UNIVERSITY OF CAPE TOWN

OVERCOMING OBSTACLES TO ELECTRIFICATION IN CONGO (DRC)

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DECLARATION

I, **David Kutelama**, hereby declare that unless properly referenced and acknowledged, the work contained in this thesis is my own work.

Signature: ________________ Date: ____________

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SUMMARY

The contrast between the very low rate of electricity access (about 6% of households) and the significant energy resources existing in Congo justified an investigation into the obstacles to electrification and ways to overcome them.

Basically electricity is generated from hydroelectric plants; the most important located in the western tip of the country (including Inga I and Inga II) and in the copper mining area in the southeast.
Only the copper mining area, the area around the capital city Kinshasa and some other towns are connected to the grid or to isolated hydro plants, leaving vast parts of the country unserved.

Description and analysis of existing electricity systems, their current problems and the sector master plans led to the identification of the following major obstacles to electricity expansion:

- Poor and declining performance of the electricity sector in terms of plant availability, overall losses, non-payment, and poor collection; depriving the national utility of the necessary capacity and resources to undertake electrification.
- High cost of expansion programs under the approach of extending networks by transmission and three-phase distribution lines in a vast country. Limited electricity demands in most areas, lack of standardization of voltages and network equipment, and high standards of connection equipment also contributed to increase electrification costs.

A review of literature showed that, where already applied, the recommendation of international organisations to restructure and ultimately privatise electricity

utilities has yielded limited results on the particular issue of electricity expansion towards low-load areas.

As electrification of such areas is a major objective in Congo, this justifies that we do not recommend this route as a key strategy in solving the electrification problem in Congo.

In other words the objective of expanding electricity throughout the country is not likely to be met by private operators that prefer large-scale electricity production for urban and industrial markets and emphasize the profitability of every project.

However possible ways to improve utility's performance were identified in the literature. These include: the use of prepaid meters to improve collection, transferring the management of distribution networks in some areas to local organisations, attribution of more authority to the utility to enforce non-payment and staff training under a more experienced utility in the field.

The liberalization of small-scale production that allows small operators such as missionaries, NGOs, or agro-processing industries to generate and possibly distribute electricity in remote areas may also contribute to expanding electricity in the country.

The literature review also revealed that alternative MV distribution technologies and connection practices tested and successfully applied in other countries for low-cost electrification were available.

Despite minor inconveniences such as their capacity restriction, and the inability to provide three-phase power for motors, single-phase technologies result in cost-effective networks as far as rural electrification is concerned.

This is attractive for rural electrification in Congo.

Applying single-phase MV technologies with adapted SABS and PIESA guidelines and standards to the design of an isolated rural network in eastern Congo, the following results were obtained:

- When loads to be served are small (about 100-200kVA) phase-phase and SWER lines are cheaper to build than three-phase lines. As loads encountered in most rural areas in Congo are generally smaller than 100kVA and can reach 100-200kVA in the medium or long run, single-phase networks can adequately supply these areas from existing networks or from local plants.
- The low cost of these networks in rural areas is a result of using a reduced number of components (conductors, poles, insulators and pole-top hardware), conductors of small size and of higher ratio strength to weight (T/w_c), such as ACSR, that result in long spanning lengths.
- If three-phase systems were systematically used, the cost of individual connection would be higher and the capacity in the networks would have been much greater than needed. Besides, given the limited financial resources other communities could not be connected owing to the high cost of three-phase lines to connect them. In addition, in order to reach the viability of the electrification project a higher tariff should be used. This is the main finding of the financial analysis carried out to investigate the viability of the electrification project in eastern Congo. As a result of high connection costs and tariffs, electricity would become unaffordable to most rural customers. This contradicts the primary objective of providing electricity to most possible customers.

In practice, as shown by the case study, the pattern of electrification should be as follows. From existing networks with sufficient capacity or from a nearby plant, an optimised three-phase line towards a main center is built.

Single-phase feeders of adequate rating (taking into account present demands and future growth) derive from the backbone towards various load centers.

This pattern can be applied to most rural areas in Congo.

At the customer level, ready boards that include isolators, protection, sockets, switches and possibly lights are installed.

The cost reduction at the network and at the customer level should result in more affordable connection costs for customers.

In addition to the introduction of lower cost technologies, planning approaches should be adapted.

The extent to which electricity contributes to socio economic development should be the main consideration in planning electricity expansion. In other words emphasis should be put on economic and socio economic electrification.
The productive uses of electricity in economic and socio economic projects bring sustainability and may attract funding for other projects from development organisations.
However some social electrification to gain political support for the economic and socio economic projects are necessary.

The traditional planning policy that justifies building three-phase lines as a precaution to avoid costlier upgrading at a later stage, is not adequate when financial resources and plant capacity are limited and when uncertainty exists about load growth.
In other words, three-phase networks, with capacity high enough to meet years of demand that can sometimes not grow as expected, deprive other customers of connections while capacity is idle in the existing tri-phase networks.

The study has shown that there is substantial scope for the application of lower cost distribution technologies than the present standards in Congo.
Applying low-cost electrification technologies such as single-phase MV distribution systems to expand electricity from existing networks and from small-scale hydro plants (as a measure to postpone the construction of more costly transmission lines), after the utility has improved its performance and skills, should significantly contribute to expand electricity in Congo.

In this process, utility's efforts can be shared and complemented by small operators such as missions, NGOs, and agro-processing companies in isolated areas and at small-scale level.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ACSR:	Aluminum Conductor Steel Reinforced.
ADMD:	After diversity maximum demand
Afrepren:	African Energy Policy Research Network.
DRC:	Democratic Republic of Congo
DWP:	Design Wind Pressure.
Gecamines;	Generale des Carrieres et des Mines.
GMR:	Geometric Mean Radius (of a conductor)
HVDC:	High Voltage Direct Current (Line).
IEA:	International Energy Agency
MIBA:	Miniere du Bakwanga.
PIESA:	Power Institute for East and Southern Africa.
SABS:	South African Bureau of Standards.
SAIEE;	South African Institute of Electrical Engineers
SNEL:	Socite Nationale d'Electricite.
SWER:	Single Wire Earth Return.
SWS:	Shield Wire Systems.
UNDP:	United Nations Development Program.
UTS:	Ultimate Tensile Strength.
WEC:	World Energy Council

SYMBOLS

-:	not applicable/not available
kW:	kilowatt

MW:	megawatt
MWh:	megawatt-hour
GWh;	gigawatt-hour
V:	volt
kV:	kilovolt
MVA:	megavolt-ampere
km:	kilometer
Vs:	sending end voltage
Vr:	receiving end voltage
Φ-Φ:	phase-phase
Φ-N:	phase-neutral
ΔV:	voltage drop
ΔV (%):	% voltage regulation
3Φ:	tri-phase

CHAPTER 1

INTRODUCTION

1.1 APPARENT PROBLEMS

Congo (DRC) is a country with significant energy resources particularly in hydroelectricity. The current installed capacity is about 2500 MW [SNEL, 2000] and until recently a significant capacity surplus existed in the country.

Despite all this potential and surplus, only 6% of households have access to electricity services in the country. [World Bank, 2002b].

This percentage has almost been stagnant over the last 20 years as, 3.5% households had access to electricity in 1983. [World Bank, 1986]

Figure 1.1 illustrates the population with access to electricity in selected African countries in 2000.

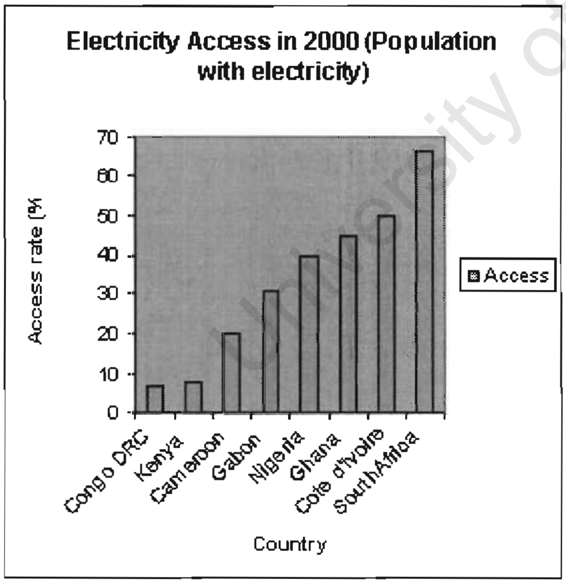

Fig 1.1: Population with access to electricity in selected African countries in 2000.

[Source: Compiled from IEA, World Energy Outlook 2002].

Basically, grid-electricity is supplied mainly to the copper mining industry and to some cities that are generally partially served.
For example only 35% of households in the capital city Kinshasa are connected to the distribution network. [World Bank, 2003]

In the connected cities the reliability of supply is poor: power cut-off and rationing are frequent, as distribution networks have severely deteriorated (this is illustrated in chapter 3).
Provincial towns with diesel generation experience sporadic supplies of some hours a day or even a week.

An overall description of the electricity sector in Congo is given by the World Bank (2002b) as follow:

> *The deterioration of electricity supply in Congo concerns all areas of activities including technical, commercial, financial and institutional aspects.*

Outside the mining areas and main cities, people still rely on fuel wood, charcoal, dry cells, candles, and kerosene to meet their energy needs.

1.2 OBJECTIVES OF THE RESEARCH

The main objectives of this study are:

- Investigate and identify the barriers to the expansion of electricity services in the country.
- Provide policy options, alternative strategies and technologies for overcoming these barriers in order to improve the electrification rate. In particular, technologies that reduce the cost of electrification will be investigated.

- Identify ways and measures for improving the technical performance of the Congo electric utilities.

1.3 RELEVANCE OF THE INVESTIGATION

The provision of efficient electricity services to more of the country's population is essential for several reasons including:

- Electricity is one of the keys to economic development. This is illustrated by the international community's adoption of the rate of electrification as an indicator of a country's overall development.
- According to Birol and Malyshev (2002), there is a clear link between poverty and low electricity access. The study shows that countries with higher share of biomass in residential consumption have a higher percentage of population under the poverty line of $2 per day. Further, regarding this poverty-electricity access link, the World Energy Outlook of IEA (2002) states: "*Lack of electricity exacerbates poverty and contributes to its perpetuation as it precludes most industrial activities and the jobs they create.*

- As for the link with agriculture and small business development, Karlson and MacDade (2000) write: *"Availability of electricity is essential for creating new employment opportunities and supporting value-added activities linked to agriculture production. Small-scale manufacturing, food processing industries, trading and marketing opportunities are all greatly expanded when energy services are available"*
- Electricity has the potential to provide significant welfare benefits such as improved lighting, entertainment, communications, refrigeration, better school and health services. [UNDP, 1999]
- As for the particular link to women development, Karlson and MacDade (2000) write: "*They* (women) *are engaged in many tasks and responsibilities that could be accomplished more easily and efficiently if*

they had access to lighting and electricity and the energy services electricity can provide. Electricity makes basic subsistence activities such as water pumping and grain grinding much less time-consuming and can power labour-saving as well as income-generating equipment".

On this basis, the provision of adequate electricity services to higher segments of the Congo's population will improve living standards and allow socio-economic and particularly agriculture development.

1.4 RESEARCH METHODOLOGY

In order to identify the major obstacles to electrification in Congo, a description of the existing supply system, its current problems and a brief analysis of the electricity sector master plan will be conducted. This will be based on statistics and published material on the Congo electric utility.
Based on the major barriers to electrification, methodologies and technologies used in other countries where successful electrification programs had taken place such as South Africa, Brazil, Australia and some Asian countries will be identified from existing literature.

The various strategies and options to improve electricity access will be analyzed and their applicability to Congo investigated.
In particular, low-cost technologies at the network level as well as at the customer level will be investigated with the aim to identify cost-effective technologies that can be used to electrify a place in Congo.

A case study investigating a cost-effective technology for an isolated rural electrification network supplied by a small hydro plant (1MW) in Eastern Congo will be conducted. Because local standards are lacking, this investigation will identify and use appropriate and existing standards and guidelines adapted to the Congo environment.

1.5 OVERVIEW OF CHAPTERS

Chapters 2 and 3 are mostly descriptive.

Chapter 2 gives a brief country profile with emphasis on topics related to electrification such as demography, economy and available energy resources to provide the context of the subsequent analysis.

Chapter 3 is a description of the existing electricity supply system in Congo. An analysis of the sector master plan (2000-2015) compared to the previous plan (1988-2005), leads to the identification of the major obstacles to electrification in Congo.

Chapter 4 and 5 review the existing literature to seek solutions, good practices, and methodologies that could be adapted to the Congo's particular conditions in order to overcome the obstacles identified in chapter 3. In particular, chapter 5 deals with reducing electrification costs.

Chapter 6 is a case study.

Suitable standards are identified and adapted to design a network to distribute electricity in a low-cost manner within an isolated rural area in eastern Congo.

The objective is to investigate the opportunities of alternative technologies that cost effectively meet needs in a rural area better than the standard tri-phase lines. For this reason a financial impact assessment will complete the case study.

In **chapter 7**, a financial analysis based on the net present value is carried out to determine the conditions of viability of the electrification project described in chapter 6.

Chapter 8 contains recommendations on ways to expand electrification in the country.

A **summary** drawing together the major findings ends the study and can be found after the front pages of this thesis.

CHAPTER 2

COUNTRY BACKGROUND

2.1 LOCATION

The Democratic Republic of Congo (formerly Zaire) is the largest country in central Africa.
The country borders 9 other countries: Angola and Zambia in the South, Tanzania, Burundi, Rwanda and Uganda in the East, Sudan and Central African Republic in the North and the Republic of Congo (Brazzaville) in the West.
With an area of 2 344 858 km^2, Congo is Africa's third largest country after Sudan and Algeria. [World Bank, World Development Database, 2003]

Figure 2.1 shows the situation of the country with respect to its neighbours and the main towns in the country.

2.2 GEOGRAPHY

The dominant geographic feature of the country is the "basin of the Congo River". It is a central low-lying region of about 2/3 of the territory surrounded by high lands. This basin draws towards it the waters of a network of feeding rivers from the North, the East and the South of the country and from outside of the country (Northern Angola, most of Congo Brazzaville, Southern Cameroon and Southern Central African Republic) [Gourou, 1998]
The Congo River is 4700 km long [Esterhuysen, 1997], crosses almost all provinces and forms the backbone of the country.
The Congo River crosses the Equator twice, thus is fed from both sides of the Equator.
In the North the wet season takes place from April to October while taking place from November to March in the South side. This complementary alternation of

rainy seasons ensures a regular flow along the River particularly to the mouth where the average flow rate is 40 000 m^3 per second. [Gourou, 1998]
Annual rainfall varies from 800-1500mm in the South to 2000-3000mm in the central basin. [Gourou, 1998]
Congo DRC is almost a landlocked country with only 37 km of Atlantic coastal line. [Esterhuysen, 1997]

Figure 2.1: Congo, neighbour countries and main cities.

2.3 POPULATION

According to estimates (the last census in the country took place in 1984 [Gourou, P, 1998]), the current country population is about 52 million people, the population growth being 2.7% and the average density of population 22 inhabitants per km^2.

About 70 % of the population live in rural areas. [World Bank, World Development Indicators Database, 2003].

The population is unevenly distributed over the territory: The inner basin is sparsely populated, while large concentrations of people are found around the following areas:

(a) Along the eastern border with about 100 inhabitants/km^2.

(b) In the west (around Kinshasa), south central and southeast particularly around Kikwit, Kananga, Mbujimayi and in the mining area around Lubumbashi, Likasi and Kolwezi.

(c) In the North around the towns of Kisangani and the areas between Kisangani and the Sudan and Uganda borders. [Esterhuysen, P, 1997]

The urbanization rate is high as illustrated by the population growth in the main towns of the country since the census in 1984.

Town	Population × 1000	
	1984	2000
Kinshasa	2654	6002
Lubumbashi	543	1500
Mbujimayi	423	1500
Kananga	291	1500
Kisangani	283	600

Table 2.1: Population growth in main towns.
[Source: Misser (1998), Estrehuysen (1998) and personal contact with Demographic Department, University of Kinshasa, September 2002].

2.4 ADMINISTRATION

Congo DRC is divided in 11 provinces.

Every province is divided in Districts and one district contains a number of territories.

Table 2.2 shows a comparison in provinces according to surface area and population density.

Province	Area (km^2)	Area (%)	Density (2000) People/km^2
Oriental	503 239	21.46	12
Katanga	496 877	21.19	15
Equator	403 292	17.19	14
Bandundu	295 658	12.60	20
Kivu	256 863	10.94	35
Kasai-East	170 302	7.17	27
Kasai-West	154 742	6.73	24
Bas-Congo	53 920	2.30	62
Kinshasa	9 965	0.42	608
Total	2 344 858	100	

Table 2.2: Provinces and population density.

2.5 ECONOMY

Mining industry and agriculture dominate the economy of Congo while the manufacturing sector is very small. [Esterhuysen, 1998]

2.5.1 Mining Industry.

Copper and diamond industries are the most important mining activities in Congo. The copper industry, located in the southeast of the country is the main activity of the state owned" Gecamines".

Up to the 1980s the output of the copper industry was about 500 000 tons of copper per year, equivalent to almost 6% of world output. [World Bank, 1986]

Figures 2.2 and 2.3 show the decline in copper and cobalt production by Gecamines since the mid 1980s.

The copper mining industry is significantly important for the Congo electricity sector, as it is the most important customer.

Before the 1990s 70 % of all the electricity generated by the national utility (SNEL) was sold to Gecamines. Besides, Gecamines activities justified the construction of the HVDC line from the west of the country to the copper mining area in the southeast.

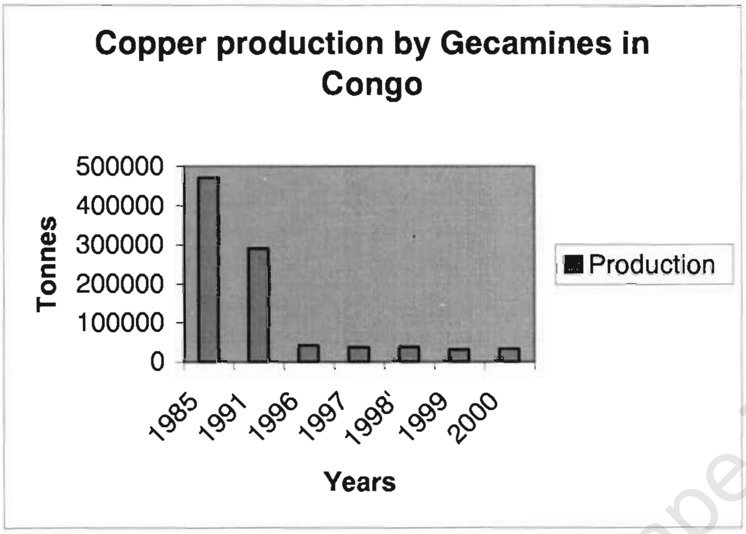

Figure 2.2: Copper production in Congo.
[Source: Misser, 1999 and World Bank, 2000b]

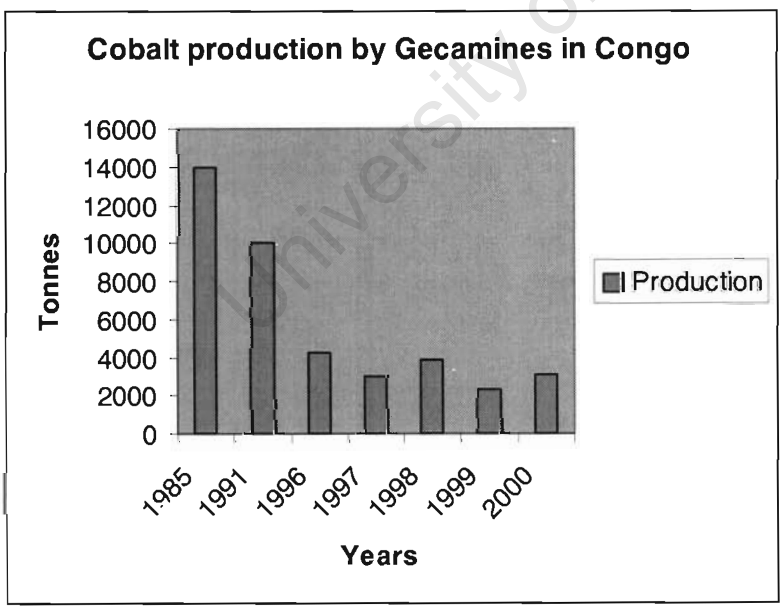

Figure 2.3: Cobalt production in Congo
[Source: Misser, 1999 and World Bank, 2000b]

The diamond industry is dominated by MIBA, the only large-scale producer located in Mbujimayi in the south center.
MIBA suffers from inadequate electricity supply, as its (private) 13 MW hydro plant on the Lubilanji River in Mbujimayi cannot meet all its electricity needs.

