wind energy technologies currently have high capital costs at low conversion efficiencies, resulting in high energy costs for the corresponding generated energy. This provides a challenge of affordability for rural consumers.
- Intermittent resources such as wind and solar, require additional technologies such as energy storage, invertors and regulators in order to optimize for reliable, adequate and efficient power supply.
- It should also be noted that, current cost comparisons between electricity generated from renewable sources of wind and solar, and the equivalent fossil fuel generators, favours the later. This presents a challenge in justifying the alternative to some customers.

Therefore, mini-grids combining both renewable and conventional diesel generation systems could provide a more competitive technical solution, providing a higher level of energy reliability, at a moderately cheaper cost. These are termed hybrid mini-grid systems. Combining these multiple technologies enables the system to overcome limitations inherent in either (Panapakidis, *et al.,* 2009).

Hybrid mini-grid systems are designed to incorporate renewable energy generation technologies with a conventional diesel generator, thus addressing limitations in terms of fuel flexibility, reliability, emissions reductions, efficiency and economics. The main advantages of such a system would include:

- The maintenance and fuel costs of the generator are significantly reduced as the diesel generator only operates when need arises.
- The system also provides opportunity for capacity expansion to cope with increasing future demand.
- The synergy achieved by combining the renewable energy generator and the diesel genset also offers, in theory, a least-cost supply option.

The application of this technology can be boundless especially for rural electrification. Hybrid mini-grid systems are capable of providing 24h grid-quality electricity, better efficiencies, and flexibility in planning and operation (Setiawan, *et al.,* 2008). However, hybrid mini-grid systems do have a number of challenges that require some attention in order for successful implementation. Decisions regarding the success of the system will not only depend on parameters such as the resources, load and topology, but also other parameters such as the willingness to pay, and the consumption growth in the households. Also, mini-grid life cycle cost are often unknown to a large extent, due to site specific conditions such as village topography, local conditions affecting the components, and time series data such as weather.

Off-grid electrification is site specific. In the design considerations, the location, available resources, and village demand profile play a significant role in the decision making process. Also the conditions of the area change over time: the demand grows, and grid extension could become a feasible option in the near future. All these factors need to be considered in the preliminary research. The probability of a successful project will also depend on the community's participation; the early assessment phase must integrate an analysis of the local conditions and the rural community's needs. Community involvement and support must be maximized in the design considerations, as the involvement of the local personnel reduces the chances of project failure and any negative image of the renewables in the region. Service providers and stake holders need the knowledge and tools to determine the least cost option for a given level of service in a specific period (Simon & Glanio, 2011).

Through software modelling a generalization of an electricity supply system can be manipulated to better understand the technical behaviour of the system under different conditions. Software models act as a desktop prefeasibility study before the implementation of the actual system.

3. Case study: Wanale village

Wanale village is located in the Mbale district, Eastern Uganda at the coordinates 1.0210522N, 34.189341E (iTouchMap.com, 2011), as shown in Figure 3. Uganda is situated in East Africa, with its capital city, Kampala district in the central part of the country. Mbale district lies approximately 245 km by road, northeast of Kampala. Wanale trading centre lies 15km east of Mbale town on the southern foothills of Mount Elgon. Traveling from Mbale town takes about 45 minutes along Murram Road to Wanale village. The equator passes through the country, just south of the capital Kampala. This proximity to the equator makes the daylight variations non-existent, with the sun-rise around six in the morning, and falling by seven in the evening. This makes Uganda's average temperature at 25-26°C all year round (Frances, 2002). Like most rural villages in Uganda, the members of Wanale are subsistence farmers. Some of the crops they grow include: coffee, maize, bananas, fruits, onions, tomatoes and carrots. Their basic energy consumptions are based on traditional fuel wood and charcoal for cooking, candles and kerosene lamps for lighting, and batteries for their small radios. Electricity can provide for some of these rural energy needs, substituting for some of the traditional energy sources such as those used for lighting, while facilitating modern communication (television sets and radios), basic appliances such as charging, and other uses such as refrigeration. The nearest utility grid access point, an11kv distribution line closest to this village is 7 km away (MPG, 2010). But given the steep nature of the terrain between the access point and the community, the chances of the electricity utility considering grid extension to this village are remote. Thus, a well-designed hybrid mini-grid system could offer a feasible electrification solution to the community's energy needs.

When designing a decentralized rural electrification system, some of the most important aspects to consider include the resource availability and the expected demand. The available resources must be enough to meet the anticipated demand.

3.1 Resource availability

The members of Wanale recognized the potential for generating hydro-electric power on the Wanale River. A feasibility study, done by Micro Power Group Uganda Ltd on the site, established a design flow rate of 20l/s at 50 metres head. At this flow, a locally fabricated pelton turbine coupled to an induction motor would be able to provide an electrical output capacity of 4.4kW, at an overall efficiency of 50% (MPG, 2010).

Also, Uganda's location along the equator, guarantees that the country receives some of the highest solar irradiation values in the world throughout the year. Photovoltaic systems (PV) are a proven technology, and numerous experiences around the world have proven their technical reliability and economic applicability in rural electrification programs (Martins, 2005). Wanale has very good solar resources, receiving on average at least 5kWh/m^2/month average solar irradiation, with a maximum of over 6.5kWh/m^2/month (NASA, 2004). HOMER simulates the annualized average solar irradiation value at 5.94kWh/m^2/day as shown in Figure 1.

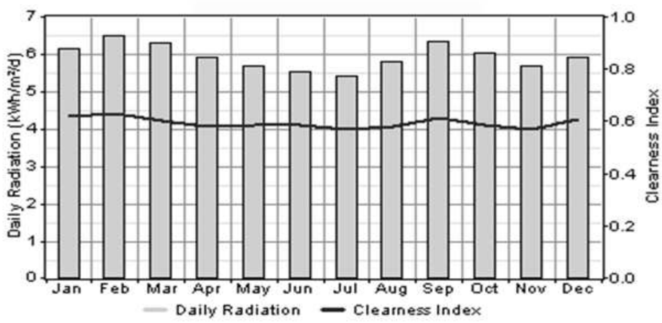

Figure 1: Homer simulation of Wanale's annual solar irradiation
(NASA, 2004)

3.2 Demand

In the pre-feasibility analysis of the location, it was established that there existed about 80 households

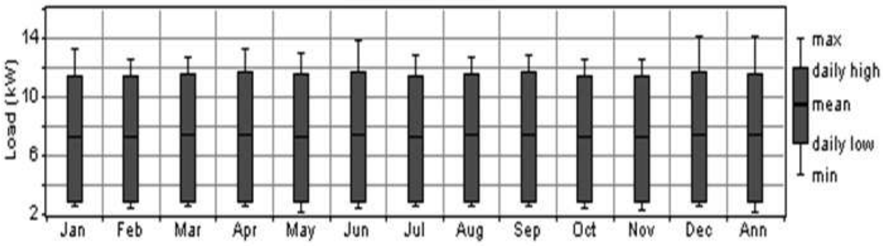

Figure 2: Homer simulation of Wanale load profile
(MPG, 2010)

within a 1 km radius in Wanale village with interest in this project who were ready to be connected once the system became operational. These also included a trading centre, with commercial activity and a dispensary among others. An estimate of the short-term demand forecast at Wanale was then done, based on consumption loads and patterns inferred from a model derived in the work done by (Blennow, 2004), for estimating electricity demand in rural villages in Tanzania.

A total load profile was then generated to represent the estimated annual short-term load profile. This is simulated in HOMER software to take on the shape as shown in Figure 2, presenting Wanale's daily demand at 144kWh, with a peak load of 14kW.

This load is observed to be greater than the available supply capacity of 4.4kW from the design supply of the Pico-hydro plant. Thus different supply configurations are investigated to determine the optimal supply system to meet the electricity demand at Wanale village. Electricity supply is based on available resources of hydro and solar. Also included in the design are battery energy storage, and a diesel generator. The objective is to achieve the most reliable system at the least Cost of Energy (COE).

3.3 Hybrid mini-grid system design

In the design of a mini-grid system, the choice and sizing of the components, and the most adequate control and management strategy must be obtained (Bala & Siddique, 2009). In this study, HOMER software is used to size and simulate the different supply configurations and performance elements of the hybrid mini-grid system design (NREL, 2005). The system configuration used by HOMER for the design simulations is based on the "parallel" architecture as shown in Figure 3.

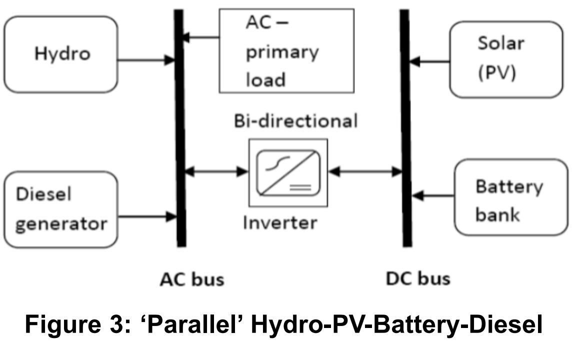

Figure 3: 'Parallel' Hydro-PV-Battery-Diesel hybrid system
(HYRESS, 2008)

This configuration allows all energy sources to supply the loads separately depending on the demand, as well as meeting an increased level of demand by combining the various energy sources. The bi-directional inverter charges the battery (acting as a rectifier) when excess energy is available from the other generators, as well as acting as a DC-AC (Direct Current to Alternating Current) converter (inverter) under normal operation (HYRESS, 2008).

3.4 HOMER system inputs

System analysis with HOMER requires information on the resources, economic constraints, and control methods. Input information will include: village demand (one year of load data), renewable resources, component technical details and costs, constraints, controls, type of dispatch strategy.

In Table 1 is the cost and technical information for the Wanale hybrid mini-grid system design. Preliminary studies done by (MPG, 2010), established the Pico-hydro plant for an output of 4.4kW. Initial capital cost estimates for small hydro plants internationally, with current technologies, can range from US$ 1. 500 to $2 500/kW (Kusakana, *et al.,* 2009), with 75% of the development cost determined by the location and site conditions, and 25% being the cost of the manufactured electrical and mechanical components (RETScreen, 2004). In this study, the cost was taken at $2 500/kW because of the remote location, and thus ragged terrain of the village and surrounding areas.

3.5 HOMER simulation results

The presence of hydro resources at Wanale guarantees a base-load supply of electricity, but the capacity would not be enough to cater for the projected short-term village demand. As shown in Figure 4, with only the Pico-hydro supplying electricity, the cost of energy (COE) would only be $0.034/kWh, but the system would incur a capacity shortage of over 57%, meeting less than half of the village's annual demand.