In addition to copper, cobalt, zinc and diamonds, other minerals such as iron ore in the Oriental province and cassiterite with associated minerals in the Kivu province are not yet exploited. [Gourou, 1998]
According to the World Bank the mining sector is one of the sectors most adversely affected by the lack of electricity supply in the country. [World Bank, 2003]

2.5.2 Agriculture.

Small-scale agriculture is by far the most important activity in the country in terms of employment. This sector has been adversely affected by the expropriation measures of privately owned plantations and agro-industries in the early 1970s. [Misser, 1999]

2.5.3 Manufacturing.

Textiles cement, breweries, and other agro-industries dominate the manufacturing sector in Congo.
An important feature of this sector is that ¾ of the manufacturing production "*is centered around Kinshasa and Lubumbashi* (while raw materials come from within the country) *owing to the availability of electricity and adequate transport facilities*." [Misser, 1999]
Adequate electricity supply in provincial and district towns could contribute to the development of agro-industries in these towns due to the proximity of plantations and farms.

2.5.4 Macro-economic Environment.

Despite the potential outlined above, the economy of Congo is performing badly.

Per capita GDP has declined from 630 US$ in 1980 to 110 US$ in 1999. [African Development Indicators 2001]

Figure 2.4 below shows the change in GDP during the decade 1990-1999 for selected African countries.

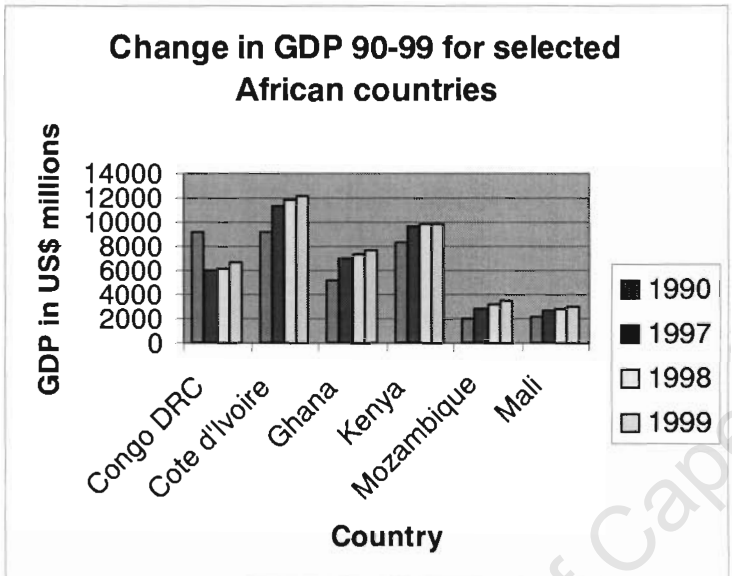

Figure 2.4: Change in GDP during 1990-1999 for selected African countries.

[Source: African Development Indicators 2001 (Drawn from World Bank Africa Database 2001)]

External debt is significant in Congo as shown in the table 2.3 below:

Year	Debt (US $ billions)
1980	4. 395
2000	10.6
2001	10.6

Table 2.3: Congo external debt

[Source: World Bank, World Development Indicators, 2003].

2.6 ENERGY RESOURCES

Hydroelectricity, oil, coal, fuel wood, and methane gas are the main energy resources in Congo.

2.6.1 Hydro electricity potential.

Current total installed capacity is about 2500MW with a potential production of about 11000 GWh a year. [SNEL, 2000]

The total hydroelectric potential is the highest in Africa [WEC, 2001] and is mainly associated with the Congo River and particularly the Inga Falls located 150 km from the Atlantic Ocean.

Two hydro plants namely Inga I (351 MW) and Inga II (1424 MW) have already been built and further developments are possible at this site including the Grand Inga scheme with an estimated capacity of 44 000 MW and a potential production of 270 000 GWh. [SNEL, 2000]

Other large-scale hydro plants are located mainly in the copper mining area and the Ruzizi River that forms the border with Rwanda and Burundi.

Furthermore it is estimated that:" *More than 300 MW can be obtained from uprating and refurbishing existing hydro plants* " [Bartle, 2002]

In addition to the existing hydro plants, more than 30 viable hydropower opportunities, of capacity up to 40 MW, have been identified around the country by the national electric utility.

Development of these opportunities can allow the existence of isolated systems, which can further develop in regional networks and support the electrification of isolated towns as well as rural areas.

2.6.2 Oil potential

Oil recoverable reserves in Congo are estimated at 26 million tonnes (or 187 million of barrels) and are located in the Atlantic coastal basin. [WEC, 2001]

Annual production is about 1.2 million tones (1.28 in 1995, 1.23 in 1996, and 1.2 in 1999) [WEC, 2001].

Table 2.4 compares Congo oil reserves to that of other African countries.

Country	Recoverable reserves (million of tonnes)
Nigeria	3000
Algeria	1235
Angola	730
Gabon	342
Congo (Brazzaville)	212
Cameroon	55
Congo DRC	21

Table 2.4: Oil reserves in selected African countries.
[Source: WEC, 2001]

Congo exports all its oil production as it is too heavy to be processed by the local refinery plant [Bisengo, 1992]. This technological limitation and the fact that reserves are limited reduce the scope of using this resource for electricity production.

2.6.3 Coal potential

Congo's commercially exploitable coal reserves are estimated at 88 million tones, [WEC, 2001] and current production (of about 50 000 tones in 1999) is directed towards local cement and copper processing industry.

Beside the fact that coal reserves are insignificant compared to hydroelectricity potential a number of reasons explain the low prospect of using coal for power generation in Congo. These include: [World Bank, 1989]

- Production is taking place in 2 areas already connected to hydroelectricity.
- Deficiencies in transport systems in the country make difficult the use of coal in other areas.
- Production takes place in deep mines using manual methods.

- The output is of average-to-low quality (high ash content) that makes it technologically difficult to utilise.

Table 2.5 compares coal reserves in Congo with reserves in other African countries. [WEC, 2001]

Country	Proven recoverable Reserves 1999 (in million tonnes)
South Africa	49 520
Botswana	4 300
Zimbabwe	502
Mozambique	212
Tanzania	200
Congo DRC	88

Table 2.5: Coal reserves in selected African countries
[Source: WEC, 2001]

2.6.4 Fuel wood reserves

With 1 352 000 km^2 (more than half of the country) covered with forest, Congo is the most forested country in Africa. [WEC, 2001]

Fuel-wood is mainly used as firewood (mostly in rural areas) and charcoal in rural and urban areas.

No use of fuel-wood is made for power generation.

2.6.5 Methane gas reserves

An estimated 50 million cubic meter of methane gas is dissolved below 300m in the Kivu Lake that forms the border with Rwanda in the east. [World Bank, 1986]

No exploitation of methane gas is made at the Congo side.

2.7 CONCLUSION

A number of features constrain the scope of electrification in Congo. These include:

- Low economic performance as illustrated by the decline in economic growth, in GDP, in per capita GDP and by the high external debt.
- The country is vast; meaning that significant capital is needed to cover much of the country with electric lines. For example about 2000 km lie between Inga in the west and Kisangani in the east.
- The low population density and the high urbanization rate will have a major impact on future energy demand and supply patterns and on the strategy of energy development.
- As reserves in oil and coal resources are limited, the country relies heavily on hydro electricity.
- The collapse of the mining industry leads to the generating capacity (at normal level) being significantly under utilised. This will be illustrated in the next chapter.

CHAPTER 3

EXISTING SUPPLY SYSTEM

3.1 INTRODUCTION

In this chapter we describe the existing electricity supply system in Congo, its current problems and the sector master plan.
The objective is to identify the main obstacles to electrification in the country.

3.2 BRIEF HISTORY OF ELECTRIFICATION IN CONGO

The copper mining industry in the southeast started the electricity industry in Congo in the 1920s.
The industry needed a cheap energy source for the mechanization of its activities around the Likasi center in order to reduce coal imports from Southern Africa.
In that respect, the Mwadingusha hydro station (68MW) was built in 1929 on the nearby Lufira River followed in 1950 by the Koni hydro station (42 MW) on the same river. [Vellut, 1983].
In the 1950s in order to extend mining production to the Kolwezi area and develop the zinc and ferro-manganese alloy industries, two other plants (Nzilo, 108MW and Nseke, 248 MW) were built on the upper Congo River. [Vellut, 1983]
The resulting capacity made possible, among other things, the electrification of 858 km of railways in the area.

Other private mining companies also built hydro power plants in the country in order to mechanize their activities. These include:

- A power plant in Manono in the southeast (29.50 MW) by the tin mining company.
- Hydro plants such as Budana, 13.5MW and Soleniama, 13.8MW in the northeast of the country by gold mining companies.

- A power plant at Mbujimayi, 13 MW (currently) on the Lubilanji River by the diamond industry (MIBA).

In the west of the country in order to supply power to various industries in Kinshasa, private companies built hydro plants in the vicinity (Sanga, 11.5MW and Zongo, 75MW)
As for the east of the country, the same reasons of supplying power to local industries led to the construction of the Tshopo power plant (18.80MW) near Kisangani and Ruzizi I power plant (28.20MW) near Bukavu.

It follows that prior to 1970, 6 private companies dominated the electricity supply industry in Congo.
In the early 1970s the power industry was nationalised. SNEL (Societe Nationale d' Electricite) was formed with a mandate to generate, transmit, and distribute electricity throughout the whole country.
With respect to electrification the main achievements of SNEL include the following: [SNEL, 2000]

- Construction of about 640 km of 220 kV lines (376km in the copper mining area and 264 km to connect the town of Bandundu from the western network)
- Intensification of households connections in Kinshasa (more than 40 000 connections), in the Bas-Congo province (about 4 500 connections) and in the eastern towns of Bukavu, Goma and Uvira (more than 6 650 connections).
- Conversion from fuel oil, gas and wood to electricity of industrial boilers and furnaces in breweries, textile companies, bakeries, chemical plants, and soap works mainly in Kinshasa and Lubumbashi. The program was aimed to encourage greater consumption of power and increase the utilization of Inga II power plant.
- Construction of the Inga I and Inga II power plants, and 1740km of HVDC line. An excess generating capacity of about 600MW existed in the country for

many years after the commissioning of the Inga II power plant. This also reflects the under utilization of Inga II.

3.3 SNEL INFRASTRUCTURE

3.3.1 Hydropower plants.

Table 3.1 shows SNEL's hydro power plants with their rated capacity and the capacity currently available.

No	Station Name.	Year commissioned.	Normal capacity (MW)		Current capacity[1] (MW)	
			Structure	Total capacity	Structure	Total capacity.
1	Inga I	1972	6× 58.5	**351**	4× 58.5	**234**
2	Inga II	1982	8 ×178	**1424**	3 ×178	**534**
3	Zongo	1955	2×18+ 3 ×13	75	1× 13	13
4	Sanga	1932	6 ×2	12	3× 2	6
5	Mpozo	1934	2 ×1.1	2.2	0	0
6	Mwadingusha	1929	3×11+3×12.5	70.5	3× 12.5	37.5
7	Koni	1950	3 ×14	42	0	0
8	Nzilo	1953	4 ×27	108	4× 27	108
9	Nseke	1956	4× 62.1	248.4	3× 62.1	186.3
10	Ruzizi I	1958	2×6.3+2 ×7.8	28.2	2×6.3+ 1× 7.8	20.4
11	Ruzizi II	1989	3 ×14.6	14.6	3 ×14.6	14.6[2]
12	Kilubi	1954	3 ×3.3	9.9	2× 3.31	6.6
13	Kiyimbi	1959	2 ×8.6	17.2	1× 8.6	8.6
14	Tshopo	1955	3× 6.26	18.78	1× 6.26	6.26
15	Mobayi	1988	3 ×3.5	10.5	1× 3.5	3.5
16	Lungudi	1949	2 ×0.78	1.56	1× 0.75	0.75
TOTAL				2433.84		1179.51
Percentage				100%		48%

Table 3.1: SNEL hydro power plants.
[Source: SNEL, 2000 and personal communication with SNEL, Generation Department (09/2003)].

These hydro stations appear on figure 3.1with the same numbering.

[1] Personal communication with SNEL, Generation Department, September 2003.
[2] This is the Congo share in the total capacity of 3×14.6MW.

As shown on figure 3.1, the hydro plants numbered 1 to 5 are located at the western tip of the country. With associated networks they form the western system, supplying Kinshasa and the surroundings. This network is interconnected to Congo Brazzaville from Kinshasa by 2 lines, 220 kV, 100 MVA, and 6.6 kV 5MVA.

Figure 3.1: SNEL Hydro plants (geographical position)

Located in the copper mining area, the hydro plants numbered 6 to 9 on figure 3.1 form the southern system. Beside the mining industry, this network supplies the towns of Lubumbashi, Likasi, and Kolwezi.
The southern network is interconnected to the western system by a HVDC line, 2×550 kV 1740 km, and to the Zambia network by a 220 kV 250 MW line.

Hydro power plants numbered 10 and 11 are built on the Ruzizi River border to Rwanda and Burundi.
With the associated networks they form the eastern system.
Ruzizi I station is entirely owned by Congo while the 3 countries own Ruzizi II jointly, the output being shared equally.
At the Congo side the eastern system supplies 3 major towns of Bukavu, Goma and Uvira.
From Ruzizi I the eastern network is interconnected to Rwanda by a 110 kV line and to Burundi by a 70kV line.

The remaining 5 hydro plants numbered 12 to 16 supply 5 isolated networks and mainly the towns of Kamina, Kalemie, Kisangani, Gbadolite, and Tshikapa.

Despite the fact that some small private mining companies still generate electricity from hydro plants to meet their own needs, their installed capacity represents about 3 % of SNEL rated capacity. And currently most of these auto producer's plants are under utilized or even abandoned (example the 29.50 MW power plant in Manono). [SNEL, 2000]
As a consequence, private energy production is generally overlooked in statistics and SNEL generation regarded as the only significant production of electricity in Congo.

However, given difficulties for SNEL to supply all areas, equal importance should be placed on SNEL and these plants in order to contribute to rural electrification.

3.3.2 SNEL Transmission and Distribution Lines.

Transmission lines (50kV-220kV) are concentrated within the southern, western and eastern systems (networks) described in section 3.3.1.

The table 3.2 shows the length (in km) of transmission lines in the different networks by voltage level.

Network	220 kV	132 kV	120 kV	70 kV	55/50 kV	Total	%
Western	649.2	185.3	-	244.5	-	1079	28.6
Southern	834.1	120	1078.8	70	188.8	2417.7	64
Eastern	-	-	-	260	-	260	6.90
Isolated	-	22.5	120	-	-	22.5	0.5
Total	1483.3	327.8	1198.8	574.5	188.8	3773.2	100

Table 3.2: Lengths of transmission lines in Congo.
[Source: SNEL, 2000]

It appears that more than half (64%) of the transmission lines are concentrated in the southern copper mining area in order to connect the various mining sites. Another significant share (28.6%) is located in the area around Kinshasa the capital city.

The rest of the country is poorly served.

Of particular importance in the Congo electricity sector is the HVDC Inga-Kolwezi line that interconnects the western and southern systems.

The main features of the line are as follow: 1774 km length, 550kV, 560 MW capacity extendable to 1120 MW, construction cost: 1 460 US$ million in 1984 prices (excluding 840 US$ million for the Inga II power plant). [World Bank, 1986]

The construction of the line and the associated power plant (Inga II) was justified by the expectation of high copper prices that could boost the production and thus power demand by Gecamines. [World Bank, 1986]

This assumption did not materialize and peak power recorded from Inga to Kolwezi since commissioning was 296MW in 1996. [SNEL, 2000]

The distribution network consists of 3096 km of MV lines (6.6-30kV) and 11 653 km of LV lines.

As shown in table 3.3 the bulk of MV and LV lines is concentrated in the western system and mostly in the capital city Kinshasa.

This explains that more than half of residential connections in the country is found in the capital city.

System	MV (km)	LV (km)	Total (km)	%
Western	1286	8248	9534	64.64
Southern	492	1479	1971	13.36
Eastern	410	630	1040	7.06
Isolated	908	1296	2204	14.94
Total	3096	11653	14749	100

Table 3.3: Lengths of MV and LV lines in Congo.
[Source: SNEL. 2000]

Within other networks around the country, MV and LV connections are concentrated in towns such as Lubumbashi (south), Bukavu (east).

Even in isolated systems, despite the existence of significant unused capacity in most of them (as shown by the successive master plans), the network is restricted to one town and even to the town center.

3.3.3 Diesel Equipment.

Typically, the main cities outside the western, eastern, and southern systems depend on thermally generated power.

However the cost of diesel fuel in these typically remote areas, maintenance problems and low revenue result in high costs of operation. As a result electricity supply is limited to some hours a day or even a week. [SNEL, 2000]

The most important towns under the poor service of diesel plants are shown in table 3.4.

Town	Population (millions)	Capacity (MW)
Kananga	1.5	2.7
Mbujimayi[3]	1.5	0.6
Kikwit	0.6	0.8
Mbandaka	0.6	2.3
Kindu	0.4	0.6

Table 3.4: Capacity of diesel plants in major towns.
Source: [SNEL, 2000]

[3] The privately owned 13 MW hydro plant in this town supplies only the diamond industry and the water utility. Diesel generators supply the other loads.

3.4. CURRENT PROBLEMS

Problems currently faced by the national utility SNEL that have an impact on the country electrification process include the following:

1) Plant availability is poor. As can be seen from the table 3.1, only 48% of the total rated capacity of hydro plants are available for production. In particular, maintenance problems have reduced the effective capacity of the 2 power plants in the Inga site from 1775 MW to 768 MW. This cancels the excess capacity brought by the Inga II power plant.
2) Transmission and distribution equipment has deteriorated leading to frequent outages. The extent of deterioration is illustrated by the funding required for a partial rehabilitation of generation and distribution equipment in Congo. This appears in table 3.5 below.

Equipment type	Location	Amount (US$ millions)
Hydro electric installations	Inga I and Inga II	5.7
	Zongo	12.2
	Mpozo	3.6
	Nzilo	1.9
	Nseke	1.6
	Mwadingusha	0.9
	Total hydro	**25.9**
Diesel Equipment	Mbandaka	7.9
	Kananga	1.7
	Mbujimayi	5.9
	Total Diesel	**15.5**
Transmission equipment	HV lines (AC)	6.2
	HVDC line	4.3
	Total transmission	**10.5**
Distribution networks.	Kinshasa	51.8
	Other towns	16.2
	Total distribution	**68**

Table 3.5: Funds required for a partial rehabilitation program.
Source: [World Bank, 2002b]

3) The sharp reduction in Gecamines activities (as shown by figures 2.2 and 2.3) has deprived SNEL of its main source of revenue. Prior to 1984, about 70% of the energy sold by SNEL were in the form of HV sales and Gecamines was the main customer. Currently the bulk of revenue comes from LV customers and mostly from the capital city. The shift from the predominance of HV sales to that of LV sales contributes to financial difficulties for the utility given the reduced tariffs that are generally applied to LV customers. Figure 3.2 below illustrates the trend in sales up to 1997.

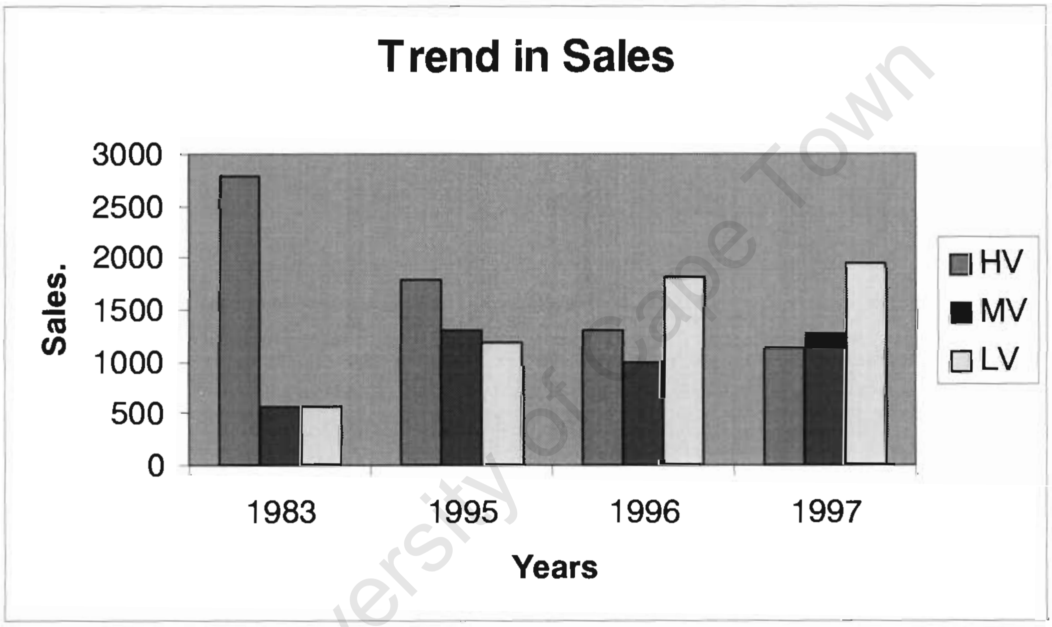

Figure 3.2: Electricity sales by category (HV, MV, LV) up to 1997

Source: [World Bank, 1986] Eskom statistical yearbooks, 1995, 1996.

4) The following elements illustrate the high levels of non-payment and energy losses within the utility[4]:

- As for September 2002, the debt of public companies to SNEL amounted at US$349.7 millions.
- During the period 2000-2002 overall losses (the difference between energy generated and energy sold) represented 25% in 2000, 24% in 2001 and 26% in 2002 (overall loss levels of 8-10% are recorded in some western European

countries. [Wamukonya, 2003], [Zomers, 2001]). In particular, during 2001, only 59% of the energy sent out in the Kinshasa network was charged.

- During the decade 1990-2001, the financial loss as a result of energy not charged was about US$ 207.8 millions.
- The monthly cash collection in Kinshasa has declined from US$ 3.12 millions in 1995 to US$ 1.43 millions in 2001 without reduction in tariffs.

While no data has been obtained to distinguish between technical and non-technical losses, the frequent use by the utility of flat tariffs and estimated meter readings reflect difficulties to repair or replace faulty or obsolete meters. These observed difficulties are an indication that the share of non-technical losses is probably significant.

5) The ratio of utility customers per employee, which is one of the performance indicators for electric utilities, was 49 in 2000 and 2001, and 44 in 2002. This is far below the internationally accepted standard of about 160 customers per employee. [Wamukonya, 2003]

3.5 SNEL LONG TERM MASTER PLAN

The under utilization of power plants, particularly of Inga II power plant (when operating at full capacity) contrasts with the low access to electricity in the country. This indicates difficulties in extending electricity to un-served areas as will be shown by the analysis of the first and second master plans.

3.5.1 SNEL first and second master plans

The first master plan (1988-2005) was an attempt to expand electricity around the country from existing systems. The focus of the plan was the construction of transmission lines and targeted the major cities in the country.
Table 3.6 summarizes the transmission lines planned.

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[4] Information in this section comes from personal communication with SNEL, Research and Development Department.

System Origin	Voltage (kV)	Length (km)	Target (town)
Western	220	300	Kinshasa (from Inga)
	220	735	Bandundu and Mbandaka (from Kinshasa)
	132	499	Kikwit (from Kinshasa)
Southern	220	758	Mweneditu-Mbujimayi-Kananga (from Kolwezi)
	132	171	Mweneditu-Kabinda.
Eastern	110	312	Butembo-Beni (from Goma)
	110	368	Kindu (from Goma)
Mobayi (Isolated)	132	716	Gemena and Bumba (from Mobayi)
Total		3859	

Table3.6: Transmission lines planned under the 1st master plan (1988-2005)

Only 264km of 220kV lines in the western system (from Kinshasa to Bandundu) were effectively constructed.

The failure of the plan was attributed to the freezing of external aid from the early 1990s. [SNEL, 2000]

The second master plan (2000-2015) is more comprehensive.

This plan includes:

(1) the construction of more transmission lines,

(2) a plant and network rehabilitation program,

(3) the construction of an extensive distribution network targeting smaller cities from major towns, and

(4) the development of small-scale (mini and small) hydropower plants.

Grid extension items under the 2 master plans are compared in table 3.7 below.

Item	First Master Plan (1988-2005)		New Master Plan (2000-2015)	
	Planned (km)	Executed (km)	Planned (km)	Executed so far. (03/2004)
220 kV lines	1793	269	2546	-
132 kV lines	1386	-	1970	-
110 kV lines	680	-	1048	-
30 kV distr. lines	140	-	6536	-

Table 3.7: Comparison of grid extension items of the 1st and 2nd master plans.

3.5.2 Analysis of the 2nd (current) master plan.

- The plant and network rehabilitation program is so crucial for the electricity sector that it should take precedence over new projects. As shown in table 3.5 rehabilitation will require the mobilization of significant financial resources. In particular, the normal plant capacity should be recovered before trying to extend supply to new areas.
- The plan is based mostly on extending existing networks. Because of long distances in the vast country and low loads in most areas, line construction costs and the cost of kWh will be high.
- While extending networks cannot be dismissed when capacity and financial resources are available, a mix with decentralised generation and distribution should be more vigorously promoted.
- The 6236km of distribution lines planned outside major towns is intended to make a significant contribution to supplying new customers. The lines are of tri-phase construction. Alternative construction standards should be investigated because of the potential savings that could be realised. .
- The new master plan (2000-2015) is so large that it seems to lack clear objectives. The connection of 775 towns (urban and rural) is scheduled. This is doubtful given the timing and the shortage of resources. Some areas included in the plan do not show any economic potential (in agriculture or business). According to SNEL the plan was set up in consultation with political leaders and inclusion of some areas may have been obtained under such influence. With limited financial resources, Congo is not in a position to extend power to rural areas by making supply available ahead of demand.

3.6 OBSTACLES TO ELECTRIFICATION

From the previous sections it appear that the major obstacles to electrification in Congo include the following:

- The poor performance of the national utility in terms of technical (plant availability, overall losses) and operational performance (non-payment, poor collection) is a major obstacle to electrification. These inefficiencies deprive the utility of the necessary capacity (MW) and revenue ($) to expand existing systems. A better performance should allow the utility to finance an expansion program or to attract external funds for development.

- The traditional development approach in Congo is to extend existing networks by transmission lines and tri-phase distribution lines. However the size of the country and the pattern of human settlement in most of Congo (villages located up to 20 km apart) imply high transmission and distribution costs. To complement the traditional policy, it is necessary to investigate and promote alternative strategies and technologies in order to bring down electrification costs.

- Lack of standardization of voltage levels and network elements is another major obstacle to electrification in Congo. As shown in table 3.2 transmission voltages include 550 kV (HVDC), 220kV, 132kV, 120kV/110kV, 70kV, and 55/50kV while 30kV, 20kV, 15kV, 10kV, and 6.6kV are the distribution voltage levels. As distribution networks have generally a large quantity of components, the cost of these networks is relatively high. Thus extensive standardization of network elements such as conductors, transformers, voltage levels, and poles, could contribute to reduce construction and operation costs of networks.

In the next chapters (4 and 5) we will search the literature for lessons and practices that can help to overcome these obstacles.

CHAPTER 4

LITERATURE REVIEW

4.1 INTRODUCTION

According to previous chapters the following can be considered as the major obstacles to electrification in Congo:

(1) inefficiencies within the national electric utility,

(2) high electrification cost under the strategy and the technology adopted,

(3) lack of standardization of voltages and network equipment.

A review cf existing literature was made to seek methods and practices that could be adapted to the particular conditions in Congo in order to overcome the obstacles to electrification in the country.

The review presents practices, lessons and policies of successful electrification programs in other countries.

4.2 PERFORMANCE IMPROVEMENT

This section investigates possible ways to improve the performance of an electric utility with poor overall performance and particularly reduced plant capacity and poor collection. As a consequence such a utility is unable to generate resources for electrification projects and to attract external funds.

An example of development by a utility able to generate own funds or to attract external funds can be found in South Africa. During the period 1994-1999, Eskom connected 2.8 million households, under a program "*entirely financed by the South African electricity supply industry itself at an average annual investment of about R1.2 billion*". [Kotze, 2000]

Results from a survey of international investors in the power sector revealed that "*adequate cash flow and collection disciplines*" are among the highest priorities sought by these investors when considering an investment in a developing country. [Lamech and Saeed, 2003]

Among ways to overcome these inefficiencies are the prepaid metering, the use of local organizations and the restructuring of the electricity industry.
These will be investigated in the next sections.

4.2.1 Prepaid Metering

When using conventional credit meters and billing system potential sources of poor performance include the following:

- Non payment (after electricity had already been consumed) or delayed payment.
- Defective or obsolete meters (not advancing), meter tampering (this include theft through bypassing the meter).
- Inaccurate meter readings as a result of poor work by unskilled meter readers or collusion between consumers and meter readers.
- Billing errors or collusion between customers and billing staff leading to fraudulent accounting practice.
- Distance between consumers and the payment office and delay in solving customer's complaints possibly leading to a reluctance to pay. [World Bank, 2001]

In countries where the pre-paid electricity system is already used it is found that some of the problems above are considerably reduced.
The major findings of an assessment of the South African pre-paid experience include the following: [Tewari and Shah, 2003]

- Although meter tampering, meter failure, electricity theft and fraud were not completely eradicated, introduction of the system had lessened the incidence of these problems.

- The system has significantly improved the cash flow and the revenue system of the utilities. In particular overhead and transaction costs related to billing and deposit management were significantly reduced.
- Considering the time and costs of day to day management and maintenance of meters, prepayment is proved to be a more cost-effective option than the billed system.
- The rapid expansion illustrates the success of the system within utilities. For the period 1994-2000 some 3.2 million prepaid meters were installed in South Africa by the electricity supply industry.

Tremolet and Neale, (2002) report that one of the key axes of SGEE's[1] commercial strategy is the widespread introduction of prepaid meters for electricity. According to the report, despite some logistical problems (such as the organisation of vendors in rural areas), the system has improved cash collection and has had a major impact on the company's financial performance.

However according to a World Bank report, the level of non-technical losses accompanying the use of pre-payment meters was 20-30% in South Africa (April 1999) and, in certain parts of Cape Town, as high as 70%. [World Bank, 2001]
While the report underlines the advantages of the system (such as preventing arrears, no meter reading and billing required, no costs incurred when consumers move to another location) it also emphasizes the fact that "*adopting a prepayment method does not substitute for good management*".

For example the monitoring of the occurrence of non-technical losses should remain critically important, this can for example be achieved by random household checks on the base of sales records [World Bank, 2001].

Gaunt (2003) reports that despite some development problems with prepayment meters and the fact that they cannot completely prevent electricity theft and

[1] SGEE (Societe d'Energie et d'Eau du Gabon): company managing electricity and water services in Gabon under a 20-year concession contract.

meter tampering, they are considered by most utilities to be a successful technology.

This success explains why other countries, including Gabon, Ghana, and most Southern Africa countries have adopted prepaid technology and meters mostly to improve collection. [Tremolet and Neale, 2002] [Gaunt, 2003]
However referring to how the system works a careful cost/benefits analysis is required when considering the application of the system to other countries.
Figure 4.1 shows a schematic of Eskom prepayment system.

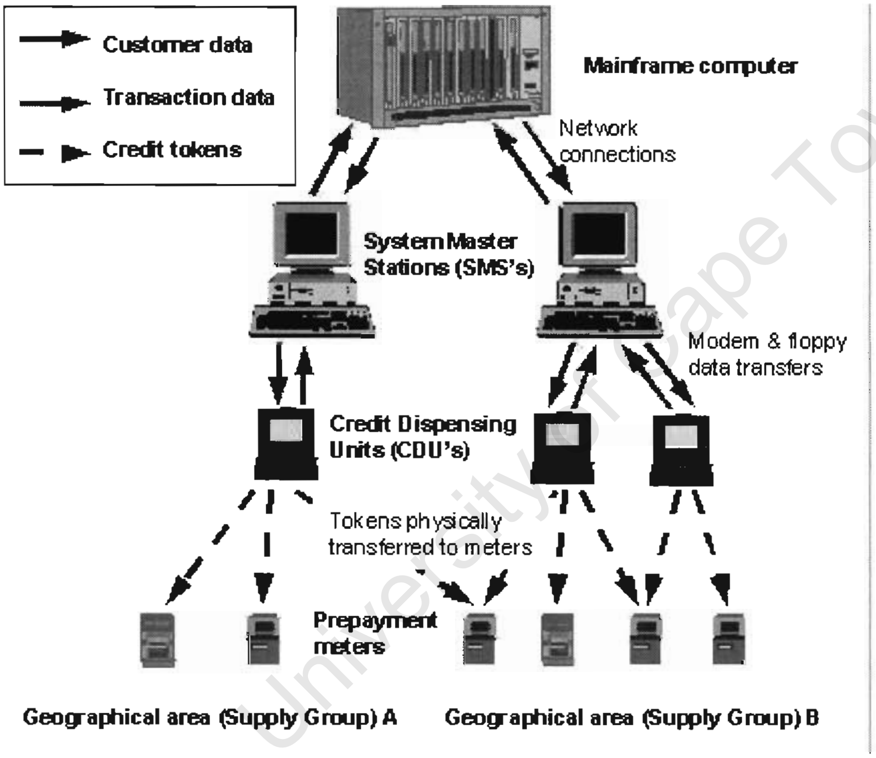

Figure 4.1: Schematic of Eskom prepayment system.
[Source: www.eskom.co.za]

It can be seen that beside the meter at the customer premises, vending machines, system master stations and mainframe computers are part of the integrated system.
It follows that the acquisition cost of the system is high.

Besides the system requires a well-organised support infrastructure as the service must be brought close to the customer and a widespread and decentalised network of agents must exist. [World Bank, 2001]

From the various reports it appears that despite the higher acquisition cost the system contributes to improved financial performance by preventing arrears (thus better collection) and by reducing meter reading and collection costs.
In addition although issues such as fraud are not completely solved, the system may reduce the scale of electricity theft.

4.2.2 Local organisation

As written in 4.1.1 prepayment meters are a technical approach to improve collection by reducing some of the non-technical losses. Given the cost of their introduction and the fact that they are not completely efficient, an institutional approach can supplement the system.

From a utility's perspective the local organisation can take a number of forms including the following: [Inversin, 2000a]

- Provide bulk power to a local organisation that will be responsible for the day to day management of the network.
- Rely on some trained members of a community to take local initiatives such as revenue collection and answering complaints from consumers.

From experience in Nepal, Inversin (1994) explains how user's organizations can be used to overcome the burden of serving remote areas with low financial return. He writes; " *The concept of user's organizations,...has been adopted to provide co-ordination between the villagers and the electric utility... to collect monthly fees from all consumers and deposit them in the utility's bank account, to maintain liaison between consumers and the utility and to resolve technical problems that may arise. The burden on the utility from operating rural systems is thereby minimized."*

From another experience in the Philippines, Inversin (2000a) describes arrangements between households in a neighbourhood (Barangay) organised in a BAPA (Barangay Power Association) and a power utility as follows: " *The utility agrees to provide bulk power to the BAPA, that is metered just below each distribution transformer and to install and maintain the distribution infrastructure. In return, the BAPA agrees to be responsible for reading individual consumers meters and collecting the amount due from each consumer on dates specified by the utility.*"

And further, he describes the gains for the utility and consumers: "*Through this mechanism, the burden of covering the cost of all losses falls on the Barangay themselves, and not on the utility. And because consumers themselves must bear the cost of losses they are encouraged to enforce all anti electricity pilferage regulations.*"

This kind of arrangement can be applied to an entire town.
In South Africa "*a portion of electricity distribution is undertaken by 368 municipal electricity departments. All these distributors buy bulk power from Eskom*". [Eberhard, A, 2001] (However this is likely to change with the proposed restructuring of the whole electricity distribution industry into 6 large Regional Electricity Distributors)
Although municipal electricity departments were not created to facilitate collection, this arrangement allows the utility to disengage in managing some areas and does improve Eskom financial efficiency.

In Bangladesh, due to poor performance the management of distribution networks in rural areas and small towns had been transferred from utilities to cooperatives. [World Bank, 2002a].
According to the report, in contrast to utilities, cooperatives have recorded higher levels of operational performance including lower system losses, better billing and collection levels.

The reported financial success of cooperatives certainly results in a higher ability to pay, and utilities supplying the cooperatives, should subsequently experience better revenues.

The cooperative approach is also experienced on a significant scale in Argentina where in several communities utilities are not responsible for direct collection. Instead, cooperatives supplied by utilities (generally by prepaid meters) are responsible for electricity distribution and revenue collection in those communities. [Pachauri, 2001]

In Congo, because of the long distance to the utility's offices and the difficulties to obtain a connection by legal ways, customers in peri-urban areas tend to collude with SNEL staff for illegal connections or meter fraud.
This can be confirmed by the results of a survey in peri-urban areas of Kinshasa. [World Bank, 2001]. According to the report, 30% of the population surveyed had an illegal connection.
This makes the community revenue collection suitable for these areas. However with the current state of the banking system, handling cash will become difficult.

4.2.3 Industry restructuring.

The purpose of this section is to assess the impact of the reform process on utility's performance and implications on electrification, the starting point being an under performing national utility operating as monopoly.

Turkson, (1998) describes the restructuring process of power sectors as involving changes in management/ownership at one hand and changes in the structure of the industry in the other hand.

Explaining these changes he writes: "*<u>Management/ownership changes</u> involve the reform of the public monopolies to operate as commercial entities to shades of private sector involvement such as management contract, contracting or* *selling out non-core activities of the industry, partial privatization and full privatization of core activities of the industry.*

Structural changes involve partial or complete unbundling of the generation transmission and distribution activities of the industry into separate business units, and introducing competition and an incentive based transparent regulatory system in the segments of the industry where appropriate."