Table 1: Technical and cost data considered for the hybrid power system
(Akyuz, et al., 2010; Simon & Glanio, 2011)

System	*Parameter*	*Unit*
PV	Capital cost (US$/kWp)	2,822
	Replacement cost (US$/kWp)	2,822
	Operation & maintenance	
(US$/yr)	0	
	Life time (yr)	25
Hydro	Capital cost (US$)	11,000
	Available head (m)	45.29
	Design flow rate (L/s)	20
	Efficiency (%)	50
Diesel generator	Capital cost (US$/kW)	400
	Replacement cost (US$/kW)	400
	Operation & maintenance	
(US$/hr)	0.15	
	Life time (year)	10
	Diesel price (US$/l)	1.3
Converter	Capital cost(US$/kW)	1,445
	Replacement cost (US$/kW)	1,445
	Operation & maintenance	
(US$/yr)	0	
	Life time (yr)	15
	Efficiency (%)	90
Battery storage 6FM200D	Type	
	Capital cost (US$/kW)	800
	Replacement cost (US$/kW)	600
	Operation & maintenance (US$/yr)	15

Total NPC: $ 11,961
Levelized COE: $ 0.034/kWh
Operating Cost: $ 90/yr

Quantity	kWh/yr	%
Excess electricity	2,094	5.9
Unmet electric load	31,282	48.4
Capacity shortage	37,067	57.4

Quantity	Value
Renewable fraction	1.00

Figure 4: HOMER simulation results for hydro supply

This system is therefore insufficient to meet the available demand, and additional generators and resources are required to match the load.

Thus, three other possible supply configurations are simulated based on the consideration of all possible available generation source options.

Case 1: Hydro + diesel generator
In this configuration, the Pico-hydro plant provides the base-load electricity supply, while a diesel generator is designed with the system to provide the additional energy supply when necessary. This configuration offers the more simplified generation system, and has been a configuration of choice in many mini-grid installations involving small hydro systems.

As shown by the results in Figure 5, the optimal system design would include the addition of a 10kW diesel generator to the 4.4kW Pico-hydro supply, at an initial cost of $15 000. With the current diesel price in Uganda averaging $1.3/liter, the Total Net Present Costs (TNPC) would equal $316,193, resulting in COE of $0.458/kWh. As observed in the sensitivity analysis in the figure, the energy cost is responsive to the variations in the fuel price, with lower diesel prices corresponding to lower COE, while rising fuel costs increase the operating costs of the system, resulting in higher energy costs.

Case 2: Hydro + solar + energy storage
In this configuration, hydro provides the base-load electricity supply, while the system is also designed to utilize the available solar resources in the village and thus incorporate PV in the electricity supply system. The intermittence of supply from the solar resource, demands the presence of an energy storage facility for improved system reliability. This is simulated in HOMER in the form of Absorbent Glass Mat (AGM) sealed deep-cycle lead-acid batteries.

As shown in Figure 6, the optimal system design includes; in addition to the 4.4kW supply from hydro, an additional 8kW from PV, with a 4 battery bank (6FM200D) energy storage facility (9.6kWh nominal capacity).

This system has a higher initial cost ($41 111) than the system in case 1 due to the cost of the PV

Diesel ($/L)		Hydro (kW)	Gen (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
1.000		4.44	10	$ 15,000	24,039	$ 271,609	0.394	0.51	0.00	13,922
1.100		4.44	10	$ 15,000	25,431	$ 286,470	0.415	0.51	0.00	13,922
1.200		4.44	10	$ 15,000	26,823	$ 301,332	0.437	0.51	0.00	13,922
1.300		4.44	10	$ 15,000	28,215	$ 316,193	0.458	0.51	0.00	13,922
1.400		4.44	10	$ 15,000	29,608	$ 331,054	0.480	0.51	0.00	13,922
1.500		4.44	10	$ 15,000	31,000	$ 345,915	0.502	0.51	0.00	13,922
2.000		4.44	10	$ 15,000	37,961	$ 420,221	0.609	0.51	0.00	13,922

Figure 5: HOMER simulation results for Case 1

	PV (kW)	Hydro (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
	8	4.44	4	3	$ 41,111	1,810	$ 60,429	0.128	1.00	0.40

Figure 6: HOMER simulation results for Case 2

	PV (kW)	Hydro (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
	3	4.44	50	1	$ 140,221	2,576	$ 167,715	0.403	1.00	0.48

Figure 7: HOMER simulation results for Case 2 with 50 batteries for energy storage

Diesel ($/L)		PV (kW)	Hydro (kW)	Gen (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
1.000		7	4.44	5	15	5	$ 51,979	14,586	$ 207,685	0.301	0.68	7,470
1.100		7	4.44	5	15	5	$ 51,979	15,348	$ 215,814	0.313	0.68	7,468
1.200		7	4.44	5	15	5	$ 51,979	16,121	$ 224,070	0.325	0.68	7,469
1.300		7	4.44	5	20	5	$ 55,979	16,517	$ 232,291	0.337	0.69	7,321
1.400		7	4.44	5	20	5	$ 55,979	17,273	$ 240,369	0.349	0.69	7,323
1.500		7	4.44	5	20	5	$ 55,979	18,028	$ 248,419	0.360	0.69	7,325
2.000		7	4.44	5	24	5	$ 59,179	21,652	$ 290,311	0.421	0.69	7,230

Figure 8: HOMER results for Case 3

panels, but it also offers lower life cycle costs, at a Total Net Present Cost of $60 429, resulting in a COE of $0.128/kWh. But although this system provides a low energy cost, the system capacity would be insufficient to meet the total demand, incurring a 40% capacity shortage. Even at an increased number of batteries, optimal system operation will always incur a capacity shortage as shown in Figure 7. This indicates that the resources are not matched to the energy storage, and further simulations do not change this situation.

Case 3: Hydro + solar +energy storage + diesel
In this configuration, the system utilizes all available generator options, with a diesel generator added in the mix to provide backup supply to the hydro, PV and energy storage. And as shown in Figure 8, at a fuel price of $1.3/liter, the hybrid mini-grid system, in addition to the 4.4kW supply from hydro, would include a 7kW PV array supply, a 5kW diesel back-up generator and a 20 battery (48kWh nominal capacity) energy storage facility.

Thus, at a system initial capital cost of $ 55 979 the Total Net Present Costs (TNPC) accumulate to $ 232 291, resulting in a COE of $0.337/kWh, for the price of diesel at $1.3/liter. And as observed in the sensitivity analysis in the figure, the rising fuel prices have a slightly negligible impact on the energy cost as compared to Case 1.

Simulation of the electrical supply properties of the system indicate that as shown in Figure 9, indicate a capacity shortage of less than 1%, meaning that the consumer demand is matched by the available supply.

3.6 Results and discussion

Three configurations of the proposed power supply system for Wanale village have been simulated. Here is a summary of the findings.

Table 2: Configuration results analysis

Supply configuration	*Initial cost ($)*	*COE ($/kWh)*	*Unmet load (%)*
Pico-hydro only	11,961	0.034	57.4
Hydro + PV + Battery	41,111	0.128	40
Hydro + PV + Battery + Diesel	55,979	0.337	0
Hydro + Diesel generator	15,000	0.458	0

- Hydro as a standalone supply system, though cheaper, has insufficient capacity to meet the village demand.
- The system in Case 2 (hydro, solar + battery energy storage) also offers a low COE, but its capacity to meet the village demand is also limited and thus power distribution to the consumers would be unreliable.
- The system in Case 1 (Hydro + diesel generator) offers a more simplified and initially cheaper supply configuration than Cases 2 & 3. But given the system's dependence on diesel fuel, its operating costs are higher and thus the higher COE. Also, its COE is dependent upon the price of fuel, as observed in Figure 5. Higher fuel costs result in a significant rise in the energy cost.
- The system in Case 3 (hydro, solar + energy storage, and a diesel generator) finds the best balance in operation, meeting the village demand at a significantly lower energy cost. Even at increasing fuel prices, the COE changes are smaller (Figure 8) compared to those in Case 1 (Figure 5).
- Also, because the diesel generator in the system in Case 3 is used less frequently than in Case 1, the operating costs are reduced through

improved system efficiency, resulting in a reduction in fuel consumption, and thus reduced emission levels.

Thus, the hybrid mini-grid system design incorporating hydro, solar + energy storage, and a diesel generator (*Case 3*), offers a reliable and economic supply system, that can best meet the demand at Wanale village. This system can potentially provide relatively cleaner (compared to predominantly based diesel systems) and reliable electricity, and thus meet some of the energy needs of the residents of the village.

3.7 Cost analysis

The electricity tariff for domestic consumers connected to the main electricity grid in Uganda is currently at Ush.524.5/kWh (Umeme, 2013). At a current average exchange rate of 1:2500 USD to Ush, this is = $0.21/kWh. At a mini-grid energy cost of $0.337/KWh, this is = Ush.842.5/kWh. This energy cost is high compared to that of grid connected consumers.

Rural consumers in Uganda are generally poor people surviving on less than a dollar a day. These consumers, though eager to upgrade to modern energy services, are constrained in their expenditure, and are in most cases unwilling to pay for an expensive service. Thus rural electrification initiatives are usually subsidized by the Government or a form of funding mechanism.

The biggest contribution to the energy cost is the initial capital investment of the system. A number of funding schemes have been proposed in various publications especially for the support of renewable energy technologies. Some of these include the Renewable energy Premium Tariff (RPT) and the Global Energy Transfer Feed-in Tariff (GET-FiT) (Girona, 2008), (Fulton, 2010). These can be used to fully or partially subsidize the system capital costs. Governments have also been known to subsidize the cost of fuel in diesel based mini-grids, though this option has been deemed unsustainable in the long run.

With capital subsidies on the renewable energy generators, the effect on the cost of energy of the system is shown in Figure 10. As observed, the subsidy effect on the capital cost of the individual renewable resource components has an impact on the lowering of the COE. But its effect is more pronounced when both the Solar and Hydro capital costs are subsidized, with the energy cost going as low as $0.29/kWh at 100% subsidy. Further subsidies on the fuel costs of the diesel generator can achieve an even lower energy cost, thus enabling the system's push towards financial sustainability.