For African countries Karekezi and Kimani, (2001) describe the unsatisfactory technical and financial performance of most African power utilities as a major reason for embarking on comprehensive reforms.

The following aspects illustrate the poor performance of most African power utilities:

- Unreliability of power supply, low capacity utilization, low plant availability suggesting deficient maintenance, and high transmission and distribution losses. [Karekezi and Kithioma, 2002]
- Inability to mobilize sufficient investment capital for the electricity sector development and expansion. This results in "*the failure to provide adequate levels of electricity services to the majority of the region's population especially to rural communities".* [Karekezi and Kithioma, 2002]

However, Girod and Percebois (1998) showed that in Africa "*reforms remain essentially the attribute of bi and multilateral financing organisations which are often their most active promoters."*

And further they write: "*reforms* (in African countries) *have been inspired by schemes already tested in industrialized countries such as: vertical de-integration introduction of competition, withdrawal of the State in its regulation functions opening up to private shareholding..."*

This uniformity of the proposed reform process despite differences across reforming countries is questionable.

For example, Wamukonya, (2003) describes this situation as follow: "*Most pioneer reformers had the advantage of mature systems (*well developed infrastructure*) with electricity accessibility levels well over 70%; this is not the case with a significant share of current reformers".*

And further: "*Despite this important variation across reformers, the design of the reform processes has been based on those of the original reformers, without taking country specific circumstances into account".*

In African countries already applying the reform process, results are not always satisfactory.

Conclusions of a regional policy seminar[2] to examine the impact of the reform process on the challenges facing African electricity sectors included the following:

- Some encouraging results had been recorded on performance improvements for example positive changes in debt collection levels by some sort of contract management [Karekezi and Kimani, 2001].
- On the particular subject of electricity expansion, results are rather disappointing. "*Past and ongoing reforms of the electricity industry have largely failed to address the challenge of expanded electrification. Consequently reforms have not made much of an impact in increasing access to electricity*." And further*: "the emphasis on profitability appears to have relegated electrification to the bottom of the priority list*." [Karekezi and Kimani, 2001]

About the encouraging results on performance improvements, Turkson (1998) writes: "*The restructuring option that pass the management of the utility to a contractor with more autonomy from the government to enforce sanctions for non-payment is emerging*" in some African countries. For example Cote d'Ivoire initiated such a reform in the early 1990s and positive results in terms of revenue collection, reduction of power outage, and financial performance of the industry were achieved. [Turkson, 1998]

[2] Organized by the African Energy Policy Network (AFREPREN), 24^{th}–25^{th} April 2001, Nairobi, Kenya.

Another example is reported in Tanzania where Net-Group Solutions of South Africa is managing the electric utility under a 2-year contract. As a result significant improvement in collection is reported: a monthly average collection of Tsh (Tanzania shillings) 15.2 billion versus 8.0 billion in the second semester of 2002 without change in tariff. (Source: Business Times of Dar-es-Salam, January 2003, www.allafrica.com 02/04/2003)

Regarding technical efficiency, Menke and Fazzari (1994) recommend "*twinning or technical assistance arrangements with more advanced power enterprises, contractors or manufacturers to bring in outside expertise and create local capacity in the sector".* In other words drawing on international hand-on experience to upgrade local skills can increase efficiency by adequate training.

As for the necessity for African countries to implement the complete restructuring process (as advocated by international organisations), Zomers, (2001) writes: "*There is evidence that publicly owned utilities can be operated efficiently, if an appropriate institutional framework and business environment exist which provides management with the authority and incentives to achieve an acceptable company performance."*

And further he explained in which particular conditions public utilities may be efficient: " *Provided that utilities have sufficient authority, government ruled structures are appropriate while the electric infrastructure is expanding and all efforts are directed at making electricity available to the whole population."*

An example can be drawn from South Africa where a national electrification forum, (NELF) established in the early 1990s to address a crisis in the electricity supply industry (mainly in distribution), concluded, among other things, that the ESI should remain in the public sector.

Steyn, (1995) explains that "*there were general agreement that the primary objective of the industry for the following years of implementing the national electrification program will be best met by a publicly owned industry."*

As for privatization of utilities, Girod and Percebois (1998) explain that in most African countries "*there is a suspicion in the capacity of the private sector to truly work for national development...*"

And Zomers, (2001) to conclude: "*Neither privatization of utilities, nor competition is a solution for the electrification of rural areas in developing countries*"

Explaining this, he writes: "*It would seem impossible to find private entreprises prepared to electrify rural areas, charge affordable tariffs and accept a very low rate of return against the background of the risks, including a low take-up of power consumption.*"

Thus the suggestion to developing countries to determine themselves "*which minimum reform would be appropriate for stopping political interference and government intrusiveness*" [Zomers, 2001]

It appears that expansion of electricity, especially towards areas outside major cities, is not likely to take place as a consequence of the restructuring process. Other solutions to complement the process should be found and implemented.

A number of measures were suggested by the AFREPREN seminar.

These include:

- The establishment of "*dedicated electrification agencies with the mandate of providing electricity to un-served areas (mostly rural areas)*"
- Channel electrification levies on tariffs towards these dedicated agencies.
- Incorporation of electrification targets as prerequisites for the purchase of current distribution and transmission assets. For example "*the purchase of attractive city distribution assets can be linked to the electrification of low-income urban settlements as well as selected rural areas.*"[3]

Turkson and Wohlgemuth, (2001) suggest a move towards decentralized generation systems when resource is available. This is in line with the

[3] For example, the 20-year concession contract signed between SGEE and the State of Gabon include coverage targets for expanding the service to previously un-served areas, including small towns and rural areas. [Tremolet and Neale, 2002]

recommendation to unbundle and introduce competition in the generation segment.
Besides, centralized generation requires investing in transmission lines while decentralized systems are closer to customers.

In conclusion the review indicates that the restructuring process as advocated by international organisations may not be effective in electricity expansion especially towards areas outside major cities with generally low loads.
However some limited form of restructuring such as in Cote d'Ivoire and Tanzania may address the revenue collection problem of the utility.

4.3 STRATEGY AND TECHNOLOGY FOR ELECTRIFICATION

The traditional approach of expanding electricity in Congo is to extend existing networks to un-served areas starting by provincial towns.
The successive master plans based on this approach failed to deliver given the high costs of transmission and distribution lines. These are generally of tri-phase construction irrespective of the load size or whether the load to be supplied is single or tri-phase.
New policies and alternative technologies to supplement the traditional approach are sought.

4.3.1 Decentralization.

Summarizing experience of extending electricity in African countries and taking into account the shortage of funds and the limited productive uses outside major towns, Ranganathan, (1992) described the following decentralised strategy: "*In terms of choice of alternatives, grid extension is the best option if the load is near the grid. The next best option is mini or micro hydro provided there is a site available close to the demand center, but far away from the grid the diesel option may be considered.*"
In other words, for areas that cannot be economically connected (because of low loads or long distances or both) to existing systems, the strategy of reverting to

small-scale production and distribution of power from diesel or small-scale hydro can complement electrification efforts.
This strategy can for example delay the construction of expensive transmission lines and allow an initial development of small independent grids to be connected to the existing networks at a later stage.

4.3.2 Outline of small-scale hydro technology and costs.

The hydro electricity production is out of the scope of this study but an outlook of the technology and costs involved is necessary. This is justified by the fact that the potential in small-scale hydro power has been identified by the Congo utility and some NGOs as being an attractive option for meeting needs in areas remote from existing systems.
However this section will concentrate only on the small and mini hydropower schemes. According to Paish, (2002) small hydro is related to schemes of below 10MW while schemes above 500kW but below 2MW are in the mini hydro category.

Figure 4.2 shows the range of costs for mini hydro projects.
However, the following technical and economic factors can contribute to reduce small and mini hydro costs:

- Use of electronic load controllers (ELC) as a governing system. As with any governing system, a change in load should not result in a change in turbine speed (and thus in supply frequency). Compared to the mechanical governor (that regulates the flow of water through the turbine) the ELC varies the amount of power that is fed to a ballast load. It is less expensive than the mechanical governor. Besides this system allows hydro plants to work unattended, thus reduce labour costs. [Kristoferson and Bokalders, 1991] [Paish, 2002]

- Use of turbines more easily fabricated in developing countries and that have better access to working parts (crossflow and pelton turbines). [Paish, 2002]. A refurbished second hand turbine can also be used.

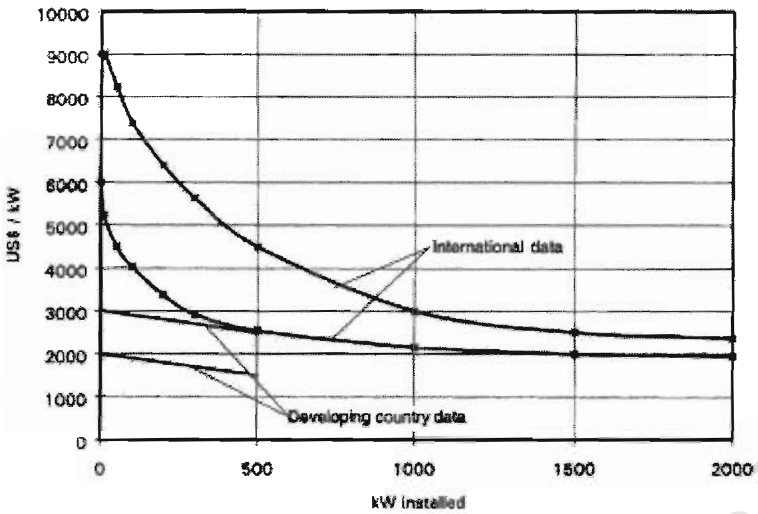

Figure 4.2: Range of costs for small-scale hydro projects.
[Source: Paish, 2002]

- Use of local and community labour as much as possible for example in the civil works.
- Achieving high load factors. This means that ways should be found to integrate different needs such as domestic uses, small business, water pumping and local industries particularly agro processing machinery. [Kristoferson and Bokalders, 1991]
- Although this technology is site specific, run-of-the-river schemes that do not involve dams or barrages are cheaper to build and should be preferred. [Paish, 2002]
- Standardisation.

According to Paish (2002), "*costs can be minimized by using indigenous expertise and technology if available such that costs below $1000/kW can be achieved*".

In a specific project costs of small and mini hydro projects should be compared to grid extension costs. An indication cost of a single transmission line under 132kV using single Wolf structure is about $ 62.000/km, transformers and switch bays not included.[4]

4.3.3 Purpose of electrification

A strategy can also be derived from the purpose of electrification.
Gaunt, (2003) describes 3 possible objectives when implementing electrification: economic, socio-economic, and social objectives.

Economic objectives are achieved when electrification is implemented because of the individual financial profitability of a project. For example when a utility supplies customers "*on the basis that the full cost will be recovered from a connection charge and the sales of energy.*" [Gaunt, 2003]
In other words electricity is supplied to productive customers such as manufacturing, mining and commercial companies.
The supplier expects that a share of revenues derived from the production will be used to pay the full cost of the electricity.

Sometimes justification in electrification is not the immediate financial profitability but rather the contribution to socio-economic development of a community.
A World Bank report, (1975) on rural electrification describes this contribution as follow: "*In regions which show clear sign of development as a result of public or private investment in agriculture and agro-industries, ...electrification can often speed development. It can help increase the output and thereby the profitability of farms agro-industries and commerce by providing a superior and cheap means of motive power lighting, refrigeration... It can also serve a number of households uses including those of low-income households.*"

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[4] Personal communication with SNEL Research and Development Department (December 2002)

In other words electricity is provided to a community as "*an investment such as for supporting employment creation, extending the scope of productive activities or improving agriculture production*" [Gaunt, 2003].

It should however be emphasized that it is the simultaneous presence of electricity and other resources such as agriculture growth, skills, local infrastructure, and trade opportunities that stimulate development. [Sanghvi and Barnes, 2001] [Pachauri, 1991]

Because of the long-term benefits to the broad economy, international development and financial institutions generally bring support to socio-economic electrification schemes.

For example, Zomers, (2001) reports that the German Development Bank (KFW)[5] imposed for some grid based electrification projects the requirement that, "*consumptive use of electricity should be less than 40% of total use*".

Electrification for social development is mostly directed towards poverty alleviation. It is expected that the supply of electricity to poor communities will improve their living standards.

Such schemes are generally motivated by factors beyond financial viability such as "*income redistribution, social equity goals and political influence*". [Gaunt, 2003]

Being mostly based on domestic uses of electricity by the poor, the sustainability of such projects may be little.

Zomers, (2001) explains the situation as follow: "W*ithout any additional productive use of power, there will be no increased income generation and thus a limit to the ability to pay for the electricity. This could hamper load growth, reduce the beneficial effects and put the sustainability of an electrification scheme at risk.*"

From the purpose of electrification, a strategy can be derived.

For example if electrification is undertaken for economic objectives the cost of interruptions is generally high, thus the capacity, the voltage quality and the

reliability of supply of systems have to be high (so that the equipment of high quality used by companies can work properly).
In socio economic electrification, the extension to the maximum number of communities to stimulate their development should take priority over the quality and reliability of supply.
As for social electrification lowest cost technologies that meet social needs will be applied with possible option of network reinforcement if loads develop.

4.3.4 Technology for electrification.

As written in 4.3.2 in order to meet economic objectives or in urban areas, the network capacity, the voltage quality, and the reliability of supply have to be high. But outside major cities changes on standards (and thus costs) should be considered.
In a report on electrification in Mozambique the World Bank (2002c) writes: "*It is possible to reduce the costs of rural electrification significantly with little, if any, loss of quality of service. The standards and procedures utilised by most power utilities are mostly inappropriate for rural conditions and often reflect past practice in developed countries. As a result, it is possible to introduce lower-cost technical standards and operational procedures that have already been tested and found acceptable in other places of the world*".

Given the importance of solving the electrification problem in Congo, possibilities on the network technology side will be developed further in chapter 5.

4.4 STANDARDIZATION

The different voltage levels for MV lines found in Congo include the following: 6.6; 10; 15; 20 and 30kV.
This leads to special stocks of spare parts.

[5] Kreditanstalt fü Wiederaufbau

However, 30kV has been introduced as standard mostly for linking communities in the vicinity to the networks of main urban centers.

Standardization can contribute to electricity expansion in many ways including: [Gower and Strachan, 1991]

- Distribution networks (MV and LV) have a relatively high share in the cost of electrification projects because of the large quantities of network components; optimization and standardization can reduce these costs. For example overhead conductors have to be chosen according to the load density in the supply area and allowable voltage drops. But it is possible to limit their number to a few different standard sizes. It follows that for each item (conductors, poles, transformers, insulators..), few sizes are held in stock and equipment of one area can easily be used in another area.
- When a number of utilities have standardized the same equipment, manufacturers of such equipment have a broader customer base. This reduces costs by economies of scale and ultimately lower electrification costs.

A frequently encountered problem is the imposition of foreign standards to developing countries through loans or aid programs that finance electrification projects.

This can be illustrated by a World Bank report on Burundi that identified the imposition of foreign technical standards as an obstacle to electrification. According to the report "*several donors active in Burundi with respect to the financing of new extension lines allow only the use of high-cost imported equipment and materials from donor countries, instead of lower-cost equipment from more advanced developing economies. Such practices should be discontinued to permit more cost-efficient expansion of the system..*" [World Bank, 1992]

In the Africa region organisations such as UPDEA (Union des Producteurs et Distributeurs de L'Electricite en Afrique) and PIESA (Power Institute for East and

Southern Africa) are, among other things, combining and rationalizing standards of various countries.
In particular PIESA standards contain most of South African standards (SABS) used in the recent successful electrification program.

4.5 CONCLUSION

Persistent poor technical and operational performance within SNEL can justify a restructuring process. But the necessity of electrifying the country and the small benefits shown elsewhere by restructuring suggest that minimum reform measures in the framework of public utility be applied.
Private institutions that always emphasize immediate profitability of each project can help to improve performance but are unlikely to contribute significantly to the electrification of low load areas. Therefore to meet socio-economic and social needs privatisation is unlikely to be the successful route.

The strategy of reverting to local available sources could delay expensive transmission lines and allow the initial development of small independent grids to be connected to the existing networks at a later stage.

When enough capacity is available, and in order to supply the most communities, alternative technologies that lead to lower costs of distribution lines might be applied.
Standardization of network voltages and equipment should be part of such efforts.

This literature review has identified some key strategies such as decentralisation and most importantly low-cost technical opportunities. In the following chapters we will develop further these possibilities at the network side.

CHAPTER 5

LOW-COST ELECTRIFICATION.

5.1 INTRODUCTION

While chapter 4 dealt mostly with institutional and management measures to overcome inefficiencies within existing systems, the present chapter continues the literature review and focuses on technical solutions, designs and standards to reduce electrification costs.

The objective is to identify networks that will be cheaper to build thus resulting in lower connection costs.

While networks should not restrict the use of electricity for meeting economic needs, the present chapter is more focused on technologies that provide the maximum benefits for socio-economic and social development in rural areas even with some limitations (such as more losses, lower capacity supplies).

For electricity expansion towards rural areas from cities already connected to the main grid or to a local plant, distribution lines are needed. At the customer level connection and wiring equipment are the main requirements.

This chapter will deal with cost reduction at the distribution level as well as at the connection and wiring level.

The investigation will be restricted to overhead lines taking into account the following elements:

- The provision of expensive materials such as PVC, XLPE, oil impregnated paper explain the high cost of cables over overhead conductors. [Inversin, 2000b)
- The easiness to locate and repair faults, to make joints in order to serve new customers and to add capacity if the load increases are further advantages associated with overhead lines.

- However due to greater exposure to weather elements, the reliability of overhead lines may be low [Gaunt, 2003]. In addition such lines are susceptible to tampering.
- In case the quality of poles used in an overhead line is low these will frequently be replaced and life-cycle costs associated with overhead construction using such material may be important.

However in most circumstances overhead lines are cheaper than underground lines for the same power to be transmitted.
For example Bayliss, (1999) reports the following cost ratio underground/overhead for three-phase lines and equal power transmitted using British costs and standards.

System Voltage (kV)	0.4	11	33	132
Cost Ratio cable/line	2	5	6	8

Table 5.1: Cost ratio underground overhead using British standards.

In the specific case of Congo, given long distances between communities in a vast country, acquisition and installation costs of underground cables may be prohibitive.
Thus, the investigation in cost reduction will be directed towards overhead lines and will focus on line configurations, conductors, poles and the supply voltage.
The restriction to overhead systems outside cities is in line with the objective of reducing network costs in order to connect the maximum number of communities.

5.2 LINE CONFIGURATIONS

5.2.1 Introduction

The common design of distribution lines in Congo is the tri-phase construction irrespective of the load size or whether the load to be connected is single-phase or three-phase.

In this section possible alternative configurations particularly those adequate in rural areas or for small loads are investigated.

5.2.2 Various configurations.

Diagrams shown in figures 5.1 to 5.5 are some of the possible network configurations that can be used in order to transfer from an existing transformer or generator a capacity P (W) over a distance L (m).
These configurations should be assessed in terms of power transfer capability and energy losses.

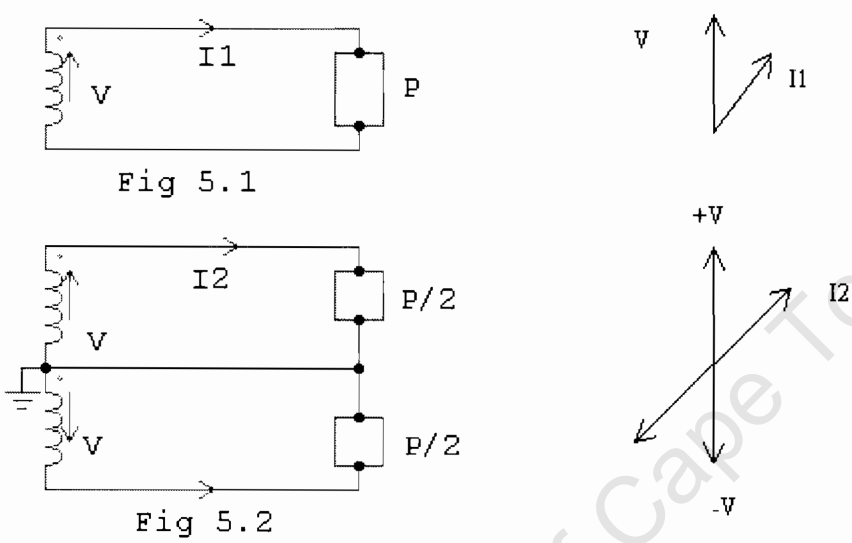

Figure 5.1 and 5.2: single-phase 2 wire and center-tapped configurations.

Figure 5.1 show a single-phase 2-wire configuration or a conductor return system.
Figure 5.2 shows a center-tapped single-phase 3-wire system (or dual phase system). In the theoretical case where loads are perfectly balanced as shown in the figure, no current flows in the neutral wire.
Figure 5.3 shows a 2 phase 3-wire system. Voltages in the 2 windings are not opposite as in the dual phase system (fig. 5.2) but are 120 degrees apart.

The vector diagram shows that the current in the neutral is equal to the current in each outer conductor (assuming the voltages are 120 degrees apart and balanced loads).

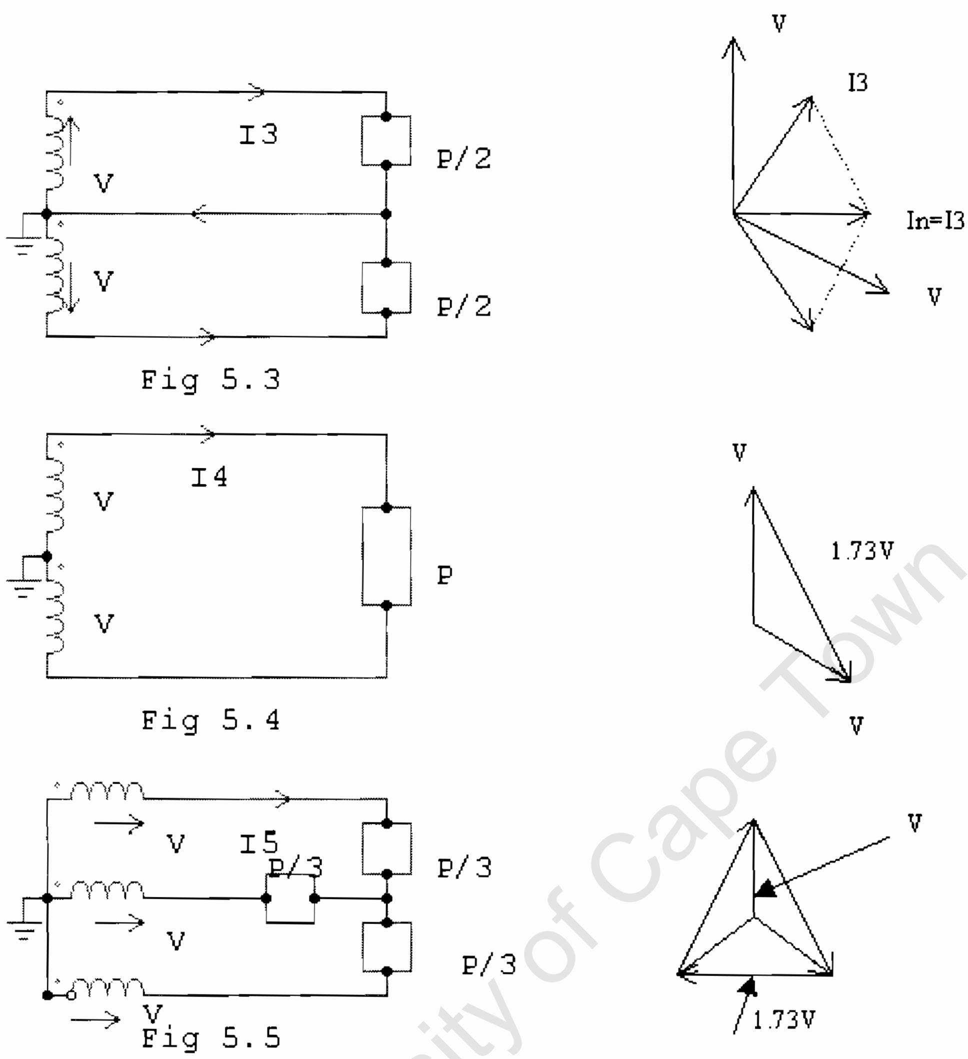

Figure 5.3, 5.4, and 5.5: 2-phase 3 wire, 2-phase 2 wire and 3-phase 3 wire systems.

Figure 5.4 shows a 2-phase 2-wire system where the load is connected across a voltage $V\sqrt{3}$.

Figure 5.5 shows a balanced 3-phase 3-wire system. A 4th conductor can be added to allow single-phase connections (mostly in LV systems and for MV systems in North America.).
Given particularities of the SWER (Single wire earth return) system, it will be dealt with in a separate section (section 5.2.4).

5.2.3 Comparison of power transfer capability and power losses.

Assuming that a conductor of unit resistance r (Ω/km) is used in the various configurations, the table shows the current in line (I_1 to I_5) and power losses at peak loads (P_{l1} to P_{l5}) for the different systems.

Configuration	Figure	Current in line	Power losses
1Φ 2-wires	5.1	$I_1 = \frac{P}{V\cos\phi}$	$P_{l1} = 2rL(I_1)^2 = 2rL(\frac{P}{V\cos\phi})^2$
Center-tapped 1Φ	5.2	$I_2 = \frac{P}{2V\cos\phi}$	$P_{l2} = 2rL(I_2)^2 = \frac{rL}{2}(\frac{P}{V\cos\phi})^2$ or **$P_{l2}=1/4 \times P_{l1}$**
2Φ 3-wire ($I_N=I_3$)	5.3	$I_3 = \frac{P}{2V\cos\phi}$	$P_{l3} = 3rL(I_3)^2 = \frac{3rL}{4}(\frac{P}{V\cos\phi})^2$ or **$P_{l3}=3/8 \times P_{l1}$**
2Φ 2-wire	5.4	$I_4 = \frac{P}{1.73V\cos\phi}$	$P_{l4} = 2rL(I_4)^2 = \frac{2rL}{3}(\frac{P}{V\cos\phi})^2$ or **$P_{l4}=1/3 \times P_{l1}$**
3Φ 3-wire (balanced)	5.5	$I_5 = \frac{P}{3V\cos\phi}$	$P_{l5} = 3rL(I_5)^2 = 3rL(\frac{P}{V\cos\phi})^2$ or **$P_{l5}=1/6 \times P_{l1}$**

Table 5.2: Current in line and power losses at peak load in various systems.

Assuming the networks operate at peak load, the table shows that:

- For the same load, smaller currents flow in the 3Φ system as compared to single-phase supplies.

- As a result, losses (P_l) are significantly smaller. In other words, higher efficiency is associated with the 3Φ system.
- A dual system and a 3Φ system using conductors of respectively ¼ and 1/6 the cross sectional area of the single-phase 2-wire conductor, will result in the same losses or in equal transmission efficiency (as a result of $P_{l2}=1/4P_{l1}$ and $P_{l5}=1/6P_{l1}$). Conversely, with conductors of the same size a greater load (4 and 6 times respectively) can be served by the dual phase and the 3Φ system. This configuration (dual system) is mostly used in LV with the following particular advantages: [Geldenhuys, 2003]

  (1) upgrade route from single phase 2-wire feeder when load grows over the line capacity (before shifting to a tri-phase system),

  (2) easiness to balance load between 2 phases instead of 3 in 3-phase line,

  (3) easier work for lines men who have to keep track of 2 phases only.

As far as capacity is concerned the power transfer capability associated with the tri-phase system is the highest (smaller losses).
However some observations have to be made in the case of rural electrification.

- Rural loads are typically small. For such systems the conductor size is "*mostly dictated by mechanical constraints*". [Inversin, 2000b] In order words, regulations state the minimum size to be used, as conductors should not break and present a hazard to customers.
- Practically, a utility "*standardizes conductor sizes* (as well as other equipment) *to take advantage of lower unit costs through quantity purchases and to facilitate maintenance and replacements*. [Gower and Strachan, 1991]

It is possible that the capacity of the single-phase system associated with the conductor selected according to safety requirements, or to the standardized size, is adequate to meet needs in rural areas.
If this is the case, adopting the tri-phase system because of its higher power transfer capability and lower losses will result in the capacity being under utilized.

It can be argued that it is better to build a tri-phase line in order to avoid upgrading later when load grows.

But, according to Ferguson, (1998) when resources are limited and the load to be served is difficult to predict such as in rural areas, it is better to "*build a less expensive network that matches more closely the load, connect more customers and upgrade when the load dictates".*

To sum up, although tri-phase lines can transfer more power, single-phase systems may be adequate in supplying low loads areas.

5.2.4 The SWER technology.

The particularity of this system is the reduction of the overhead line to 1 wire so that the load current returns to the source through the body of the earth.

Figure 5.6 illustrates the composition of the SWER system.

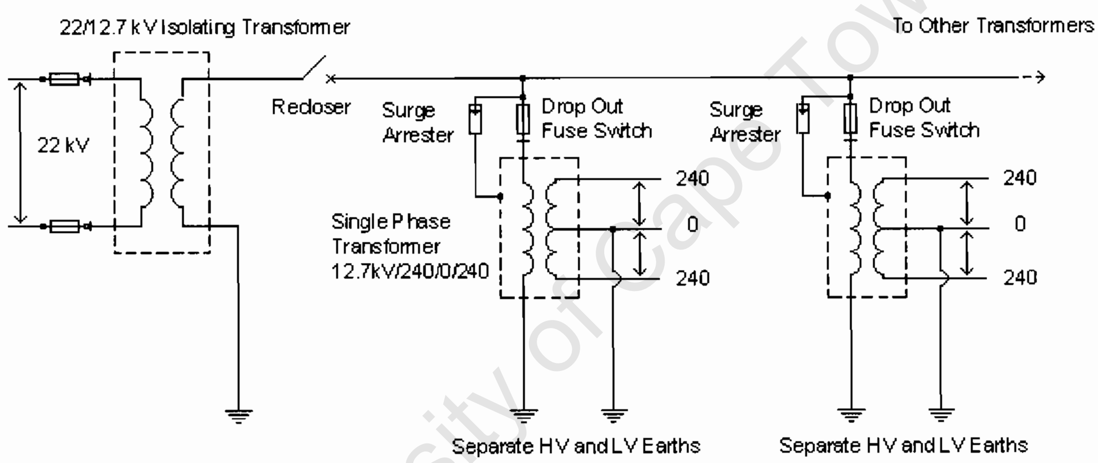

Figure 5.6: Main elements of a SWER system. (Source: www.ruralpower.org, 17/02/2004)

Main elements of the system are:

(1) the isolating transformer

(2) earthing electrodes

(3) the distribution transformer

(4) the SWER conductor and

(5) line protection

The following factors limit SWER currents and loads:

- As SWER electrodes carry load currents continuously, voltages around these electrodes should not result in step and touch potential dangerous to animals and humans. For this reason, electrode grounding resistances or load currents or both have to be restricted. [Chapman, 2001]
- Beside safety reasons, possible interference of SWER currents on telecommunications networks (if any) also limit load levels. Such networks do not exist in Congo rural areas.
- Protection in SWER lines requires a clear discrimination between load currents and fault currents. For this reason, there is interest to adopt a SWER voltage as high as possible, so that the resulting low load currents are more precisely discriminated with a fault current[1]. [Ferguson, 1998]

In addition to the protection requirements and to power transfer capability, the possibility to use in SWER lines the same equipment as in existing lines also influences voltage choice.

For example as 30kV has been adopted as standard for future MV lines in rural Congo, a SWER line under 17.32kV ($30/\sqrt{3}$ kV) will use the same standard equipment such as insulators and surge arresters, as the tri-phase MV lines.

Standards for SWER lines in South Africa and other Southern Africa countries are: a maximum continuous current of 25A, a fault clearing level of 30A, a SWER voltage of 19.1kV ($33/\sqrt{3}$ kV), a maximum feeder capacity of 475kVA and standard isolation transformers of 50, 100, 200, and 400kVA. [Ferguson, 1998]

[1] This is largely used in railway electrification. In DC systems (3kV or 1.5kV) normal traction current is large and the selective interruption of fault is difficult. Special (and expensive) relays are used to improve the selective breaking performance. Such relays use the fact that a fault current shows a large sudden increase (large di/dt). In AC systems (generally 25kV) the difference between the normal load current and the fault current is large and the selective breaking of the fault easier. Thus simple over current protection can be used.

SWER lines can achieve longer spans for the following reasons:

- As loads are limited (in rural areas), currents are small under distribution voltage levels and small size conductors can be used. Wind spans are therefore longer as the conductor diameter is small and there is only one conductor (see appendix 1).
- The unique conductor is generally placed on top of the intermediate pole thus the maximum sag (or the vertical height available for sag) is higher. As explained in appendix 2, this results in long ground clearance spans. Spans will be even longer if conductor with high strength (high UTS value) is used.

The long spans of SWER lines will considered further in chapter 6.

The limitation of loads on SWER lines and the fact that these systems can achieve long spans make them suitable for rural areas (where loads are small and distances between communities longer than in urban areas).
A further interest is the low capital cost of SWER systems. In chapter 6 we will show that these systems cost much less than tri-phase lines for the same power to be transmitted.

5.2.5 Shield Wire Systems

The idea of using the shield wire of HV transmission lines in rural electrification emerges from the fact that "*communities located in the vicinity of these lines cannot be connected because the cost of a HV/LV substation is too high for the small loads involved*". [Inversin, 2000a]
Electrification of such communities can take place after the shield wire is insulated from the tower and energised at MV level. To supply a village a single-phase transformer connected between the shield wire and ground is used. [Gatta et al, 2000].
This is in fact a SWER line whose conductor is located on top of the HV line.

Traditionally shield wires of HV lines are designed to reduce the chance of a lightning strike to the transmission conductors and, being directly connected to towers, to direct any electric charge to earth. After the shield wire is energised (in order to supply the rural community) a way must be found to keep this safety requirement.

Gatta et al (2000) have shown from "*laboratory investigations and more than 14 years of field experience*" that "*energising the shield wire of HV line (V≥115kV) at MV level (up to 34.5kV) does not erode the lightning shielding efficiency of the shield wire".* The lightning protection is achieved thanks to arcing horns at the shield wire insulators. In the case of a lightning strike "*the shield wire is grounded by the arc that appears at the arching horns of the shield wire insulators and the resulting short circuit is cleared by protection*". [Gatta et al, 2000]

If the HV line has 2 shield wires a tri-phase scheme can be implemented by insulating and energising the 2 wires with ground return as a 3rd conductor, as shown in figure 5.7.

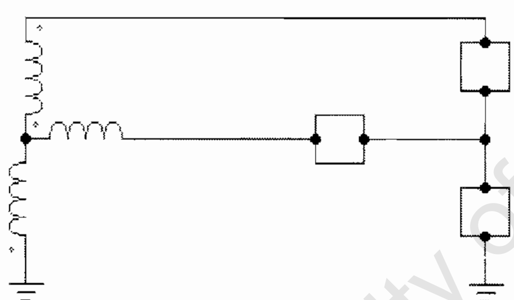

Figure 5.7: Tri-phase system with ground return as 3rd conductor.

5.2.6 Conclusion (regarding line configurations)

Although tri-phase systems are more efficient than single-phase networks, these are adequate when loads to be served are small, in the range of 100kVA-200kVA. [Dingley, 1988]

This explains why single-phase systems, including SWER are extensively used in rural areas of other countries such as Australia, Brazil, USA, Costa Rica, and Thailand. [Dingley, 1988]
In particular, shield wire systems are used in Laos, Ghana, Sierra Leone and Ethiopia. [Gatta et al, 2000]

5.3 COST REDUCTION AT THE CONDUCTOR LEVEL

The following elements influence the cost of conductors in an overhead MV line:

- The material used (copper, aluminum, ACSR or steel). [Inversin, 2000a]
- Conductor number depending on the system adopted for electrification.
- Conductor size that is determined by the supply voltage, the load to be met and the maximum acceptable voltage drop.
- The conformity to standard sizes already existing within the utility in order to minimize sizes held in stock. [Bayliss, 1999]

Among ways to reduce conductor cost is the reduction of its size by adopting a higher supply voltage.
In addition to the size and cost reduction brought by the higher voltage, weight and wind effect will decrease.
As explained in appendix 2, wind on a conductor results in a horizontal force that creates a moment on the pole. The force and the moment are proportional to the conductor diameter.
Using a conductor of smaller diameter reduces the wind effect on poles and lighter poles (of smaller cost) can be used[2].
Besides, with a higher supply voltage the voltage drop is reduced if the same conductor is used.

[2] In Railway electrification structures on 25kV AC system are much lighter than structures on 3kV lines where conductors used are of larger size and heavier.

However a higher supply voltage imply the following: [Mehta, 2003], [Inversin, 2000a]

- Wider cross arms and higher ground clearance are needed. This may require longer poles.
- Higher insulation levels of equipment such as transformers, circuit breakers and lightning arresters.
- Increased cost of insulators.

It follows that the voltage level should be determined such that the saving in conductors and poles outweigh the cost of wider cross arms, higher insulation of conductors and equipment. However standardization within the utility should also be taken into account.

A proper estimation of the load to be supplied and the pattern of load growth can also lead to the limitation of the conductor size.

5.4 COST REDUCTION AT THE POLE LEVEL

As steel and concrete poles are more expensive and given transport deficiencies in Congo, wood poles should be recommended.
Possible ways to reduce the initial cost of these wood poles include (1) reducing their number and (2) reducing their length.

However the proper mechanical design of overhead lines suggests that these two alternatives are hardly met at the same time.
The figure shows a conductor suspended between 2 supports A and B at the same level.

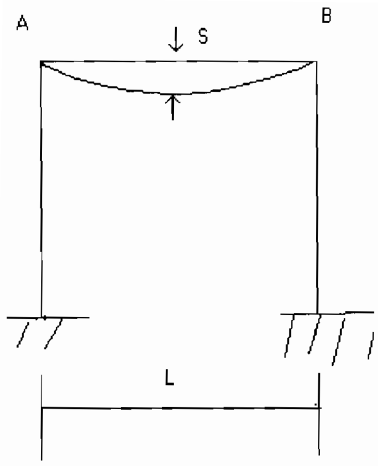

Figure 5.8: Maximum sag on conductor suspended at A and B.

Guile and Paterson (1981) showed that the conductor normally takes the shape of a catenary but if the sag is small compared to the span (in the order of 1/10 of span length), the curve approaches a parabola.

As in practice the maximum sag (S) in MV distribution lines is less than 1/10 span length, the parabola approximation can be applied.

Under such conditions a conductor of unit weight w_c (N/m) on a span length L (m) and under tension T (N) will have maximum sag S (m).

These quantities are linked by the equation: [Guile and Paterson, 1981]

$$S = \frac{w_c L^2}{8T} \qquad (5.\ 1)$$

This equation can also be written as:

$$L = \sqrt{\frac{8ST}{w_c}} \qquad (5.\ 2)$$

For a given conductor of load w_c the tension T is generally limited by regulations to a certain percentage of its ultimate tensile strength.