4. The Impact of energy storage on hybrid mini-grid system operation

Customers expect electricity supply which is available all the time, is free from impromptu interruptions and provides for the safe operation of all their appliances. With the intermittent nature of supply from renewable energy resources, available methods to ensure supply, require utilities over size their

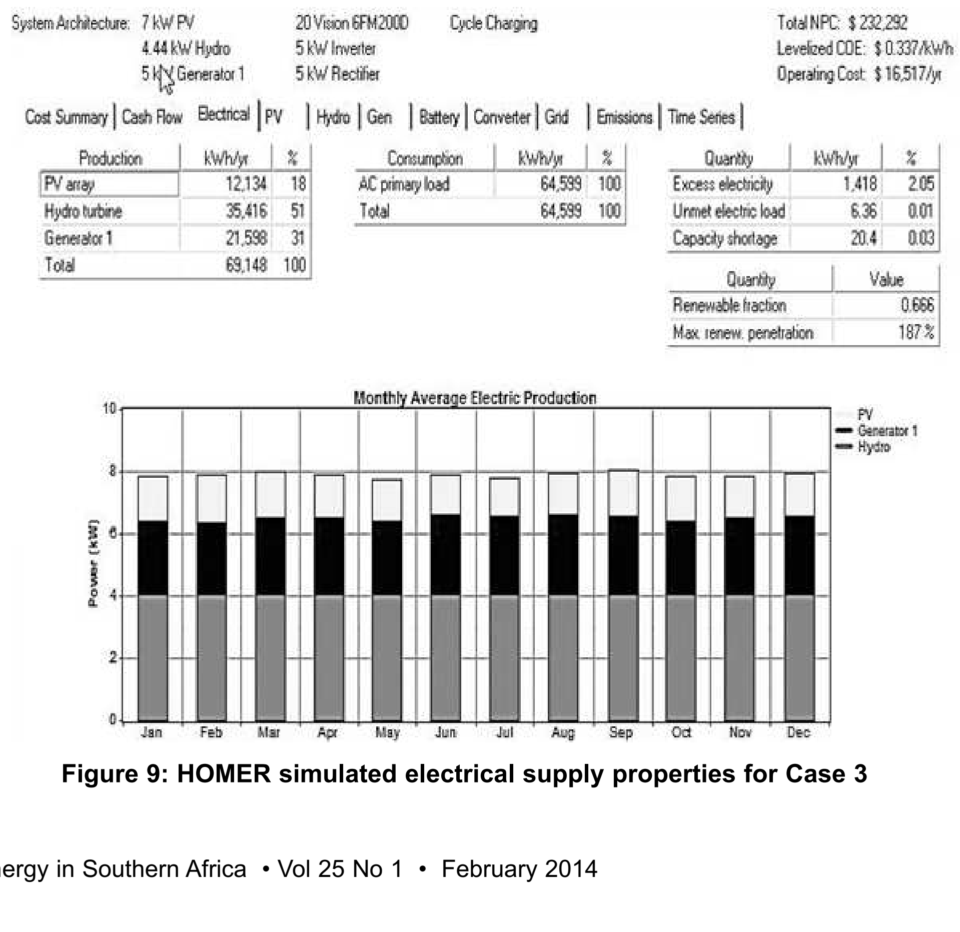

Figure 9: HOMER simulated electrical supply properties for Case 3

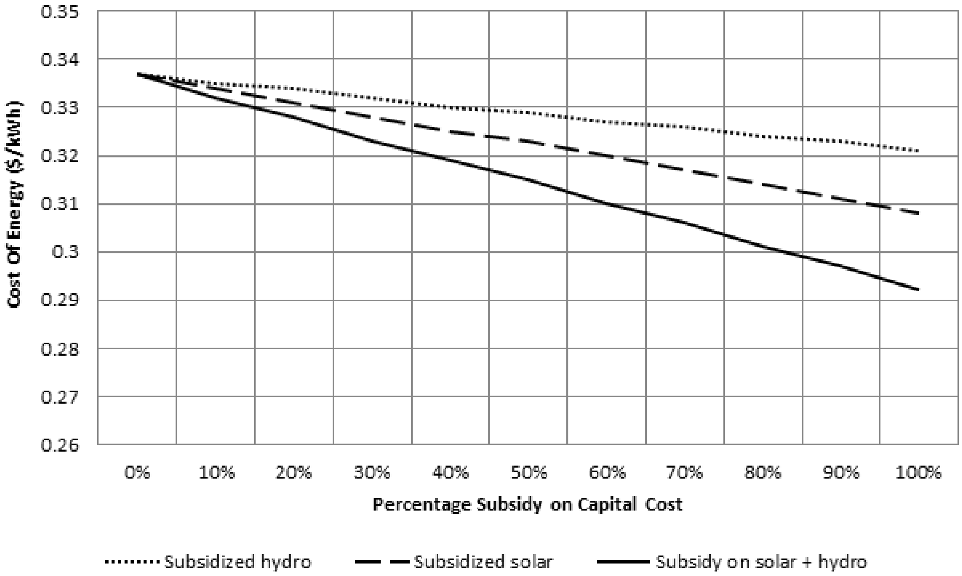

Figure 10: Effect of subsidizing the system capital costs

Gen (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
15	$ 12,000	57,314	$ 744,668	0.902	0.00	28,382	8,760

Figure 11: Homer results for a diesel only mini-grid

supply systems to meet peak demand, and the redundancy of system equipment and/ operation, to cater for demand fluctuations. With power systems currently constrained by fuel economics, and global concerns over emissions from fossil-fuel-based electricity generation, running diesel generators for extended periods is no longer a sustainable solution for meeting daily load fluctuations (Sutanto, 2002).

As can be observed in HOMER's simulation of a diesel only mini-grid in Figure 11, at a fuel price of $1.3/liter, the COE is very high at $0.902/kWh. This is mainly due to high operating costs brought about by fuel consumption of 28 382 liters annually.

This system, though able to effectively cater to the demand of the village, is too expensive in the longer term. This coupled with the associated emissions would make for an unsustainable solution.

In small isolated power systems utilizing renewable energy technologies configured with conventional diesel generators, in order to save fuel, diesel generators should not be operated continuously. The addition of energy storage to system operation eliminates this problem to some extent, providing a variety of operating flexibilities, which can have significant impacts on system reliability and economics (Roy & Bagen, 2006).

In this study, HOMER's simulation of the hourly operation of the Wanale system design is used to demonstrate the impact of the presence of energy storage on the power systems operation. System characteristics in Case 3 are compared to a similar system design without the inclusion of an energy storage facility. This system would take on the form shown in Figure 12, with simulation characteristics shown in Figure 13.

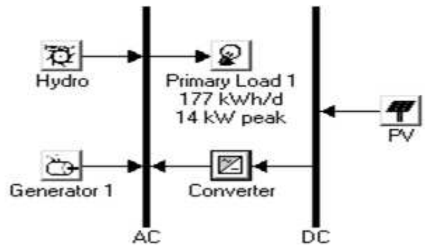

Figure 12: HOMER hybrid mini-grid system model

As observed in Figure 12, without energy storage, the hybrid mini-grid system architecture would comprise a 20kW PV array, a 10kW diesel generator and the 4.4kW base supply of hydro. And as noted the electrical supply properties, the amount of excess electricity (28.5%) indicates system oversizing and/ redundancy in system operation to match the fluctuating demand. The impact of energy storage on system operation can quantitatively be evaluated through the values in Table 3, indicative of the different system characteristics.

And as can be observed from the table, the inclusion of an energy storage facility in the hybrid mini-grid design offers a number of operational advantages:

- With energy storage, a smaller size of the diesel generator is sufficient, which operates at a better load factor, and will make fewer starts/year, and

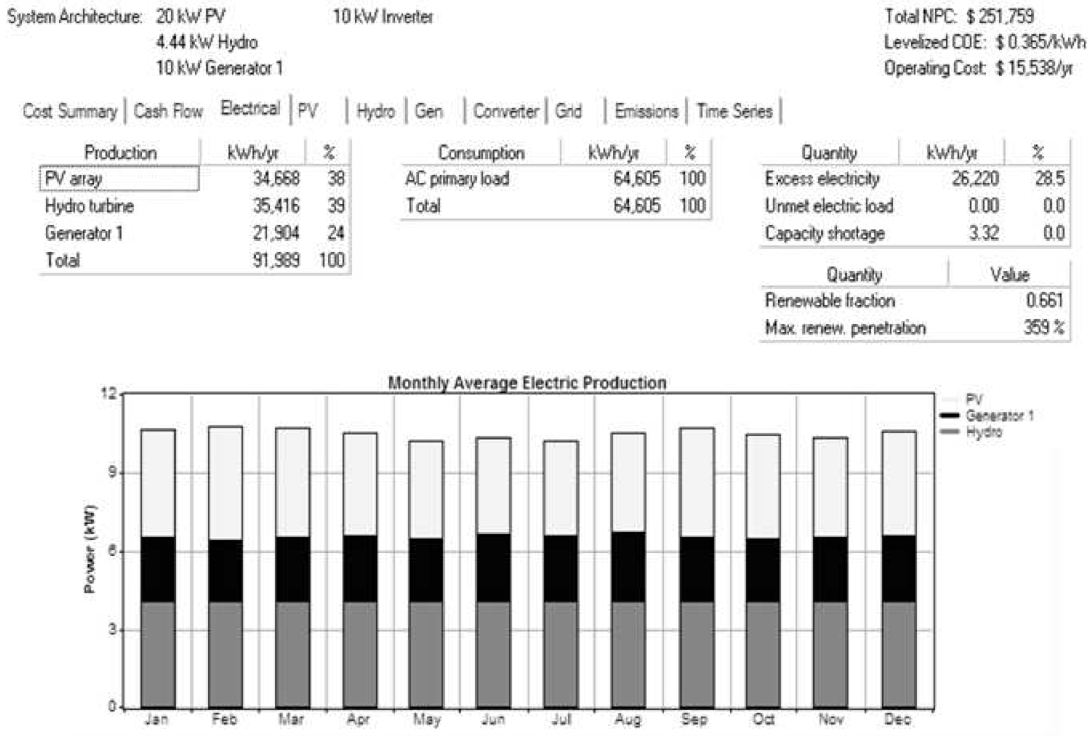

Figure 13: System electrical supply properties

Table 3: Effect of energy storage on hybrid mini-grid system operation

		With storage	*With no storage*	*Savings*
		Values		
PV	Size (kWp)	7	20	
Generator	Size (kW)	5	10	
	Number of generator starts/yr	671	745	
	Hours of operation (hr/yr)	4,803	4,166	
	Load factor (%)	50	25	
	Fuel consumption (l/yr)	7,321	8,809	- 1,488
	Mean electrical efficiency (%)	30	25.3	
System	Surplus electricity (kWh/yr)	1,418	26,220	
	Surplus electricity (%)	2.05	28.5	
	Carbon dioxide emissions (kg/yr)	19,277	23,196	- 3,919
Economics	Initial capital cost ($)	55,979	85,890	- 29,911
	Total NPC ($)	232,292	251,759	-19,467
	COE ($/kWh)	0.337	0.365	

is thus more efficient in operation.

- Another observation is that although the diesel generator in the system without energy storage operates for fewer hours a year, it uses more fuel compared to the other system. This is mainly because of the generator size, and also given that it operates even for periods of low demand, generator operation at low capacity leads to efficiency losses in fuel consumption (Ross, *et al.*, 2011).
- Also, with energy storage in the system there are savings on fuel consumption, and thus the associated operation and maintenance costs, and given the reduced operation of the generator, the carbon dioxide emissions are also significantly reduced.
- With the presence of energy storage, a smaller size PV supply is required, thus saving on the capital costs, also the excess energy generated by the PV array is stored, while in the absence of energy storage, a larger PV supply is required, in the process producing a lot more energy than is required at particular times.
- Also, because of the need for a larger PV supply without energy storage, there is a significant addition to the initial cost of the system;

Thus energy storage is an essential component of a hybrid mini-grid system incorporating renewable energy and conventional diesel generation. With energy storage, the electricity supply system will be more efficient in matching the resources to the demand, thus improved reliability, and will therefore have lower operating costs and life cycle costs, resulting in a lower energy cost.