Equation (5.2) shows that for a given tension T if long spans are used in order to reduce the number of poles (and thus their cost) the maximum sag will have to

be increased. This reduces the ground clearance of the conductor and long poles may be needed (to ensure appropriate conductor clearance).
Conversely if shorter spans are used the maximum sag is reduced and shorter poles can have the adequate height to achieve the required clearance.
However the number of these shorter poles on the entire length of the line will be higher. It follows that a cost analysis comparing the cost of few long poles to the cost of the higher number of short poles is needed. This should determine an optimum length of poles. [Inversin, 2000b]

Equation (5.2) can also be useful in selecting the conductor type for an overhead line between copper and ACSR conductors. Gonen (1988) has shown that because copper conductors have a lower ratio (T/w_c) they require greater sag for a given span length, thus higher poles. If these are not available, shorter spans should be used to provide the adequate clearance.
The determination of the optimum length of poles and conductor selection will be considered further in the case study in chapter 6.

Other factors are also taken into account in the determination of pole length. These include:

- Standardization (a utility will determine a few sizes of poles in order to reduce acquisition cots) [Bayliss, 1999]
- Easiness of maintenance work, environmental impact and availability. [Inversin, 2000b]

5.5 COST REDUCTION AT THE CUSTOMER LEVEL

The major components of connection and house wiring equipment in Congo are based on Belgium practice and are summarized in figure 5.9

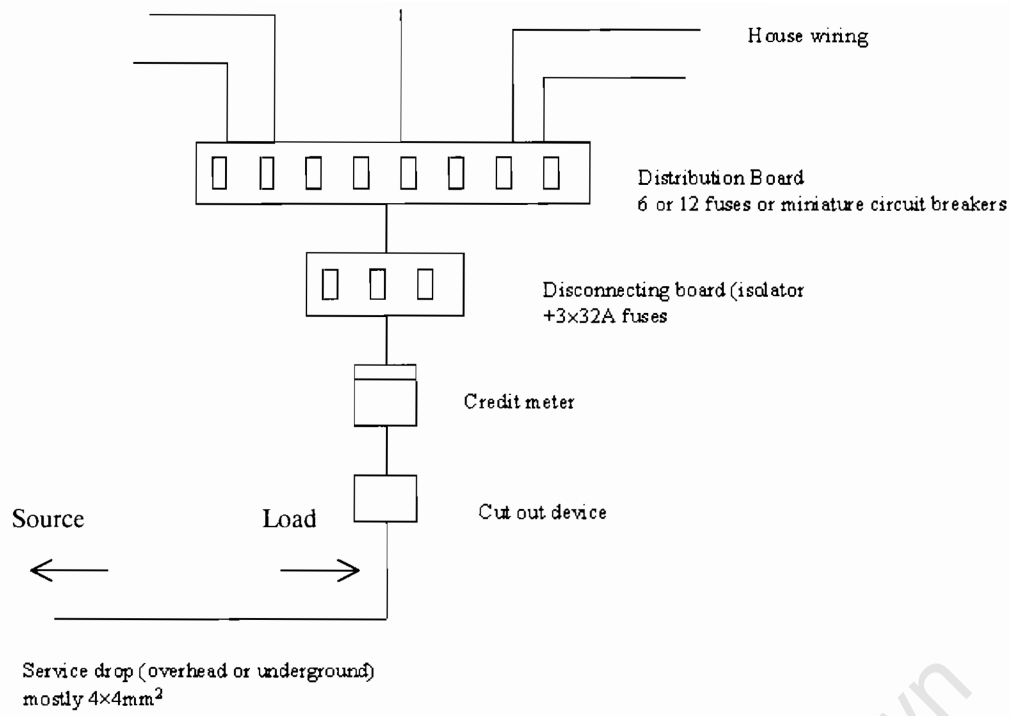

Figure 5.9: Connection equipment at customer premises in Congo.

The cut out device (see figure 5.9) is used by the utility to isolate the supply for example in case of non-payment. Sometimes it is located on top of the supply pole.

The disconnecting board serves to isolate the home from the supply when modifications or repairs are made to the house equipment; it is also a protection against faults in the distribution board.

These standards designed for urban areas are also applied to rural areas.

The high number of components involved result in high cost for connection and wiring. For example typical cost of a 32A disconnecting board in Congo is about 80 US$, which is a large investment for a rural household and a real obstacle for consumers to afford a connection.

This problem is common in many African countries.

Karakezi and Majoro, (2002) underline the very high standards resulting in a long list of material required for wiring a house in African countries.

According to their report, such list in Zimbabwe contains elements shown in table 5.3 and the estimated cost is said to be prohibitive for most poor households.

Material	Quantity
Conduits	12
Surface boxes	4
Round boxes	15
Single pole switches	4
Socket outlets	4
Nipples	15
Couplings	20
Lamp holders	4
Cooker units	1
Miniature circuit breakers	3
MCB Box	1
1.6mm^2 wire	35m
Earth wire	3
Screws	50

Table 5.3: List of material for wiring an average home in Zimbabwe

With the objective of cost reduction ready-boards that include isolators, protection (generally circuit breakers), socket outlets and switches are a way to reduce costs at the house level. In order words all equipment in figure 5.9 except the meter is included in one device: the ready board.

Figure 5.10: Ready board for township electrification.

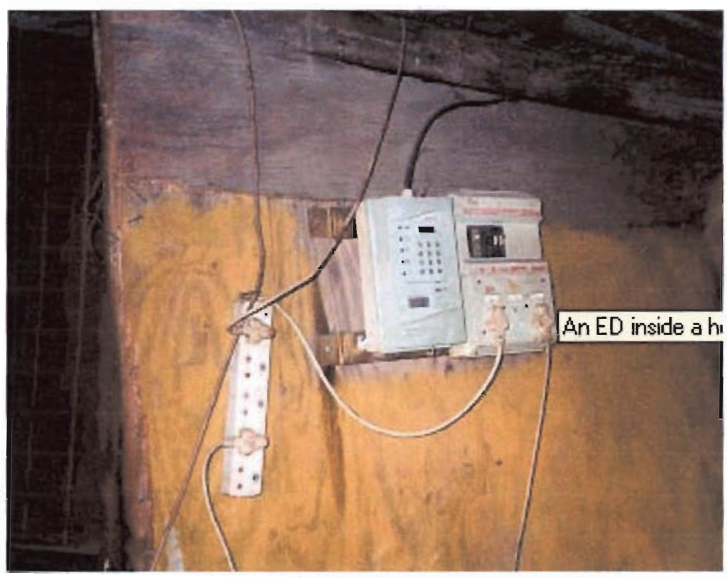

Figure 5.11: Extension cords from ready board's sockets.
Source: http://repo-nt.tcc.virginia.edu

Figure 5.12: Ready board with top mounted light.

Figures 5.10 and 5.12 show ready boards used in township electrification in South Africa. The model of figure 5.12 includes a top mounted light.

As switches, sockets and (possibly) lights are already available on the ready board, house wiring can be postponed or implemented using extension cords from the sockets as shown on figure 5.11.

Cost reduction can also be considered at the meter level. Given the low electricity consumption in some rural areas "*a power-based tariff that eliminates the need for, and costs associated with meter reading and billing*" can be used. [Inversin, 1994]

Practically, load limiters disconnect the supply in case the current drawn (thus the power consumed) exceeds a prescribed and agreed upon limit.

This unmetered supply may improve the utility's revenue collection and as load limiters (generally miniature circuit breakers) cost much less than a credit or prepaid meter, the power-based system using load limiters is more affordable to rural customers.

However in an environment of high non-technical losses, such a system should be disregarded as the device can be easily bypassed.

5.6 CONCLUSION

A number of measures can be considered in order to reduce the cost of electrification outside major cities. These include:

- Adoption of single-phase supplies with sufficient capacity. The reduced number of components allows cost reduction.
- Use of conductors with higher ratio T/w_c in order to achieve longer spans such that fewer poles will be erected.
- Use of a voltage high enough to reduce conductor size and cost.
- A proper estimation of the load to be served and the pattern of load growth.
- Use of ready boards to reduce the number and cost of connection components and possibly postpone house wiring. Load-limiters that cost less than meters could also be used in areas with limited energy consumption if the environment allows.

Most of these methods identified in the literature will be tested in the case study of the next chapter.

CHAPTER 6

TECHNOLOGY FOR AN ISOLATED RURAL ELECTRIFICATION NETWORK.

6.1 INTRODUCTION

The high cost of building three-phase distribution networks is one of the major obstacles to electricity expansion in Congo.

As a result, it is common to find in Congo a network with significant unused capacity while communities in the vicinity are not connected. Appropriate technologies and standards for the design of networks to distribute electricity in a low-cost manner are lacking.

This case study is an investigation into the use of cost-effective technologies for rural electrification in Congo.

Drawing lessons from the experience of successful programs, SABS and PIESA guidelines and standards adapted to Congo are used in the design of a distribution system that cost effectively meets needs in an isolated rural area around Moba in eastern Congo.

The objective is to establish whether other technologies are cheaper and can be applied for electricity expansion in the country.

This case study was developed in the SAUPEC-04 conference in Stellenbosch, 22, 23 January 2004. [Kutelama, 2004]

6.2 THE MOBA AREA.

Moba is a small port on the Tanganyika Lake in eastern Congo.

The following features characterize the area around Moba:

- Fertile soils and high agriculture outputs (the main crops being maize, beans, garlic, and wheat).
- Important fishing activities (however lack of refrigeration facilities lead to products being sold smoked)

- Active business activities mostly involving the sale of agriculture and fishing products.

The layout of the area is shown in figure 6.1

The nearest network is located at Kalemie, 366km away. This means that there is little hope of being connected to that network in a reasonable future.

However electrification of the area can be implemented from a 1 MW hydro project initiated by missionaries at Ngando Fwamba, 11km from the main center Kirungu.

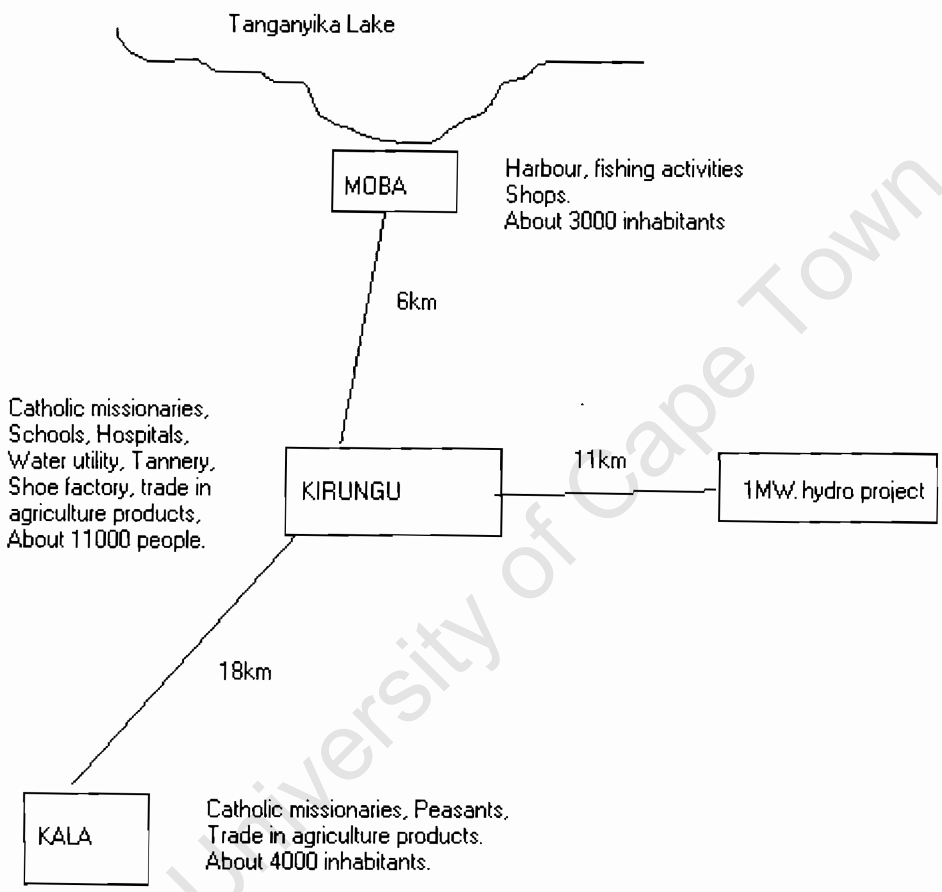

Figure 6.1 Layout of the area around Moba and major characteristics.

Currently no public electricity supply exists in the area. However diesel sets generators supply some loads at Kirungu and Kala as shown in table 6.1 [1]

Site	Total capacity (kVA)
Tannery + shoe factory at Kirungu.	65
Water utility-Kirungu	55
Hospital-Kirungu	25
Catholic mission-Kirungu	30
Catholic mission -Kala	15
Total	**190**

Table 6.1: Existing diesel equipment

In addition to the provision of home lighting and a better service from the local hospital and water utility, it is expected that the electrification of the area will help to establish or improve socio-economic activities.

These include: (1) agro-processing schemes such as grain-hulling and milling, oil and juice extraction, (2) refrigeration activities, (3) small scale economic activities including carpentry, welding, or brick manufacturing.

As far as electrification is concerned, the Moba area is a typical example of rural areas in Congo for the following reasons:

- Like most of rural areas in Congo, Moba is far from existing networks and a local source is needed for electrification. In general a hydro site or a local industry using diesel sets or agriculture residues will exist. From this source the various technologies described in this case study will be applied for the electrification of the area.
- Electricity needs in Congo rural areas are almost identical. These include: lighting, small commercial loads such as hotels, shops and pubs, powering agro-processing machinery, water pumping and some entrepreneurial activities such as brick pressing, sawmills, carpentry, welding shops and sometimes refrigeration. Besides, no major differences in climate and house construction among areas exist in Congo.
- The pattern of electrification proposed in this case study comprises a tri-phase line from a hydro-site to a main center. Feeders of technology to be

[1] Personal communication with missionaries in the area.

determined derive from the backbone to connect smaller communities in the area. As rural areas are always organised around a main center, this pattern can be applied to any rural area in Congo, the tri-phase backbone originating from an existing network or a local source.

6.3 LOAD ASSESSMENT

6.3.1 Residential load.

The quality of housing will be used to assess the ability to pay.

In this area and in most of Congo, low standards in housing suggest a low or irregular income or a lack of permanence. It is a practice to restrict electrification to houses with corrugated iron roofs as this shows a reasonable level of income and thus an ability to pay for electricity.

At an initial stage only such houses should be considered for connection.

A local count by missionaries gave the following results: 315 households at Kirungu, 43 at Moba, and 52 at Kala. This represents about 35%, 25% and 18% of all households in Kirungu, Moba and Kala respectively.

This restriction is also aimed at allowing economic activities to take place for more sustainability of the scheme.

The residential load can be assessed by comparison with Ilebo, another rural area in central Congo with similar agriculture and trade opportunities.

Electricity in Ilebo is supplied by the Congo Railways from diesel units to 828 customers divided into 2 consumption categories as follow:

- About 90 % of customers use electricity mostly at the evening for lighting and cassette players with a maximum consumption of 100kWh per month (during the day most people are working on their own farms).
- About 10% of customers mostly railway employees, administrative staff, and businessmen may use electric irons and/or refrigerators (in general wood and charcoal are used for cooking even in urban areas). Consumption at this category is about 200kWh per month.

Such levels of service correspond to designs with after diversity maximum demands (ADMD) of about 0.5 and 1 kVA. [NRS 034-1: 1997]
As consumers of the same level of consumption are generally found in the same area, the residential maximum demand can be calculated using the following formula: [NRS 034-1: 1997],

$$(1+\frac{2}{N})\times N\times ADMD. \qquad (6.1)$$

(N is the number of consumers in the given area).

Applying the pattern of consumption in Ilebo at Kirungu leads to the following residential maximum demand:[2]

$$(1+\frac{2}{283})\times 283\times 0.5+(1+\frac{2}{32})\times 32\times 1=176.5kVA$$

For Kala that is a pure rural community, the 100 kWh per month level of service will apply to the 52 households. The residential maximum demand for this community is:

$$(1+\frac{2}{52})\times 52\times 0.5=27kVA$$

As for Moba, where mostly shop owners live, the consumption of 200kWh per month will be considered for the 43 prospective customers. This leads to a maximum demand of:

$$(1+\frac{2}{43})\times 43\times 1=45kVA$$

6.3.2 Existing load.

According to Metha (2003) the demand factor for general power service in the range of 15-75kW is 0.55. Applying this to the existing generators at Kirungu leads to a maximum demand of:
(65+55+25+30)×0.55=96.25 kVA.

If it is assumed that MV transformers with a diversity factor of 1.3 between them (typical value of diversity factor between transformers in general power supply according to Metha (2003)) will replace the various diesel generators, the maximum demand for the existing load is:

$$\frac{96.25kVA}{1.3} = 74kVA$$

At Kala, a demand factor of 0.65 can be applied to the existing generator. This leads to a maximum demand of

$$15kVA \times 0.65 = 9.75kVA = 10kVA$$

The table 6.2 below summarizes the maximum demands in Kirungu, Moba and Kala.

Location	Residential max demand (kVA)	Max demand existing load (kVA)	Diversity factor	Maximum demand (kVA)
Kirungu	176.5	74	1.3	193
Moba	45	-		45
Kala	27	10	1.3	28

Table6.2 Maximum demands at Kirungu, Kala and Moba.

6.3.3 Long-term maximum demands.

Given economic activities that are expected to take place at Kala (mostly milling grains), at Moba (refrigeration, shop and harbour lighting) and at Kirungu (small-scale agro-industries) and given the limited capacity of the generator we can adopt the following long-term maximum demands:

100 kVA for Kala.

200 kVA for Moba, and

700 kVA for Kirungu.

Thus the layout of the proposed isolated system is as follow:

[2] (283)= 90% of 315 households.

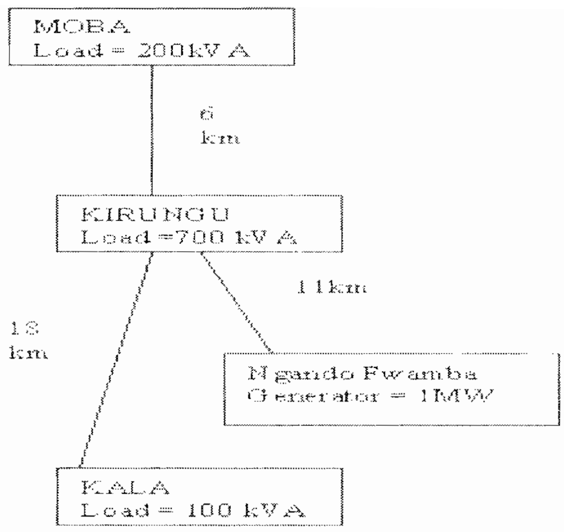

Figure 6.2: Layout of the proposed isolated network with long-term maximum demands.

In the next sections, electric and construction characteristics of lines connecting the various loads will be investigated.

6.4 LINE HYDRO SITE TO THE MAIN CENTER KIRUNGU (11km).

As there is no hope of being connected to an external source in the near future and given economic activities taking place and expected to expand at Kirungu, it is recommended to build a line that taps the total capacity of the scheme. Thus a three-phase line, 11km long with 1MW capacity that can serve as backbone for other feeders should be built.

This section investigates electric and construction characteristics in order to optimise the cost of this three-phase line.