5. Discussion

The decision to implement a mini-grid system in a rural area such as Wanale is often made, based on among other factors, a comparative basis with the cost of extending the electricity grid. But other factors also play an important role in the decision making (Ezor, *et al.,* 2009):

- The difficulty in the terrain between the grid access point and the location,
- Profitability of the project, given utility concerns such as the theft of power, transmission equipment and losses, given the remoteness of rural locations.

Therefore, although grid electricity offers a number of advantages in the quality and stability of supply, a properly designed and operated hybrid mini-grid system is capable of providing 24 hour grid quality electricity. Wanale's location offers a convincing case for the implementation of a mini-grid, while offering flexibility in future system expansion and operation. With the current global shift towards clean energy sources, these systems offer an opportunity to explore electricity generation options with renewable energy resources, while also providing opportunities to extend modern energy services to rural consumers.

6. Conclusion

In this study, a systematic approach to the design of a hybrid mini-grid system for Wanale village in Eastern Uganda was presented. Resource availability was established, a short-term demand profile was estimated; and based on the available hydro and solar resources, generators and associated components were chosen for the mini-grid system design. Using HOMER software, different configuration options of the generation systems were simulated to establish the most appropriate design. This was based on a number of factors:

1. The ability of the electricity supply to match and satisfy the demand;
2. The reliability and efficiency in operation of the system;
3. And the affordability of the system.

It was thus established that the most effective hybrid mini-grid configuration would include a supply system utilizing hydro, solar PV, with battery energy storage and a diesel generator providing the backup. This system was demonstrated to offer the least cost of energy for the required quality and level of service. And the system's supply was shown to better match the village demand compared to the others. But despite the many benefits of the system, the energy cost was still too high in comparison to the residential grid tariff in Uganda, and alternative funding mechanisms would therefore be required to provide financial support in the form of subsidies, to enable system financial viability.

Hybrid mini-grid systems, when properly designed can be a powerful technology for achieving rapid rural electrification, especially in sub-Saharan Africa where the biggest portion of the population resides in remote villages.

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Numerical simulation of atmospheric boundary layer and wakes of horizontal-axis wind turbines

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Abstract
Simulations of wind turbine wakes are presented in this paper using the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations employing the k-ε turbulence model appropriately modified for the atmospheric flows. The actuator disk approach is used to model the action of the turbine rotor. Modified formulations of the inlet conditions and the wall functions are used to allow consistency between the fully developed atmospheric boundary layer (ABL) inlet profiles and the wall function formulation. Results are presented and compared with three wind turbines running under neutral atmospheric conditions. The results demonstrate that the accurate simulation of the atmospheric boundary layer applying enhanced inlet conditions and wall function formulation consistent with the k-ε model can give very useful information about the wakes, directly contributing to the accurate estimation of the power of the downstream turbines.

Keywords: atmospheric boundary layer, wake, wind turbine, actuator disk

1. Introduction

The wind turbine wake is characterized by streamwise velocity deficit, which leads to less power available for the downstream turbines. It also causes high turbulence levels which can give rise to high fatigue loads. Thus, it is important to predict the effect of these wakes so as to maximize the power output of a wind farm. To predict the wakes in the near and far wake regions of a wind turbine, the representation of the rotor forces with a computationally inexpensive method is necessary. Further, modelling the equilibrium atmospheric boundary layer (ABL) in the computations is important as it is a precondition for modelling the flow of wind turbines.

The actuator disk method, which is a simplification in the representation of the turbine rotor, allows for the gross effects of the rotor to be captured with an appreciable decrease in computing time as the blade geometry is not resolved. It was intensively used by Masson and his team for wind turbine simulations (Masson *et al.,* 2001; Smaili and Masson, 2004; Masson and Smaili, 2006). Despite its simplicity, it is often a useful representation to reproduce wind deficits and wake losses. However, it bears the assumption that the rotor is just acting as a momentum sink without any further influence on the Reynolds stress tensor. Using the actuator disk model, along with the standard *k-ε* model failed to predict the wake behaviour accurately, and a significant underestimation of the near wake deficit compared to the measurements was observed (Rethore, 2009; Rados *et al.,* 2009; Cabezon *et al.,* 2009).

Since the dissipation rate equation is highly empirical, improvement in model performance is usually achieved by modifying the dissipation rate ε equation (Hanjalic and Launder, 1980). Chen and Kim (1987) have taken a general approach, testing for several problems; their approach yielded much better results than had the standard *k-ε* model. El Kasmi and Masson (2008) used a numerical model based on the actuator-disk model, combined with the Reynolds-Averaged Navier-Stokes (RANS) equations, to calculate the flow in the vicinity of the turbine. An extra term has been added to the ε equation in the near wake. The method proposed has been shown to yield much better results than the standard *k-ε* model. Despite the improvement, the term added to the ε equation has a constant that is to be determined through the experimental data and a single optimum value for the constant cannot be extracted. On the contrary, the optimum values for each case are so far from each other that they cannot define an optimum constant value, even for neutral conditions (Prospathopoulos *et al.,* 2011).

Atmospheric turbulence has a major contribution to the turbulence in the wake of a wind turbine and within a wind park. Therefore, modelling equilibrium ABL in computational fluid dynamics (CFD) is an important aspect in the simulations. The practical simulations of the ABL flows are often carried out using RANS in combination with two-equation k-ε turbulence models. This model, with standard model constants, has been applied over a wide range of turbulent flow problems. Crespo *et al.* (1985) have proposed values for the model constants appropriate for the neutral atmospheric boundary layers. As far as the inlet profiles for ABL simulations are concerned, profiles by Richard and Hoxey (1993) were usually used as inlet conditions. They proposed fully developed inlet profiles of mean velocity, turbulent kinetic energy and dissipation rate for neutral stratification conditions. However, the inflow boundary conditions should satisfy the turbulence model employed. The inflow conditions proposed by Richard and Hoxey are not accurate to satisfy these conditions. Furthermore, the assumption of constant turbulent kinetic energy k proposed by Richard and Hoxey contrasts to wind-tunnel and full scale measurements, where a decrease of k with height is observed. It is mentioned by Richards and Quinn (2002) that in some published CFD studies, the combination of the inlet conditions, the turbulence model and the ground roughness resulted in a boundary layer which changed considerably between the inlet and the object under investigation. Improper ABL modelling can yield large errors in the numerical results. Yang *et al.* (2009) proposed a new set of inflow turbulence boundary conditions as an approximate solution to the standard k-ε model transport equations. The capability of these boundary conditions to produce equilibrium ABL was demonstrated in their numerical simulations.

There is still a gap between CFD results and wake measurements, and the transition to the 3D CFD computations using more improved realistic boundary conditions to simulate the atmospheric boundary layer seems a logical extension for better wind farm and turbine design. In the present paper, a numerical method based on the actuator-disk model, combined with RANS and employing a k-ε turbulence closure suitably modified for neutral atmospheric boundary layer flow, has been used to simulate the wakes of a wind turbine. The rotor disk is simulated as a momentum sink through the actuator force, which is related to a constant thrust coefficient over the rotor area. A set of enhanced inflow turbulence boundary conditions proposed by Yang *et al.,* (2009) as an approximate solution to the standard k-ε model transport equations were conducted.

2. Theory

2.1 Rotor modelling

The wind flow is governed by the incompressible steady three-dimensional Navier–Stokes equations. The wind turbine rotor is simulated as a momentum sink through the actuator force, which represents the effect of the rotor on the flow, according to:

$$F = 0.5\, \rho C_T A U_{ref}^2 \tag{1}$$

2.2. Turbulence formulation

The standard k-ε model proposed by Jones and Launder (1972) appropriately modified for the atmospheric flows is considered in the present simulation. The transport equations for the turbulent kinetic energy k and its dissipation rate ε are written as:

$$\frac{\partial \rho k u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_t - \rho\varepsilon \tag{2}$$

and

$$\frac{\partial \rho \varepsilon u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_t - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{3}$$

where u_j is the velocity vector. σ_k, and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. $C_{1\varepsilon}$, $C_{2\varepsilon}$ are constants. P_t is the production of the turbulence kinetic energy,

$$P_t = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{4}$$

The turbulent (eddy) viscosity μ_t is computed according to:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

where C_μ is a constant.

A constant ratio of $\sigma_k/\sigma_\varepsilon = 1.5$ was recommended by Poroseva and Iaccarino (2001) for practical purposes instead of the standard values. The value of the coefficient $C_{1\varepsilon} = 1.44$, which depends on the type of flow and on the Reynolds number, has large effects on the calculated results (Poroseva and Iaccarino, 2001). There are some formulations available in the literature to define the value of $C_{1\varepsilon}$ as function of various flow and geometrical parameters (Durbin 1995). Based on this information and the relationship between the constants in the standard k-ε model (Richards and Hoxey, 1993), the modified turbulence model constants used by Yang *et al.*, (2009) are:

$$\sigma_k = 1.67,\ \sigma_\varepsilon = 2.51,\ C_{1\varepsilon} = 1.5,\\ C_{2\varepsilon} = 1.92,\ C_\mu = 0.028 \tag{6}$$

The fully developed inlet profiles of mean velocity, turbulent kinetic energy and dissipation rate for neutral stratification conditions proposed by Yang *el al.* (2009) are implemented. The mean velocity profile is represented by the logarithmic law as:

$$u(z) = \frac{u^*}{\kappa}\ln(\frac{z+z_0}{z_0}) \quad (7)$$

Where, u^* is the friction velocity, $u^* = \sqrt{\tau_0/\rho}$ and τ_0 is the surface shear stress. κ is the von Karman constant (equal to 0.42) and z is the vertical distance, and z_0 is an aerodynamic roughness length that corresponds to the site topology. The inflow boundary condition of the turbulent kinetic energy is represented by:

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}}\sqrt{C_1\ln(\frac{z+z_0}{z_0}) + C_2} \quad (8)$$

Where C_1 and C_2 are constants that can be determined from experimental data.