6.4.1 Conductor selection

Under the different distribution voltage levels found in Congo, and assuming a power factor of 0.85, currents in line and the ACSR conductors selected according to the current carrying capacity are shown in table 6.3

Line voltage (kV)	Current (A)	ACSR Conductors		
Supply Voltage (kV)	I in line (A)	Code Name	I rating (A)	Φ (mm)
6.6	102.91	Squirrel	130	6.33
10	67.92	Mole	87	4.50
15	45.28	Mole	87	4.50
20	33.96	Mole	87	4.50
30	22.64	mole	87	4.50

Table 6.3: Conductor selection according to I rating

For safety reasons, conductors of less than 5mm diameter are not used in MV lines in Congo, thus the squirrel conductor should be adopted and tested for voltage-drop criterion.

In order to determine the impedance of the line the pole top arrangement in figure 6.3 used by Eskom in MV lines up to 22kV on wooden pole structures and bare conductors can be adopted. [NRS 033:1996]

For the 30kV level, the structure will be adapted by using the appropriate insulator (380mm long instead of 300mm).

Figure 6.4 is related to the structure for 6.6 to 20kV. Conductors are located at A, B, and C. The physical dimension DB shown in figure 6.3 comprises 2 insulators of 300mm each and 180mm of pole top thickness.

Figure 6.5 is related to the arrangement for the 30kV line. The dimension DB in this case comprises 2 insulators of 380mm each and 180mm of pole top thickness.

According to Metha (2003), the inductance per phase of a transposed 3-phase line using copper or aluminum conductors is given by:

$$L = (0.5 + 2\ln\frac{\sqrt[3]{d_{AB} \times d_{BC} \times d_{CA}}}{r}) \times 10^{-7} H/m \qquad (6.\ 2)$$

(where d_{AB}, d_{BC} and d_{CA} are distances between conductors and r is the radius of the conductor for copper conductors and equal to the geometric mean radius (GMR) for ACSR conductors)

The line impedance per phase is: $X = wL$ (Ω/km), (w=314 in case frequency is 50Hz)

Using the pole top arrangements shown, line inductance (Ω/km) and line impedance (R +j X) per phase under the 2 arrangements above and for various ACSR conductors are shown in table 6.4

Conductor	R(Ω / km) At 20°C	Radius (mm)	GMR (mm)	X (Ω / km)		Line impedance (R+jX) (Ω / km)	
				6.6-20kV	30kV	6.6-20kV	30kV
Bantam	4.303	2.1525	1.8241	0.4148	0.4201	47.333+j4.5628	47.333+j4.6211
Squirrel	1.3677	3.165	2.2962	0.4004	0.4056	15.044+j4.4044	15.044+j4.4616
Magpie	2.707	3.175	2.3028	0.4002	0.4054	29.777+j4.4022	29.777+j4.4594
Gopher	1.0933	3.540	2.5682	0.3934	0.3986	12.026+j4.3274	12.026+j4.3846
Fox	0.7822	4,185	3.0362	0.3829	0.3881	8.6042+j4.2119	8.6042+j4.2691
Mink	0.4546	5.49	3.9829	0.3658	0.3710	5.0006+j4.0238	5.0006+j4.0810
Hare	0.2733	7.080	5.1365	0.3498	0.3551	3.0063+j3.8478	3.0063+j3.9061
Goat	0.0891	12.98	9.8648	0.3089	0.3141	0.9801+j3.3979	0.9801+j3.4551
Moose	0.0547	15.88	12.0846	0.2961	0.3013	0.6017+j3.2571	0.6017+j3.3143

Table6.4: Line impedance with various ACSR conductors.

Under the different distribution voltages found in Congo (6.6, 10, 15, 20, 30 kV), a power factor of 0.85, and adopting a voltage-drop limit of 6% (a voltage drop limit of 6% allows for only limited automatic voltage control and for limited voltage drop in the low voltage conductors), the conductor selection is carried out as in table 6.5. The conductor in bold on this table is the adequate conductor (voltage drop ≤6%) to be used under the voltage level shown in the first column. For 30kV level, bantam, magpie or squirrel conductor can be used.

Vr (V) (Φ-Φ)	Vr (V) (Φ-N)	I (A)	Conductor	ΔV= (RcosΦ+XsinΦ)×I	Vs (V) (Φ-N)	Vs (V) (Φ-Φ)	ΔV (%)
30 000	17320.5	22.64	**Bantam**	965.9786	18286.4786	31673.11	**5.57**
			Magpie	626.1929	17946.6929	31084.58	**3.61**
			Squirrel	342.7084	17663.2084	30593.57	**1.97**
20 000	11547	33.96	Bantam	1447.9253	12994.9253	22507.87	12.53
			Magpie	938.2672	12485.26	21625.11	8.12
			Squirrel	513.0371	12060.037	20888.59	**4.44**
15 000	8660.25	45.28	Squirrel	684.049	9344.299	16184.8	7.89
			Fox	431.6044	9091.8544	15747.55	**4.98**
10000	5773.50	67.92	Fox	647.4066	6420.9066	11121.33	11.21
			Hare	311.2026	6084.7026	10539.014	**5.39**
6600	3810.51	102.91	Goat	269.891	4080.4017	7067.46	7.08
			Moose	229.1702	4039.6802	6996.9314	**5.9**

Table6.5: ACSR conductor selection (according to voltage drop limit)

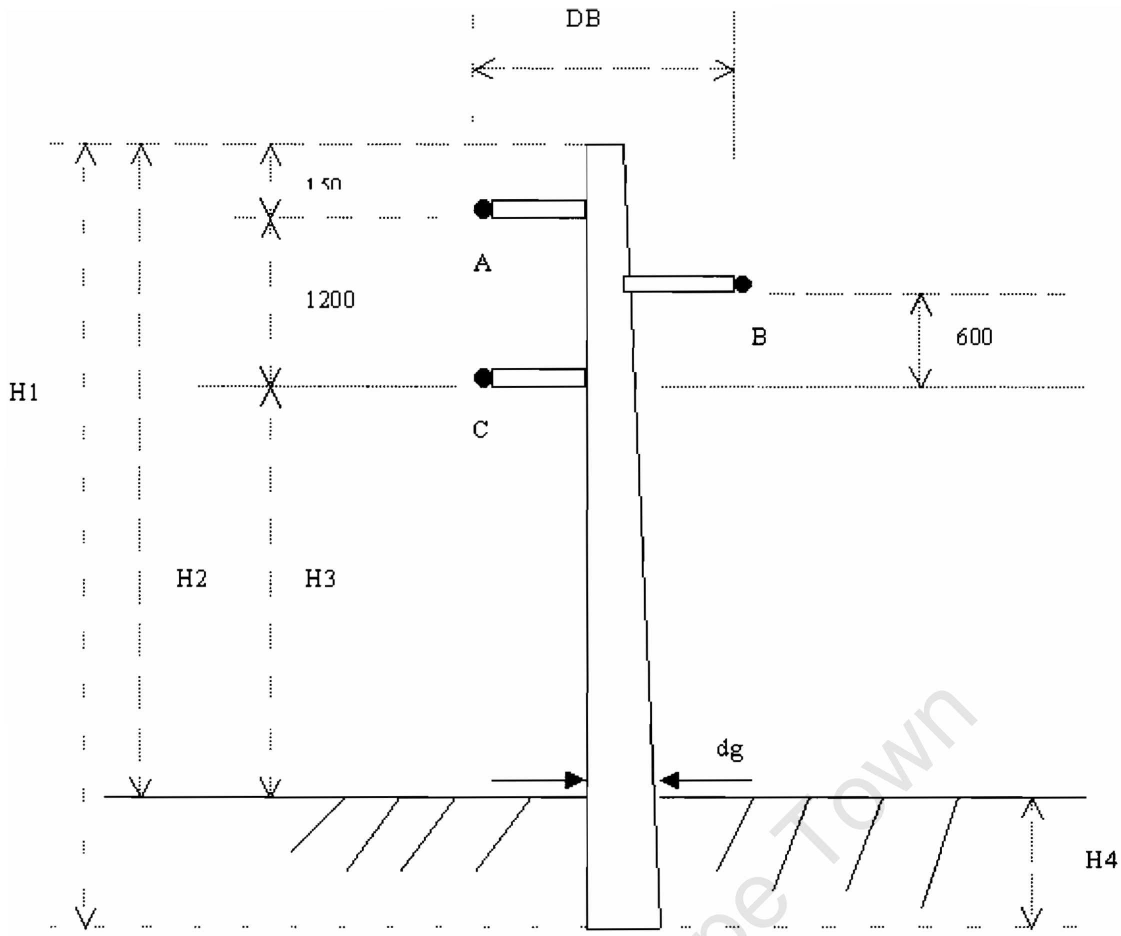

Figure 6.3
Dimensions in mm

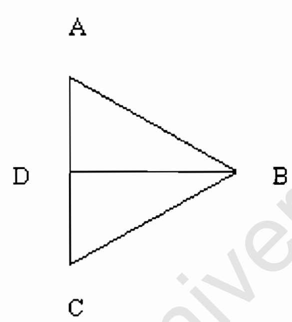

Figure 6.4
AD=DC=600
AB=BC=984
DB=300+180+300=780

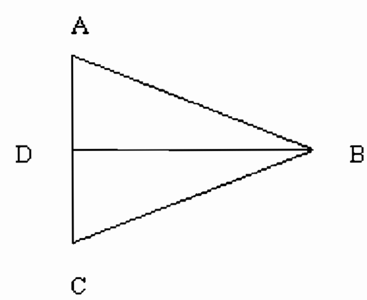

Figure 6.5
AD=DC=600
AB=BC=1115
DB=380+180+380=940

As Congo is a copper producer and copper conductors have traditionally been used in electrification, this investigation should include copper conductors.
For various copper conductors line inductance (Ω/km) and line impedance (R + j X) per phase under the 2 conductor arrangement (6.6-20kV and 30kV) are shown in table 6.6.

Conductor	R (Ω/km)	Radius (mm)	X (Ω/km)		Line impedance (Ω/km)	
			6.6-20kV	30kV	6-20kV	30kV
7/1.7	1.127	2.55	0.3938	0.3990	12.397+4.3318	12.397+j4.389
3/2.64	1.088	2.835	0.3872	0.3924	11.968+j4.2592	11.968+j4.3164
3/3.30	0.8431	3.225	0.3791	0.3843	9.2741+j4.1701	9.2741+j4.2273
7/2.1	0.7373	3.150	0.3805	0.3858	8.1103+j4.1855	8.1103+j4.2438
3/3.37	0.6695	3.620	0.3718	0.3770	7.3645+j3,9127	7.3645+j4.147
7/3.12	0.3342	4.675	0.3557	0.3610	3.6762+j3.9127	3.6762+j3.971
7/3.45	0.2723	5.200	0.3491	0.3543	2.9953+j3.8401	2.9953+j3.8973
12/4.02	0.1203	8.350	0.3193	0.3246	1.3233+j3.5123	1.3233+j3.5706
37/3.49	0.0535	12.230	0.2954	0.3006	0.5885+j3.2494	0.5885+j3.3066

Table 6.6: Line impedances with various copper conductors.

The selection of copper conductors under the different voltage levels found in Congo, a power factor of 0.85 and a voltage-drop limit of 6% is carried out in table 6.7 below.

Vr (V) Φ-Φ	Vr (V) Φ-Φ	I (A)	Conductor	ΔV= (RcosΦ+XsinΦ)×I	Vs (V) Φ-N	Vs (V) Φ-Φ	ΔV (%)
30 000	17320.5	22.64	**7/1.7**	290.901	17611.40	30503.84	**1.67**
20 000	11547.0	33.96	**7/1.7**	421.65	11968.65	20730.31	**3.65**
15 000	8660.25	45.28	**3/3.30**	456.3861	9116.636	15790.47	**5.26**[3]
			7/2.1	411.96	9072.216	15713.53	4.75
10 000	5773.50	67.92	7/3.12	352.199	6125.69	10610	6.1
			7/3.45	310.258	6083.75	10537.37	**5.37**
6 600	3810.51	102.91	12/4.02	306.126	4116.63	7130.22	8.03
			37/3.49	226.200	4036.2	6990	**5.9**

Table 6.7: Copper conductor selection (according to voltage drop limit)

Table 6.8 shows a summary of conductor selection.
For every distribution voltage level the conductor of minimum appropriate size is provided.

[3] The 3/3.30 has been preferred to the 7/2.1 because of lower actual area (21.20-24.26mm^2), lower nominal weight (190-217 kg/km).This suggests that 3/3.30 costs less than 7/2.1

For the 30kV level, the bantam and magpie ACSR conductors are added. These conductors can be interesting for their extra strength or lower costs.

Voltage level (kV)	ACSR Conductors		Copper Conductors.	
	Conductor	Area (mm2)	Conductor	Area (mm2)
30	Bantam	15.48	7/1.7	15.88
	Magpie	24.71		
	Squirrel	24.48		
20	Squirrel	24.48	7/1.7	15.88
15	Fox	42.80	3/3.30	21.20
10	Hare	122.48	7/3.45	65.60
6.6	Moose	596.99	37/3.49	360.12

Table 6.8: Summary of conductor selection

From the tables above it appears that:

- Higher supply voltage results in lower line currents, lower voltage drops and smaller conductors (of lower cost) can be used.
- For the same voltage level, appropriate copper conductors are of smaller size than ACSR conductors. This has a favorable impact on the wind effect on the line. But as shown in section 6.4.2 conductor size is not the only element to consider in line construction
- Although the 20kV voltage level is adequate for this line (no gain in conductor is recorded for a higher voltage level, 30kV will be used for this project as it is the newly standardized voltage for connecting rural areas from cities or from the grid. Another reason making the 30kV a better alternative is that in case single-phase supplies such as SWER are planned, the SWER lines will use the same equipment (fuses, reclosers, lightning arresters) as the tri-phase 30kV lines in the country.

As the conductor size (and cost) is not the only element that determines the cost of an overhead line, investigation to determine the conditions in which the cost of the 3-phase line is optimised should include construction elements such as spanning lengths, pole number and lengths. This is carried out in the next section.

6.4.2 Construction characteristics.

The knowledge of physical or weather conditions is important for the proper design of overhead lines.

These are built under still air and normal temperature conditions but must comply with changes such as winds.

This justifies that in most countries regulations generally specify the following:

- The tension limits in the conductor under specified conditions for example under low temperatures (conductor length and sag is reduced while its tension is increased) or under the worst probable condition of temperature and wind loading that lead to the maximum stress in the conductor.
- The minimum vertical clearance (or the maximum sag) of conductors and the conditions under which this maximum sag is calculated.
- Factors of safety.

In Congo, reliable weather data are difficult to obtain and no specific standards are available.

For this study, PIESA and SABS standards adapted to Congo will be used.

For the design of overhead lines in South Africa, SABS standards consider the following data and requirements: [SABS 0280, 2001]

- A maximum wind velocity of 115km/h and a design wind pressure of 700 N/m^2 for structures of up to 20m height.
- A minimum temperature of -5°C and a maximum conductor temperature of 60°C (general practice). Although the thermal rating of a conductor is determined under 80°C, in practice the conductor temperature is unlikely to approach 80°C. Owing to the voltage drop it is considered uneconomic to operate a conductor at a current of more than about half its thermal rating. Thus 60°C is adopted for the design of sag and clearance of a conductor. [SABS 0280, 2001]
- Maximum tensions T in the conductor should be such that $T \leq 25\%$ of the ultimate tensile strength (UTS) at minimum temperature with no wind and $T \leq$

40% UTS at the worst conditions of minimum temperature and maximum wind pressure.

- Maximum sag in the conductor should be measured at maximum conductor temperature with no wind[4].

In Congo, practice in railway electrification considers a minimum temperature of 6°C and a maximum wind velocity of 120km/h (or 33m/s)

As it is not possible to state exactly what pressure corresponds to a given maximum wind velocity, we take into account that the area is around the Tanganyika Lake with frequent and strong winds. We can consider a design wind pressure of: [Bayliss, 1999]

DWP= $0.613\times (33 \times 1.1 \times 1.03)^2 = 857$ N/m^2 (see equation A.1.2 in appendix 1)

(The factor 1.1 corresponds to the topography and is associated to exposed sites, and 1.03 is the ground roughness factor corresponding to structures of less than 20m height, in an open country with scattered windbreaks).

In summary the following data will be considered for the mechanical design of the tri-phase overhead line:

- A minimum ambient temperature of 6°C and a maximum conductor temperature of 60°C.
- A design wind pressure of 857N/m^2
- T≤ 25% UTS at 6°C with no wind. (initial condition)
- T≤ 40% UTS at 6°C and wind pressure of 857N/m^2 (worst conditions)
- Worst sag at a conductor temperature of 60°C with no wind.

Under the above conditions wind spans, weight spans and ground clearance spans will be calculated.

[4] The "no wind" condition is adequate in calculating the maximum sag because with the wind blowing horizontally, the conductor set itself in a plane that makes an angle θ with the vertical. The sag in the new plane S ×cosθ is lower than the sag in the vertical plane S. [Mehta, 2003]

The wind span refers to the maximum span length of an overhead line such that the pole supporting conductors will have sufficient strength to counter the expected moments resulting from the maximum winds.

As explained in Appendix 1, the maximum span length L (m) for a line with n conductors is approximately given by the equation:

$$L \leq \frac{0.0982 \times f \times d_g^3}{SF \times (K \times 0.6 \times DWP \times n \times d_c \times h_c} \qquad (6.3)$$

Where f is the ultimate fibre stress of the pole (N/m^2), DWP the design wind pressure (N/m^2), K the shape factor, d_c the conductor diameter (m) and h_c the height of the center of gravity of wind load (m).

If poles of 9, 10, 11, 12, and 13m are considered and under the pole top arrangement of figure 6.3 the various heights and ground level diameters for wind spans calculations are summarized in table 6.9.

H_1 (m)	H_4 (m)	H_2 (m)	H_3 (m)	hc (m)	dg (mm)		
					ϕ=140	ϕ=160	ϕ=180
9	1.5	7.5	6.15	6.75	177.5	197.5	217.5
10	1.6	8.4	7.05	7.65	182	202	222
11	1.7	9.3	7.95	8.55	186.5	206.5	226.5
12	1.8	10.2	8.85	9.45	191	211	231
13	1.9	11.1	9.75	10.35	195.5	215.5	235.5

Table 6.9: Heights and ground level diameters for wind spans calculations (ϕ is the thickness of the pole top in mm).

In table 6.9:

H_1 is the pole length,

H_4 is the planting depth (0.6+1/10 pole length, practice in Congo)

H_2 is the exposed length of the pole (H_1-H_4),

The lower conductor is at a height of H_3 (H_2-1350mm).

The center of gravity of wind load on the 3 conductors is at a height h_c (H_3+600mm) and (dg) is the pole thickness at the ground level.

A taper of 5mm/m is used. [SABS 753: 1994] [PIESA 001: 2001]

Considering poles of $55N/m^2$, wind spans of the three-phase line using ACSR or copper conductors on 9, 10, 11, 12, and 13m poles (of shape factor 0.6 with top thickness of 140, 160, 180mm) are summarised in table 6.10.