The dissipation rate profile at inlet is given by:

$$\varepsilon(z) = \frac{u^{*3}}{\kappa(z+z_0)}\sqrt{C_1\ln(\frac{z+z_0}{z_0}) + C_2} \quad (9)$$

2.3 Wall function formulation

The Richards and Hoxey (1993) boundary condition has been implemented at the wall to specify velocity, turbulent kinetic energy and turbulent dissipation rate consistently with the inlet profiles and turbulence model. The production of turbulent kinetic energy at the wall is not integrated over the first cell height but computed at the first cell centroid (Parente *et al.,* 2011).

$$u_w = \frac{u^*}{\kappa}ln\left(\frac{z_p+z_0}{z_0}\right) \quad (10)$$

$$\varepsilon_w = \frac{C_\mu^{0.75}k^{1.5}}{\kappa(z_p+z_0)} \quad (11)$$

$$G_k = \frac{\tau_w^2}{\rho\kappa C_\mu^{0.25}k^{0.5}(z_p+z_0)} \quad (12)$$

Where z_p is the distance between the centroid of the wall-adjacent cell and the wall.

3. Computational domain

A side view of the computational domain considered for analysis is shown in Figure 1. The rotor disk that represents the wind turbine is located 2 D downstream of the inlet boundary (D is the rotor diameter) and the centre of the disk is considered as the origin point. The domain is extended 25 *D* downstream of the turbine in the axial direction and 8 D in the spanwise direction.

The static pressure at the outlet boundary of the domain is considered to have a zero value relative to the atmospheric pressure. The side boundaries are far enough from the wind turbine, and are considered as symmetry boundary conditions. The height of the domain above the rotor hub is 4 D. The computational domain was meshed by ICEM with a mixed three-dimensional mesh, to carry out the wind turbine fluid flow simulation. A fine mesh is constructed in the area of the wind turbine rotor disk with grid spacing close to 0.025 D, and the mesh grows in size outward from the rotor surface to the extended domains.

4. Solution methodology

The complete set of fluid equations consists of the continuity equation, the three momentum equations for the transport of velocity, and the transport equations for k and ε. To solve the RANS equations in the near and far wake regions of the wind turbines, the wind turbines are modelled as momentum absorbers, through the actuator disk approach, by means of their thrust coefficient.

In this paper, CFD is applied using the commercial multi-purpose CFD solver FLUENT. The inlet conditions described in section 2.2 are implemented in the solver using user defined functions UDF. A special treatment is conducted to account for the wall function formulation, as described in section 2.3. The three-dimensional fluid flow equations are solved using control-volume-based technique for converting the governing equations into algebraic equations, to be solved numerically. The solution algorithm adopted is SIMPLE, and the first-order upwind scheme is used for all the dependent properties to avoid convergence problems associated with higher order schemes (Ameur *et al.,* 2011). The results were extracted from the computational domain along different sections downstream of the wind turbine rotor.

5. Results and discussion

The results presented in this section are intended to demonstrate the ability of the proposed model to accurately predict the wind turbine wakes by comparing the numerical predictions with the measurements of three wind turbines concerning neutral atmospheric conditions.

The first comparison is the three-blade Nibe-B 630-kW wind turbine operating at a rotational speed of 33 rpm with a 40 m diameter located at a hub height of 45 m (Pederson and Nielson, 1980; Taylor *et al.,* 1985). The computations are carried out at different conditions including the freestream wind speed at hub height U_{ref}, the free stream turbulence intensity *Ti*, and the thrust coefficient C_T of the wind turbine. The cases studied corresponding to the measured data for the Nibe wind turbine are illustrated in Table 1.

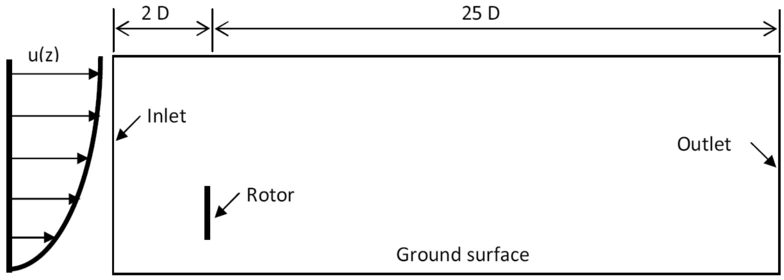

Figure 1: Side view of the computational domain

Table 1: The test cases for the Nibe wind turbine

U_{ref} (m/s)	C_T	Ti%
8.54	0.82	11
9.56	0.77	11
11.52	0.67	10.5

Figures 2, 3 and 4 compare the results obtained using the present methodology with the measurements for different inflow conditions. It presents the horizontal profiles of the axial velocity *u/U* in a centreline passing through the centre of the rotor at hub height at distances of 2.5, 6 and 7.5 D downstream of the wind turbine. In the near wake (*x/D=2.5*),

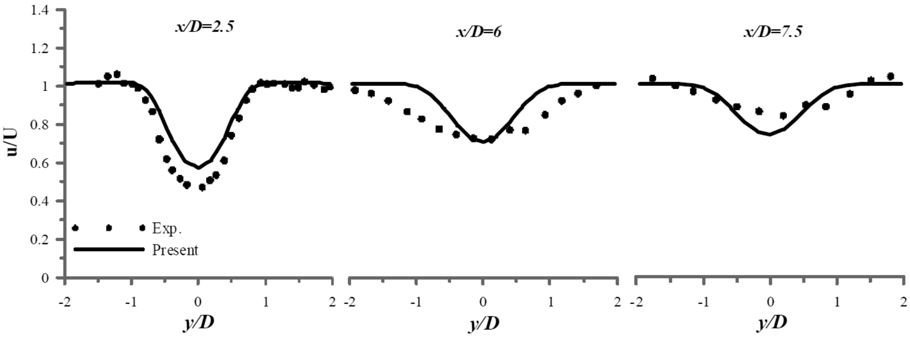

Figure 2: Wake velocity predictions for Nibe experiment (U_{ref} =8.5 m/s, Ti=11% and C_T=0.82)

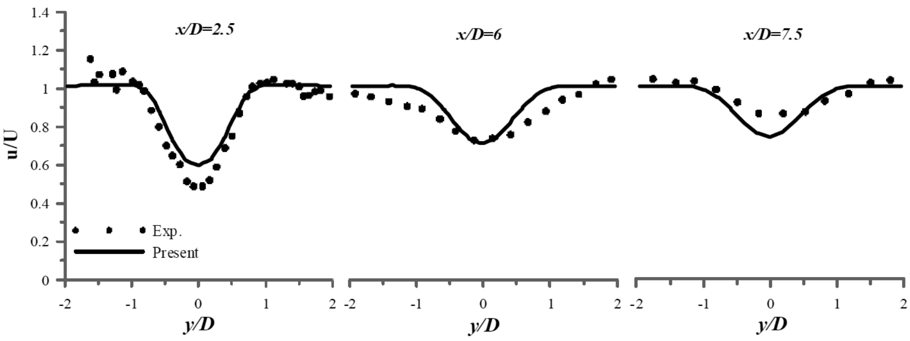

Figure 3: Wake velocity predictions for Nibe experiment (U_{ref} =9.56 m/s, Ti=11% and C_T =0.77)

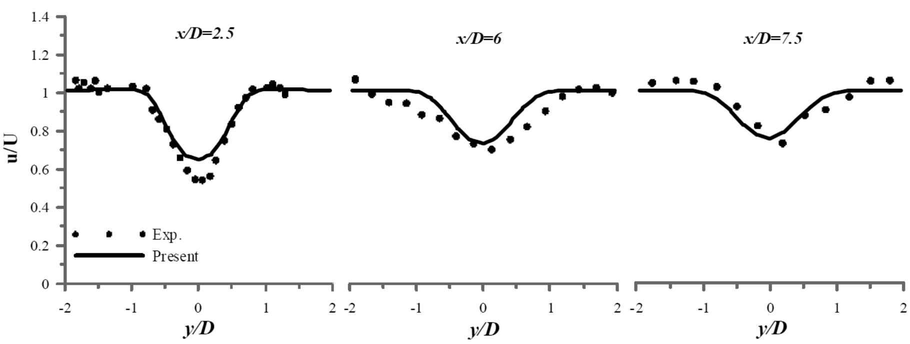

Figure 4: Wake velocity predictions for Nibe experiment (U_{ref} =11.52 m/s, Ti=10.5% and C_T =0.67)

the present simulation slightly over-predicts the velocity deficit, but captures the spreading of the wake observed in the experimental data and predicts the correct trough-like profile. At the distance of 6 D downstream the turbine, the predictions produce a relatively thin shear layer. However, the evaluated velocity deficits at the centre of the wake match well with the measurements. Due to the turbulent diffusion, the shear layer thickness increases with downstream distance of 7.5 D, which causes the wake recovery. The higher thrust coefficients produced at lower wind speeds causes the numerical results to give slow wake recovery.

The second case is the Sexbierum wind farm (Cleijne, 1993) which is composed of 18 W/Ts with 310 kW rated power, 30 m diameter and 35 m hub height, positioned in three parallel rows of six wind turbines. In addition to the wind speed, the turbulence intensity was measured in different positions located in the wake of the wind turbine. During the experiment, the free stream conditions at hub height were U_{ref} = 8.5 m/s and Ti = 10%. For this free stream wind speed, the thrust coefficient of the turbine was estimated to be C_T = 0.75. The numerical simulations provide a good agreement with the measurements, as shown in figure 5. However, the wake deficit at x/D=2.5 downstream the wind turbine is slightly underestimated for this case also.

The turbulence intensity predictions of the Sexbierum wind turbine are illustrated in Figure 6. The characteristic double shoulder pattern is not reproduced by the predictions. Measurements of the turbulence intensity exhibit a different pattern at the 2.5 *D* distance. Higher peaks appear at the regions of mixing flow caused by the rotation, while much lower levels exist in the inner region of the wake, almost reaching the undisturbed value of turbulence intensity. It seems that the different characteristics of the wind turbine have an influence in the near-wake turbulence pattern. These differences attenuate as the distance from the wind turbine increases.

The last case is the three-blade Danwin 180-kW wind turbine, operating at a rotational speed of 42 rpm with a rotor diameter of 23 m and located at a hub height of 31 m (Magnusson *et al.,* 1996; Magnusson and Smedman, 1999). Figure 7 depicts the predictions from the simulation of the Danwin wind turbine for wind speed of 8 m/sec. There is good agreement between the obtained flow velocity, and the available experimental results.

The results of the above wind turbine are also tested for the inflow wind speed of 11 m/sec, for which the experimental data are available at 6.2 D downstream the turbine. It is seen from Figure 8 that, the results obtained from the numerical simulations are matching well with the experimental results.

6. Conclusions

In the present paper, three-dimensional numerical simulations of flow around horizontal-axis wind tur-

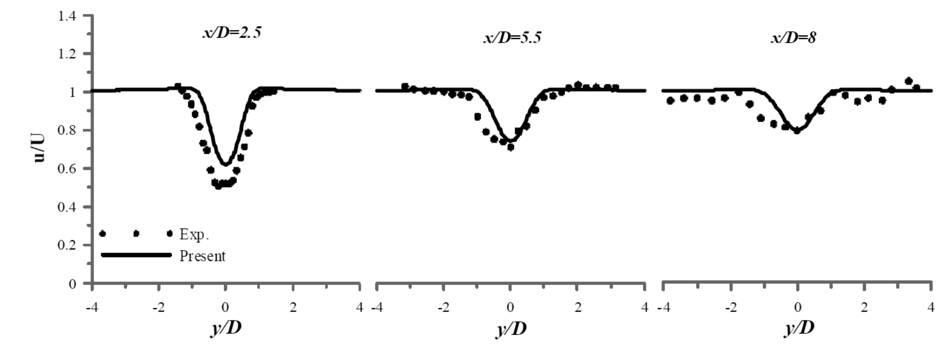

Figure 5: Wake velocity predictions for Sexbierum experiment (U_{ref} =8.5 m/s, Ti=10% and C_T =0.75)

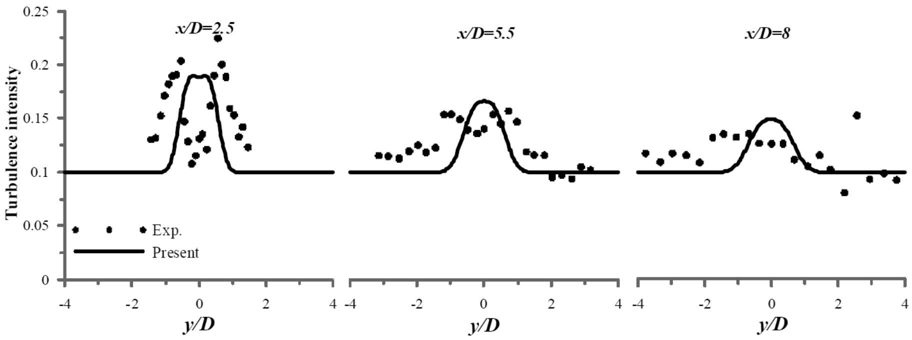

Figure 6: Wake turbulence intensity predictions for Sexbierum experiment (U_{ref} =8.5 m/s, Ti=10% and C_T =0.75)

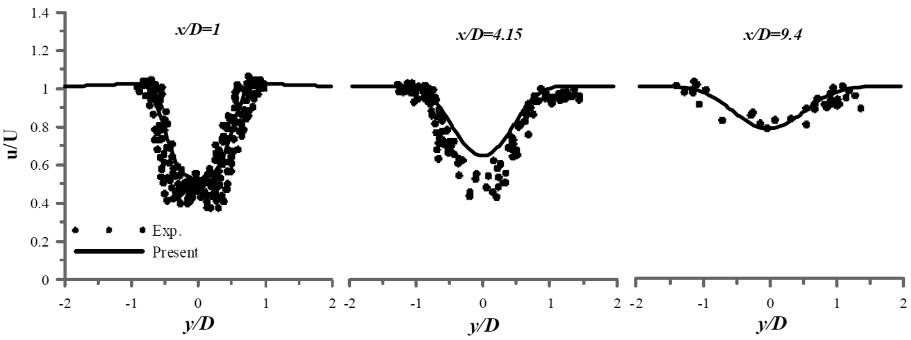

Figure 7: Wake velocity predictions for Danwin experiment (U_{ref} =8 m/s, Ti=7% and C_T =0.82)

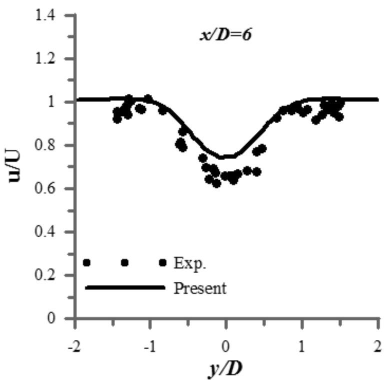

Figure 8: Wake velocity predictions for Danwin experiment (U_{ref} =11 m/s, Ti=6% and CT =0.65)

bines were conducted. The proposed method was tested by comparison of the predictions and the experimental measurements of three wind turbines. The rotor was modelled using the actuator disk approach and the turbulence was modelled using *k-ε* model appropriate for the neutral atmospheric stratification.

For a more realistic representation of the flow field, a set of enhanced inlet conditions are used to satisfy the *k-ε* turbulence model equations. An additional requirement for modelling equilibrium ABL is the correct modelling of the ground roughness. A modified wall function formulation consistent with the inlet profiles of the neutral atmospheric flow was conducted.

Comparison of the results obtained from the numerical analysis and the measurements indicates the capability of proposed approach of predicting the wind turbine wakes. There is good agreement between the flow velocity evaluated from the CFD analysis and the experimental results measured downstream the wind turbine. The characteristic double shoulder pattern of the turbulence intensity was not reproduced by the predictions. However, the peak values are in reasonable agreement. This suggests the need to model the atmospheric boundary layer accurately and its effect on the turbulence quantities to better understand the physical mechanisms that govern the wind turbine wakes.

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Solar water heater contribution to energy savings in higher education institutions: Impact analysis

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Abstract
This paper focuses on the impact of Solar Water Heaters (SWH) at a higher institution of learning. An energy audit was conducted for the evaluation of the energy conservation measure: energy conoduction Energy is a key element in the development of any country or institution; as a result any shortage in energy will have a serious effect on the economy and social aspect of such country or institution. South Africa has, in recent years, experienced high economic growth as well as a rapid expansion in the elsumption analysis, correlation of consumption with weather; financial criteria, payback period and needed solar heater system (SWH) to determine the energy that may be termed as wastage or can be saved. The method of investigation includes assessment of the hot water usage within the institution campus and residencies, analysis of bills, metering and development of a software model for the analysis of energy use, system needed and environmental variables. This renewable measure (SWH) showed a high potential of energy and financial savings for higher education institutions especially those with residences.

Keywords: energy, solar water heater, software development and validation

1. Introduction

Energy is a key element in the development of any country or institution; as a result any shortage in energy will have a serious effect on the economy and social aspect of such country or institution. South Africa has, in recent years, experienced high economic growth as well as a rapid expansion in the eectric power consumer base (Ijumba & Sebitosi, 2001). As a result, the demand for electricity has escalated but has not been matched by corresponding investment in generation (Ijumba & Sebitosi, 2001). The South Africa White paper on Renewable energy and Clean Development, 2003 set a target of 10 000 GWh as its contribution to final energy consumption, and this is expected to be achieved through partnerships and will, overcome market barriers and promote widespread use of sustainable energy solutions (Department of Energy, 2012).

Investment in renewable energy and energy efficiency is important so as to reduce the negative economic, social and environmental impacts of energy production and consumption in South Africa. Currently, renewable energy contributes relatively little to primary energy and even less to the consumption of commercial energy (Winkler, 2005). There are various sources of renewable energy e.g. from biomass, wind, solar and small-scale hydro, however in this part of the world solar is readily available. The Southern African region, and in fact the whole of Africa, has sunshine all year round. The annual 24-hour global solar radiation average is about 220 W/m^2 for South Africa. Most areas in South Africa average more than 2 500 hours of sunshine per year, and average solar-radiation levels range between 4.5 and 6.5kWh/m^2 in one day (www.energy.gov.za). Solar energy, like all other renewable energies, is very safe and environmentally friendly. There are no emissions; the source of fuel is the sun, unlike coal-powered stations (Department of Energy, 2012). There are various technologies hinged on solar usage, such as solar-photovoltaic, solar water heaters etc.

Water-heating accounts for a third to half of the energy consumption in the average household (www.energy.gov.za; Department of Mineral Resources, 2007). In South Africa, water heating is derived mainly from electricity, being the most common energy-carrier employed. The equivalent of a large coal-fired power station (2 000 MW+) is used to provide hot water within the domestic sector alone (www.energy.gov.za; Department of Mineral Resources, 2007).

Since the inception of the accelerated domestic electrification programme through grid extension in South Africa, a major distortion of the national load curve has emerged, with the early evening load peak growing significantly. Modelling indicates that the introduction of solar water-heating can ameliorate the situation substantially. As a result of such deduction, according to the Department of Energy resource on water heating made available for solar water heating, switching from electrical to solar water-heating can, therefore, have significant economic and environmental benefits (www.energy.gov.za).

The South Africa country's utility and policy makers have proposed domestic solar water heating as one of the most viable complimentary solutions to the country's energy and environmental crises (Ijumba & Sebitosi, 2011). Economic benefits may include reduction of energy bills, reduction on peak load at the power utility, greenhouse gas (GHG) emissions reduction, and release of scare capital to other pressing needs.

On the other hand, there are some issues negating the use of SHW, this includes high up-front-capital cost of the system and limited funding for SWH installation by government, banks and other private partnerships. Others include savings impact analysis as well as good economic and financial investigations in terms of investment- payback period.

To alleviate the issues centred around funding and investment, the South African government brought on board a Standard Offer Incentive Scheme that will fund Energy Efficiency and Demand Side Management (EEDSM) interventions. This scheme is aimed at creating an expanded opportunity for attracting the much-needed sustainable financial stimulus into the energy efficient and renewable programme. SWH is amongst the allowable technologies (Department of Energy, 2012).

Commercial buildings and residential home owners' have not shown much interest due to the negating issues raised earlier. In order to assist and give a good perspective of SWH contribution, there is the need to investigate both the savings impact and cost with respect of the high upfront capital involved in the implementation of SHW.

2. Problem description

As a result of electricity shortage and outages in South Africa, coupled with ambiguous tariffs increases within short intervals by the power utilities, this has resulted in high maintenance costs (e.g. generator running and fuel cost) and reduced capital expenditure for the higher education institutions. There is the need to find ways of reducing energy consumption and energy bills.

This project aims at evaluating the impact of SWH usage at an institution of higher learning which will inevitably reduce its energy consumption. The case study is Tshwane University of Technology (TUT), Pretoria Campus.

3. Objectives

The main objective of this study is to demonstrate to management of higher education institution, TUT, that renewable energy (Solar Water Heaters) implementation can yield significant benefits and improve competitiveness of the institution within the limited financial resources available to it. Others objectives include:

- The need to explore the usage of renewable energy sources and its integration to the existing electrical sources at the campus.
- Pollution levels and the energy prices are increasing on a daily basis. Consequently, there is the need to find ways to reduce such issues.

4. Method of investigation

The method of investigation includes audit of hot water usage within the campus, analysis of bills, metering and development of a software model for the analysis/evaluation of the energy impact and solar system design. To achieve the steps outlined, the following were applied in the evaluation of energy savings measures.

4.1 Solar water heating solution

For the model development, Matlab software environment Matlab 7.10. (R2010) was employed. The developed model is expected to give an ample view of investment and payback period, energy and cost saving effects etc. With this evaluation, the usage of SWH may or not be justifiable. The synoptic schematic of the working steps of the software using Matlab is shown in Figure 1.

The model development and software analysis was undertaken in steps (see Appendix 1). Firstly, consideration of the environmental values (latitude, declination, solar radiation, slope of the collectors, cold-water temperature and etc.). Secondly, water heating load in KWh per year. Thirdly, energy savings due to the use of the collectors taking into consideration the fraction of saving the user needs. Lastly, makes a synthesis about the financial part and gives the energy saved, the money saved, the initial investment, the number of collector needed and the payback period.

For the investigation, several inputs are needed. However, for this model or software application analysis, the following were taking into consideration: collector and tank model, electricity price, the outside temperature and days of the year. To achieve the outputs as shown in Figure 1, the following calculations were undertaken.

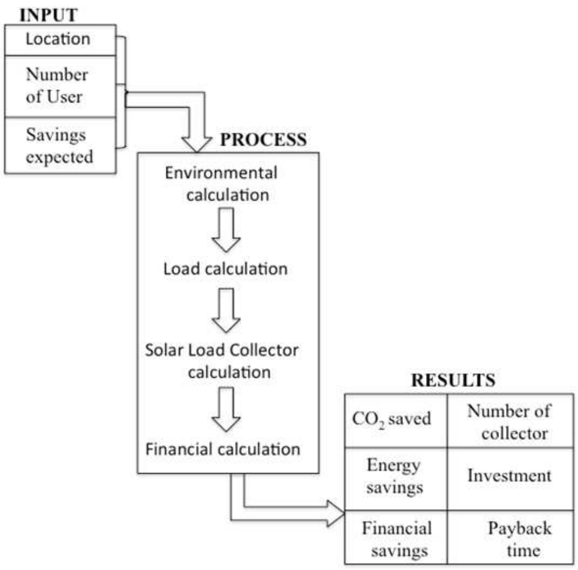

Figure 1: SWH software process

(a) Estimated load calculation

Load calculation is necessary for determining the water heating energy consumption without the solar system as a baseline reference point. This is used for evaluating how much energy and funds (money) will be saved.

From the sampling survey conducted in terms of human behaviour and usage within the campus hostel, findings showed that consumption of hot water during a day is around 7.5 Litres per individual using the number of beds at the hostel as occupants. The total hot water consumption is therefore is the number of people in a building multiplied by the consumption (Duffie & Beckman, 1991).

At TUT University, most of the hot water consumption is at the hostels, hence the number of people is assumed to be the number of beds in each hostel. The energy required can be express as (Redpath, 2012):

$$Qload = Cp * \rho * Vl(Th - Ts)$$

Where Cp is the heat capacitance of water (4 200 (J/kg)/ °C); ρ its density (1 kg/L); and Ts is the cold water temperature afterwards; Q_{load} is calculated for a year period; "Th" is the hot water temperature in the tanks in most cases, the average value is 60 °C.

Yearly load took into consideration the type of buildings as well as the purpose and activities in such buildings. For instance, at the hostels, investigation showed that buildings were fully occupied during the week. However, as a result of the rest periods and holiday of between 2-3 months (no other activities took place during this period at the audited residences), the yearly average occupation per year is ~ 75 %.

(b) Calculation of environmental variables

The variables outlined here were applied in the SWH model analysis.

Cold water temperature

To determine the cold water temperature, the following formula was applied:

$$Tcoldw = \frac{Tmin - Tmax}{2} - \frac{Tmax - Tmin}{2} * h * \cos(2\pi * \frac{N-2}{12})$$

Tmin and Tmax are the value of maximal and minimal cold water (corresponding to the soil temperature from 2m deep), in Pretoria these values are around 19.7 and 15.7 Celsius degrees; h indicates the location of the project, if it is in south or north hemisphere (1 if north or -1 if south hemisphere); and N is the number of the month (between 1 and 12). From the formula, it is possible to have the average value of cold water for each month of the year. Figure 2 shows the estimates cold water temperatures for Pretoria according to number of days.

Sky irradiance

The sky irradiance variable is an indispensable parameter used for calculating the energy collected by the solar panels. In order to calculate the sky irradiance value, the basic concept of energy engineering was applied as shown by the evaluation.

Declination

Declination: is the angular position of the sun at solar noon (corresponds to the moment when the sun is at its highest point in the sky).

$$declination = 23.45 * \sin\left(2 * \pi * \frac{284 + n}{365}\right)$$

The declination for each day of the year (n is the day number) was calculated using Matlab software and the result obtained is from 23.45 at June 21^{th} to -23.45 as at December 21^{th}.

Sunset hour angle

The sunset hour angle 'ws' is the solar hour angle corresponding to the time when the sun goes down. It is given by the following equation:

$$\cos(ws) = -\tan(\Psi) * \tan(\sigma)$$

It takes 15 degrees per hours (positive in afternoon and negative in the morning) correspond for 360 degrees per day.

Figure 3 shows the sun set hour for Pretoria (latitude = 25.732 S) according to days. For example, on 14th July, the sun set at 17h16 (note: this value is an average considering the sun at noon (12h00).

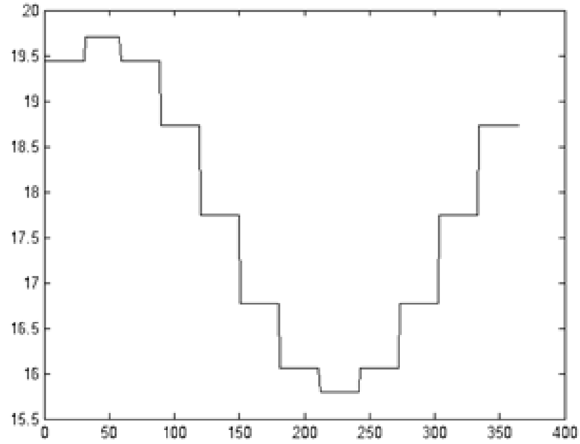

Figure 2: Pretoria cold water temperature for the year

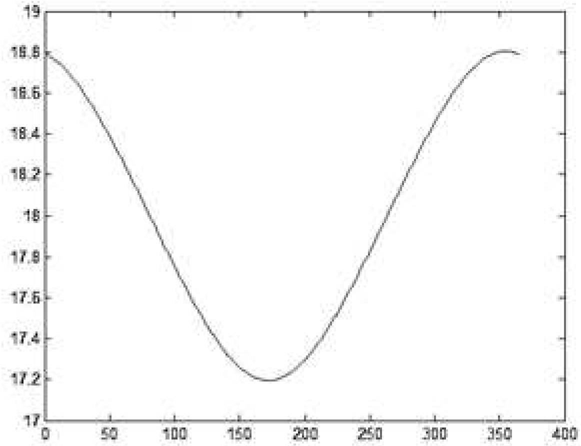

Figure 3: Sunset hour for Pretoria

Extra-terrestrial radiation

The extra-terrestrial radiation is the solar radiation before it reaches the atmospheric land layer. The extra-terrestrial radiation in a horizontal plane 'H0' can be evaluated for days of the year with the following equation:

$$H0 = \frac{24 * Gsc}{\pi} * \left(1 + 0.033 * \cos\left(2\pi * \frac{n}{365}\right)\right) * (\cos(\psi) * \cos(\sigma) * \sin(ws) + ws * \sin(\psi) * \sin(\sigma))$$

Where Ψ is the latitude, σ the declination, ws the sunset hour angle, and n the number of the day. Gsc corresponds to the solar constant equal to 1367 W/m^2. The value of H0 with this formula is dimensioned in Wh\m^2.

Solar radiation for an inclined plane

The solar radiation for an inclined plane has to be known so as to be able to evaluate the load of the solar panels and the amount of solar energy that can be accumulated. The formula for solar radiation in an inclined plane is given by the equation:

$$Ht = H\left(1 - \frac{Hd}{H}\right) * Rb + Hd * \frac{1 + \cos(\beta)}{2} + H * \rho * \frac{1 - \cos(\beta)}{2}$$

ρ is the ground reflectivity supposed to be equal to 0.2 if the yearly temperature is higher than 0 °C; and 0.7 if the temperature is lower than -5°C. In this case, the value for Pretoria is 0.2 as a result of the average yearly temperature being equal to 20°C.

Hb is the product of monthly average beam radiation: Hb = H-Hd; Rb is a geometric factor depending on the slope of the collector (β), the latitude (Ψ), the declination (σ) and days:

$$Rb = \frac{\cos(\psi + \beta)\cos(\sigma)\cos(ws) + \sin(\psi + \beta)\sin(\sigma)}{\cos(\psi)\cos(\sigma)\cos(ws) + \sin(\psi)\sin(\sigma)}$$

The formula is used for the southern hemisphere. As for the northern hemisphere, the sign before β in the cosine and sine function needs to be changed. ws is the sunset hour angle which is dependent on Ψ and σ previous. Hd is the monthly average daily diffuse radiation calculated in two different cases using the global irradiation (H) and the clearness index (Kt).

$$Hd = \frac{1.3991 - 3.560 * Kt + 4.189 * Kt^2 - 2.137 * Kt^3}{H}$$

If ws>81.4 degrees:

$$Hd = \frac{1.311 - 3.022 * Kt + 3.427 * Kt^2 - 1.821 * Kt^3}{H}$$

If ws<81.4 degrees:

And β is the slope of panels. The slope of the surface will be fixed for each day and will be:

$$\beta = |\,latitude - declination\,|$$

Two cases were considered using the software, the collector as a tracking collector which can be programmed to the value above; or consider as a fixed collector using the mean value of 'beta'. For Pretoria TUT campus, a test fixed collector was considered because tracking collectors are rarely in use nowadays apart from the difficulty in estimating the initials.

Sky radiation

The value of the sky irradiance is needed to quantify radiative transfer exchanges between a body (solar collector) and the sky. The actual sky radiation falls somewhere in-between the clear and the cloudy values. If *c* is the fraction of the sky covered by clouds, sky radiation may be approximated by:

$$Lsky = (1 - c)Lclear + c * Lcloudy$$

Where clear sky long-wave radiation (in the absence of clouds) is:

$$Lclear = 5.31 * 10^{-13}(Ta + 273.2)^6$$

Ta is the ambient temperature in °C. For cloudy skies, the average temperature is assumed to be Ta-5°C and emit long wave radiation with an emittance of 0.96, that is, the irradiance of a sky cloudy is computed as:

$$Lcloudy = 0.96 * \sigma(Ta + 273.2 - 5)^4$$

Where σ is the Stefan-Boltzmann constant assumed to be equal to 5,669×10-8 (W/m2)/K^4.

To find an approximate monthly value of 'c' the formula below may be applied:

$$c = \frac{Kd - 0.165}{0.835}$$

Kd is calculated by using the average clearness index ('Kt') and the Collares-Pereira and Rabl correlation:

$$for\ Kt \le 0.17,\ \ Kd = 0.99$$
$$for\ 0.17 < Kt < 0.75$$

$$Kd = 1.188 - 2.272Kt + 9.473Kt^2 - 21.865Kt^3 + 14.648Kt^4$$

$$for\ 0.75 \le Kt < 0.80,\ \ Kd = -0.54Kt + 0.632$$
$$for\ Kt \ge 0.80,\ \ \ \ Kd = 0.2$$

Load collected

The energy collected per unit collector area per year is described by the following equation:

$$Qcoll = Fr(\tau\alpha)(1 - fdirt)\left(G + \left(\frac{\varepsilon}{\alpha}\right) * L\right) - FrUl * \Delta T \quad (1)$$

Where Fr(τα) and FrUl are collector characteristics explained in due course, G is the global incident solar radiation of the collector (taking the yearly average irradiation in an optimally inclined plane from the Joint Research Centre–European Commission website, the ratio ε/α is set to 0.96 (ε is the long wave emissivity of the absorber), ΔT is the temperature differential between the working fluid entering the collectors and outside ambient temperature that is Ts-Ta. *L* is the relative long wave sky irradiance. It is defined as:

$$L = Lsky - \sigma(Ta + 273.2)^4$$

Where *Lsky* is the long wave sky irradiance previously calculated and *Ta* the ambient temperature expressed in °C.

This model includes also the losses due to snow, dirt and piping. The dirt value is the losses due to snow; dirt can affect the irradiance level experienced by the collector. Therefore, Fr(τα) is multiplied by (1− f dirt), typical values range from zero to a few percent. In the project location study (Pretoria, South Africa) it rarely snows, hence the value depends only on the dirt. This value is around 5%.

Hot water is stored in tanks and run through imperfectly insulated pipes giving rise to heat being lost to the environment. The load collected value is affected by these losses as shown in the equation:

$$Qcoll' = Qcoll(1 - floss)$$

The value loss is the losses in the pipes and the tank (if needed). This value varies between 1 to 12 %; hard to estimate due to its dependency on several factors such as length of the pipes and water usage in the tank.

Collector panels

Three types of solar collector are considered in equation 1; these are glazed collectors, evacuated collectors and unglazed collector. The needed changes in the applicable equation are the collectors characteristics, namely FrUl and Fr(τα). There are generic values for these characteristics if not provided by the manufacturers.

Water pump load

To direct the heated water in the collector to the water tank or the existing water heating process, one or more water pumps is needed. The energy value of the water pump is based on this formula:

$$Q_{pump} = N_{coll} * P_{pump} * S$$

Where Q_{pump} is the energy needed to pump the water in a year. P_{pump} is the power by surface unity of the collector (this value is generally between 8 and 22 W/m^2). S is the area taken by the collectors in m^2. And N_{coll} the number of working hours the solar collector is used.

The value of Ncoll can be approximated as:

$$Ncoll = \frac{Qcoll(1 - floss)}{S * Fr(\tau\alpha) * Ht} * Nclearness$$

This value is given by the energy collected by the solar system taking into account the losses divided by the energy without losses and multiplied by the number of daytime hours of days in the years $N_{clearness}$. $N_{clearness}$ is the factor of the clearness index (computed in "Extra-terrestrial radiation" part) number of hours in the days.

(c) Financial evaluation

Using the various calculations as previously mentioned, the energy and cost savings will be justified as shown by the graph in terms of payback period and profitability. The energy saved is attributed to the use of the solar water heating system/process.

The money saved in relation to years is shown in Figure 4.

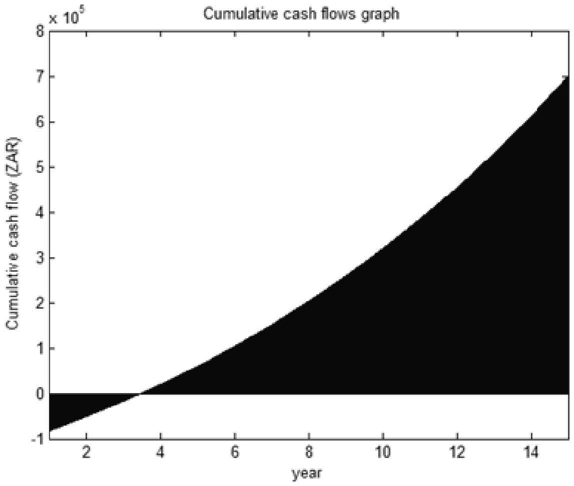

Figure 4: Cumulative cash flow for solar water heater

Figure 4 is the result of the eco formula below using inputs such as the initial investment, the inflation and the electricity price.

$$eco = \frac{Pe}{(1 - inflation)^{year}} * Qcoll * year - Pinit - maintenance$$

P_e is the electricity price; Q_{coll} is the energy calculated earlier; P_{init} is the initial price which corresponds to the price of collectors and the tank (if needed). Solar collector lifetime is around 25-30 years; however, for the software analysis the value of 20 years was (will be) used. This is to take care of the possible maintenance cost according to the piping or the tanks. The maintenance is estimated by the initial price of the items divided by the lifetime per year (in a lower value), however, the value of the initial price is based on this formula:

$$if\ \ 0 < saving \leq 15\%$$

$$Price_{init} = price_{collector} * nb_{collector} + tank_{nb} * Price\_tank$$

$$if\ \ 15\% < saving < 70\%$$

$$Price_{init} = price_{collector} * nb_{collector}$$

The price of the water pump is included in the price of the solar collector. Only the power consumption of the water pump is considered in the financial part. That is the cost of power consumption by the water pump will be subtracted from the money saved as a result of the installed SWH. For estimation of the inflation rate, the mean value (5.47%) for the last 10 years in South Africa was (will be) applied (see http://www.global-rates.co for the last ten-year inflation rate).

5. Model validation and application

The goal of this software is to give an ample view of investment, energy and money saving, payback, baseline energy of the building, environmental variable-cold water temperature profile, solar irradiation on an inclined plane, number and slope of collector for better efficiency, energy required by the water pump etc.

To evaluate and validate the developed model applications, the proposed energy saving measure was evaluated using the following procedures:

5.1 Solar water heating – process

The SHW process in Figure 1 was applied in the application development (Appendix 1). In order to substantiate the implementation of the solar water heating process using the developed application, the following parameters were inputted (Duffie & Beckman, 1991; Redpath, 2012; Retscreen):

- Location of installation: 25°43'56" South, 28°9'42" East; Elevation: 1310 m a.s.l.
- Type and size of solar collector: 12 Pipe Evacuated Solar Collector (Xtreme solar company) with a surface area of 2.2256 m^2 (total cost ZAR 7439.28)
- Type, size and cost of water storage tank: JoJo; 10000 litres capacity; ZAR 8366.00

The number of the tanks in the project is dependent on the number of people using hot water and the fraction of energy/money saving expected.

Other needed inputs for the MATLAB SWH application include:

5.2 Water consumption

From the audit exercise carried out at the campus, the total number of beds at the six residences is 1 250. The average daily hot water usage per day was estimated to be 9 500 litres (average of 7.6 litres).

5.3 Hot water electricity consumption per year

The use of hot water corresponds to electrical consumption, however, in order to quantify the yearly water consumption, the holiday period in South Africa needed to be taken into account. Using the South Africa school calendar (www.kwathabeng.co.za/travel/south-africa/destinations.html?cal=school, 2011), there is around 94 days of vacation in a year which is about 25% of the number of days in year. As a result, the use of residences is consequently around 75% in a year with an estimated annual water heating consumption of around 1 279MWh/year.

5.4 Energy consumption and energy saved

The fraction of energy saving is set to 70% (maximum) so as to be able to reduce most of energy thereby cumulating into financial savings consumption; while the remaining will be supplied by electric resistance heating (electric geysers).

5.5 Lifetime of project

The lifetime of the existing project is fixed to 10 years.

5.6 Result obtained

Using the SWH model, the energy required to heat water is 1 535 MWh/year while the energy produced by the solar water process is 1 074 MWh/year. This shows that the amount of energy consumed without the solar water heating system is 461 MWh/year according to software application. This is expected to be saved using SWH.

According to the cumulative cash flow graph in Figure 5, the intended project implementation or solution shows a payback time of 3 years and 10 months. The slope of the collectors needs to be inclined at an around 25.2 degrees for maximum irridance utilization.

The number of collector needed to achieve the expected energy from SHW is 329, with an area of 732 m^2. This means that 54 collectors of 120m^2 area need to be implanted on each residential building roof. The SHW impact is expected to bring about 938 ton of CO_2 emission reduction. In summary, the impact of SHW will translate into around 7.1 million rand financial savings over a 10 year period.

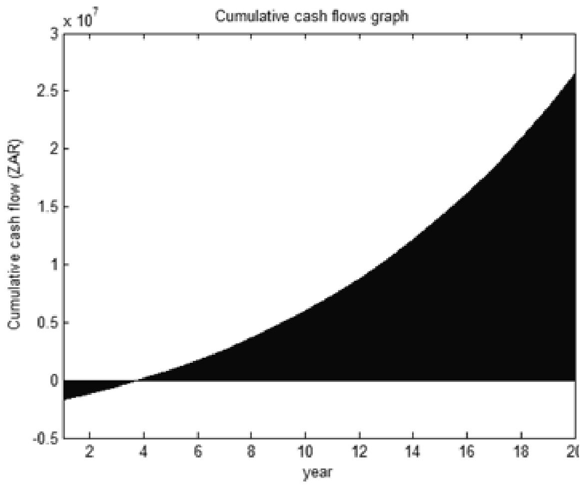

Figure 5: Cumulative cash flows graph for the intended project implementation

6. Conclusion and recommendation

In order to assist policy makers in the areas of energy management, the impact of SWH in a learning institution was investigated. In the course of the investigation, study of the existing usage pattern, development of simulation techniques for analyses and evaluation was carried out. The highlights of this study were the introduction of environmental variables which are very crucial to SHW implementation, operation and justification. This was mathematically modelled and very much differs from the existing models currently available.

Results obtained show that financial, operational and environmental benefits will arise as a result of solar water heating implementation at learning institutions. These benefits include maintenance cost reduction (geyser repairs, generator repairs/ maintenance. fuel cost etc.) and, more importantly the electricity consumption reduction thereby cumulating into financial savings for the institutions.

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In 2012 he joined Makerere University, Uganda as a lecturer and is currently an Associate Professor where he is involved in teaching, research and supervision of PhD and Masters Students. Dr. Okou has consulted for the German Technical Cooperation, Office of the Auditor General in Uganda among others. He has published widely in international peer reviewed journals and conference proceedings. His research interests include renewable energy and smart grid which includes: power management of energy storage in grid connected micro grids, grid integration of renewable energy at the transmission level, Electric vehicles as energy storage buffers, rural electrification, and electrical machines among others. Dr. Okou is a registered engineer in Uganda, a member of the IEEE, IET, Engineering Council of South Africa (EWSA) and Uganda Institute of Professional Engineers (UIPE).

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