Conductors	diam (mm)	Wind spans for the 3-phase 11km line (m)														
		9m			10m			11m			12m			13m		
		140	160	180	140	160	180	140	160	180	140	160	180	140	160	180
ACSR Conductors																
bantam	5.03	213	294	383	203	277	368	195	265	350	190	256	336	186	249	325
magpie	6.35	169	233	303	160	220	292	154	210	277	150	203	266	147	197	257
squirrel	6.33	169	234	312	161	221	293	155	210	278	151	203	267	148	198	258
fox	8.37	128	177	236	122	167	221	117	159	210	114	154	202	112	150	195
hare	14.16	76	104	139	72	99	131	69	94	124	67	91	119	66	88	115
moose	31.77	34	46	62	32	44	58	30	42	55	30	40	53	29	39	51
Copper Conductors																
7/1.7	5.1	210	290	387	200	274	363	192	261	345	187	252	331	183	245	320
3/3.30	6.45	166	229	306	158	216	287	152	207	273	148	199	262	145	194	253
7/3.45	10.4	103	142	190	98	134	178	94	128	169	91	123	162	90	120	157
37/3.49	24.46	43	60	80	41	57	75	40	54	72	39	52	69	38	51	66

Table 6.10: Wind spans for the 3-phase 11km line

From table 6.10 above it appears that with wind spans as small as 30-50m the ACSR moose and 37/3.49 copper conductors and the associated voltage level of 6.6kV can already be dismissed from the investigation.

The ground clearance spans are calculated using the constraint that the conductor clearance to ground at any physical condition and particularly at the time of maximum sag should not be less than the distance specified in regulations.

As explained in appendix 2 the ground clearance of an overhead line can be calculated from equation (6.4) that governs changes in physical conditions: [Chard, 1976] [Bayliss, 1999]

$$\frac{L^2}{24}[(\frac{w_1}{T_1})^2-(\frac{w_2}{T_2})^2]-\frac{(T_1-T_2)}{AE}-\alpha(t_2-t_1)=0 \quad (6.4)$$

Where:
L is the span length.
T_1, w_1, and t_1 are the tension in the conductor, the load on the conductor and the conductor temperature at an initial condition.
T_2, w_2, and t_2 are the tension, load and temperature of the conductor at a final condition.
A, E and α are the conductor total area, the Young's modulus of elasticity and the coefficient of linear expansion respectively.
By specifying the initial condition as "minimum temperature with no wind", and the final condition as "maximum temperature with no wind" (condition that leads to the maximum sag) equation 6.4 can be modified as:

$$\frac{L^2}{24}[(\frac{w_c}{Af_1})^2-(\frac{8S}{L^2})^2]-(\frac{f_1}{E}-\frac{w_cL^2}{8AES})-\alpha(t_1-t_2)=0 \quad (6.5)$$

Where w_c, A, f_1, E, and α are conductor characteristics.

For a particular conductor solving this equation for L gives the ground clearance span.

From the equation above, it appears that ground clearance span is function of the conductor characteristics (w_c, A, f_1, E, α), the maximum sag S (in other words of the pole length and pole top arrangement, as the minimum conductor height is determined by regulations) and of the maximum conductor temperature. It is independent of the pole thickness.

Under the pole-top arrangement of figure 6.3 and poles of 9, 10, 11, 12 and 13m the vertical space available for sag (maximum sag) in each case are given in table 6.11.

Pole length (m)	Planting depth (m)	Minimum clearance (m)	Height of lower conductor (m)	Maximum sag (m)
9	1.5	5.6	6.15	0.55
10	1.6	5.6	7.05	1.45
11	1.7	5.6	7.95	2.35
12	1.8	5.6	8.85	3.25
13	1.9	5.6	9.75	4.15

Table 6.11: Maximum sags for the three-phase 11km line

As for conductor characteristics, these can be found in the table 6.12.

Conductor	wc (N/m)	ϕ (mm)	A (mm2)	E (N/mm2)		α ($\times 10^{-6}$/°C)	UTS (N)
				Initial	Final		
Bantam	0.8613	5.03	15.48	-	133 760	13.68	11 679
Magpie	1.3704	6.35	24.71	-	133 760	13.68	18 573
Squirrel	0.8538	6.33	24.48	54 600	80 400	19.31	8 020
Fox	1.4616	8.37	42.80	50 700	80 400	19.31	13 100
Hare	4.1888	14.16	122.48	48 500	80 400	19.31	36 000
7/1.7	1.3969	5.1	15.88	-	124 000	17	6 622
3/3.30	1.8639	6.45	21.20	-	124 000	17	8 584
7/3.45	5.7692	10.4	65.60	-	124 000	17	26 095

Table 6.12: Conductors characteristics for ground clearance calculations.
[Source: Aberdare Power Cables].

Using information in tables 6.11 and 6.12, and equations described in appendix 2 the ground clearances on poles of 9, 10, 11, 12, and 13m, for ACSR and copper conductors are summarized in table 6.13. For conductor temperature, 60 °C and 50°C are considered to emphasize the impact of conductor temperature.

As explained in appendix 2, ACSR conductors of same composition such as 3/4 (Bantam, Magpie) and 6/1 (squirrel, fox, hare) have the same ground clearance span.

Ground Clearance Spans (m) for the 3-phase 11km line.										
	9m		**10m**		**11m**		**12m**		**13m**	
	0.55		1.45		2.35		3.25		4.15	
	60°C	50°C	60°C	50°C	60°C	50°C	60°C	50°C	60°C	50°C
3/4 conductors	89	95	152	161	200	210	242	252	279	289
6/1 conductors	49	58	102	116	143	154	180	190	212	222
7/1.7	44	48	87	91	120	124	147	151	172	175
3/3.30	43	48	86	91	119	124	146	151	170	175
7/3.45	43	48	85	91	119	124	146	151	170	175

Tale 6.13: Ground clearance spans for the 11km three-phase line

Weight spans are based on the failing load of the pole-top insulator.

In principle the insulator should not break under the weight of the conductor lying in the adjacent half spans of an intermediate pole. If an insulator of failing load 4kN is used the condition to ensure adequate strength of insulator is:

$$(\frac{L_1 + L_2}{2}) \times w_c(\frac{N}{m}) \leq 4(kN) \qquad (6.\ 6)$$

From the equation above the maximum weight span $(L_1+L_2)/2$ can be known.

For the adequate ACSR and copper conductors of this project, weight spans are as in table 6.14.

Conductor.	Wc(N/m)	**Weight span (m)**
Bantam	0.8613	4644
Magpie	1.3704	2919
Squirrel	0.8358	4786
Fox	1.4616	2737
Hare	4.1888	955
7/1.7	1.3969	2863
3/3.30	1.8639	2146
7/3.45	5.7692	693

Table 6.14: Weight spans for the 3-phase 11km line.

Ultimately, maximum spans for this three-phase line are the smallest among the wind span (table 6.10), the ground clearance span (table 6.13) and the weight span (table 6.14). The result of this comparison for the adequate ACSR and copper conductors, on poles of 9, 10, 11, 12 and 13m with thickness of 140, 160, 180mm, and a conductor temperature of 60 °C is shown in table 6.15.

Maximum span lengths for the 3-phase 11km line (m).															
	9m			**10m**			**11m**			**12m**			**13m**		
	140	160	180	140	160	180	140	160	180	140	160	180	140	160	180
Conductors															
Bantam	89	89	89	152	152	152	195	200	200	190	242	242	186	249	279
Magpie	89	89	89	152	152	152	154	200	200	150	203	242	147	197	257
Squirrel	49	49	49	102	102	102	143	143	143	151	180	180	148	198	212
Fox	49	49	49	102	102	102	117	143	143	114	154	202	112	150	195
Hare	49	49	49	72	99	102	69	94	124	67	91	119	66	88	115
7/1.7	44	44	44	87	87	87	120	120	120	147	147	147	172	172	172
3/3.30	43	43	43	86	86	86	119	119	119	146	146	146	145	170	170
7/3.45	43	43	43	85	85	85	94	119	119	91	123	146	90	120	157

Table 6.15: Span lengths for the 11km three-phase line.

On the basis of figures in table 6.15, the following lessons can be drawn:

- For all conductors poles of 9 and 10m result in shorter spans and these spans are determined by the ground clearance criterion. Thus the number of poles used will be high.
- Comparing spans lengths for copper and ACSR conductors it appears that for small size conductors that are adequate for the load on this line (and generally for loads encountered in rural areas) spans are longer or similar for ACSR conductors on the mostly used poles of 9, 10, and 11m. In addition to the unfavourable cost of 12 and 13m poles, maintenance is easier on poles of 9, 10 and 11m. Besides these are generally available and their environmental impact is smaller. The comparison is shown on figures 6.6 and 6.7.

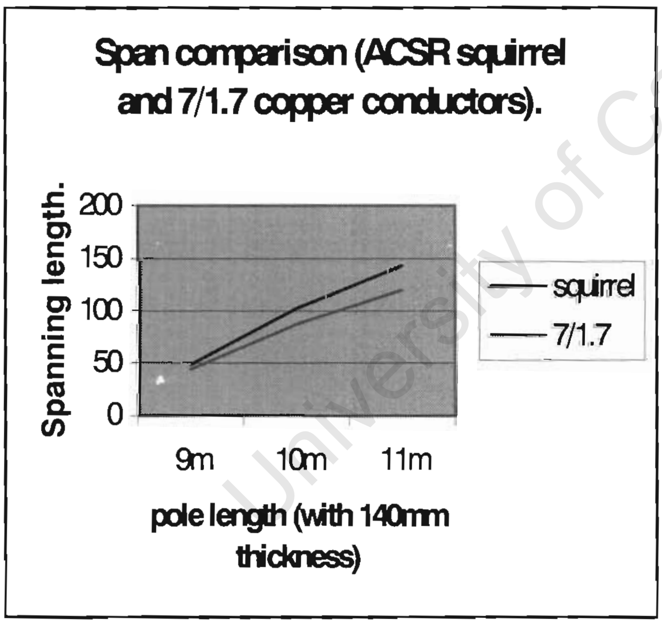

Figure 6.6: Span comparison squirrel and 7/1.7 conductors.

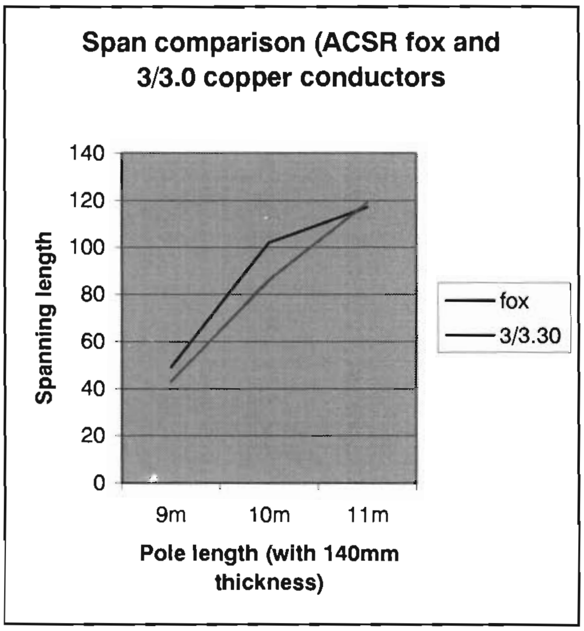

Figure 6.7: Span comparison fox and 3/3.30 conductor

Apart from the span results, the cost structure (copper conductors are not manufactured currently in Congo and must be imported) and the theft threat lead to ACSR conductors being preferred.

In order to determine which poles and which ACSR conductor should be used to lower the line cost, a cost analysis is required and this is carried out in the next section.

6.4.3 Cost Analysis.

Total cost of an electric line comprises (1) material cost, (2) transport and labour costs, and (3) overhead costs.

Having no elements on transport, labour and overhead costs, these will not be included in the present cost investigation.

For structure costs, strain structures cost more than intermediate structures because guys and special insulators are used.

As no information is available from the field on the number and cost of strain structures, the cost analysis will take into account only conductor cost and the average number of poles according to spans lengths calculated in section 6.4.2.

Conductor costs are as follow: [Aberdare Power Cables, 2003]

- Bantam: R3.00/m
- Magpie: R3.80/m
- Squirrel: R2.89/m and
- Fox: R3.96/m

As for poles, only poles of 140mm top diameter (Φ) will be considered in the investigation and the costs shown in table 6.16 will apply.

Pole height	Top Φ (mm)	Unit cost ®
9	140	251.64
10	140	290.52
11	140	353.05
12	140	399.06
13	140	468.00

Table6.16: Pole costs.
[Source: Woodline Timber Industries (Tel 021 903 2181)]

The pole amount for a given average span length is found as follows:
(line length (11km)/average span)+1

Each conductor alternative has its maximum span length. During construction and depending on the geography actual span is generally less than the maximum, thus the introduction of the "average span". For example the maximum span for a bantam conductor on 10m pole is 152m, so no calculation should be carried out for an average span higher than this value.

The cost analysis is carried out by varying the average span length, conductor type and pole length, and result being a cost in Rand/km in each case.

			Cost/km on 9m poles 3-phase 11km line.			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox.
40	276	69452.64	15313.88	17713.88	14983.88	18193.88
50	221	55612.44	14055.68	16455.68		
60	184	46301.76	13209.25	15609.25		
70	158	39759.12	12614.47	15014.47		
80	138	34726.32	12156.94	14556.94		
90	123	30951.72				

Table 6.17a: Line (3-phase, 11km) unit cost in R/km on 9m poles

			Cost/km on 10m poles, 3-phase 11km line			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
40	276	80183.52	16289.41	18689.41	15959.41	19169.41
50	221	64204.92	14836.81	17236.81	14506.81	17716.81
60	184	53455.68	13859.61	16259.61	13529.61	16739.61
70	158	45902.16	13172.92	15572.92	12842.92	16052.92
80	138	40091.76	12644.71	15044.71	12314.71	15524.71
90	123	35733.96	12248.54	14648.54	11918.54	15128.54
100	111	32247.72	11931.61	14331.61	11601.61	14811.61
110	101	29342.52	11667.5	14067.5		
120	92	26727.84	11429.8	13829.8		
130	85	24694.2	11244.93	13644.93		
140	79	22951.08	11086.46	13486.46		
150	74	21498.48	10954.41	13354.41		

Table 6.17b: Line (3-phase 11km) unit costs in R/km on 10m poles

			Cost/km on 11m poles 3-phase 11km line.			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
40	276	97441.8	17858.35	20258.35	17528.35	20738.35
50	221	78024.05	16093.1	18493.1	15763.1	18973.1
60	184	64961.2	14905.56	17305.56	14575.56	17785.56
70	158	55781.9	14071.08	16471.08	13741.08	16951.08
80	138	48720.9	13429.17	15829.17	13099.17	16309.17
90	123	43425.15	12947.74	15347.74	12617.74	15827.74
100	111	39188.55	12562.6	14962.6	12232.6	15442.6
110	101	35658.05	12241.64	14641.64	11911.64	15121.64
120	92	32480.6	11952.78	14352.78	11622.78	
130	85	30009.25	11728.11	14128.11	11398.11	
140	79	27890.95	11535.54	13935.54	11205.54	
150	74	26125.7	11375.06	13775.06		
160	69	24360.45	11214.59			
170	65	22948.25	11086.2			
180	62	21889.1	10989.92			
190	58	20476.9	10861.54			

Table 6.17c: Line (3-phase, 11km) unit costs in R/km on 11m poles

			Cost/km on 12m poles 3-phase 11km line			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
40	276	110140.56	19012.78	21412.78	18682.78	21892.78
50	221	88192.26	17017.48	19417.48	16687.48	19897.48
60	184	73427.04	15675.19	18075.19	15345.19	18555.19
70	158	63051.48	14731.95	17131.95	14401.95	17611.95
80	138	55070.28	14006.39	16406.39	13676.39	16886.39
90	123	49084.38	13462.22	15862.22	13132.22	16342.22
100	111	44295.66	13026.88	15426.88	12696.88	15906.88
110	101	40305.06	12664.1	15064.1	12334.1	
120	92	36713.52	12337.59	14737.59	12007.59	
130	85	33920.1	12083.65	14483.65	11753.65	
140	79	31525.74	11865.98	14265.98	11535.98	
150	74	29530.44	11684.59	14084.59	11354.59	
160	69	27535.14	11503.19			
170	65	25938.9	11358.08			
180	62	24741.72	11249.25			
190	58	23145.48	11104.13			

Table 6.17d: Line (3-phase 11km) unit costs in R/km on 12m poles

			Cost/km on 13m poles 3-phase 11km line			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
40	276	129168	20742.55	23142.5	20412.55	23622.545
50	221	103428	18402.55	20802.5	18072.55	21282.545
60	184	86112	16828.36	19228.4	16498.36	19708.364
70	158	73944	15722.18	18122.2	15392.18	18602.182
80	138	64584	14871.27	17271.3	14541.27	17751.273
90	123	57564	14233.09	16633.1	13903.09	17113.091
100	111	51948	13722.55	16122.5	13392.55	16602.545
110	101	47268	13297.09	15697.1	12967.09	16177.091
120	92	43056	12914.18	15314.2	12584.18	
130	85	39780	12616.36	15016.4	12286.36	
140	79	36972	12361.09	14761.1	12031.09	
150	74	34632	12148.36			
160	69	32292	11935.64			
170	65	30420	11765.45			
180	62	29016	11637.82			

Table 6.17e: Line (3-phase 11km) unit costs in R/km on 13m poles.

It appear from tables 6.17 a, b, c, d and e that:

- In each alternative larger span lengths lead to lower line costs. In other words, line costs approach a minimum if the average span approaches the maximum span. There is interest to use conductors that result in longer spans as pole number and cost are reduced. In addition, to reduce line costs span lengths should be as near as possible to the maximum span. In practice, this is not always possible as span lengths depend on the geography of the site.
- Average costs/km for bantam and squirrel conductors are generally lower than the cost for the 2 other conductors and the lowest minimum is achieved on poles of 11m. This appears on figures 6.8 and 6.9.

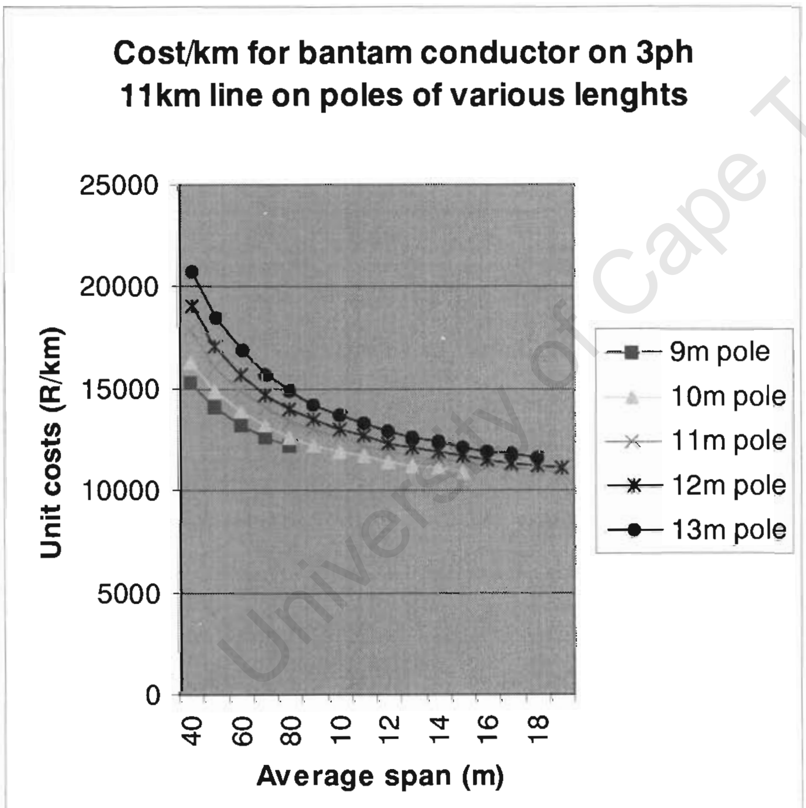

Figure 6.8: Cost/km for the bantam conductor.

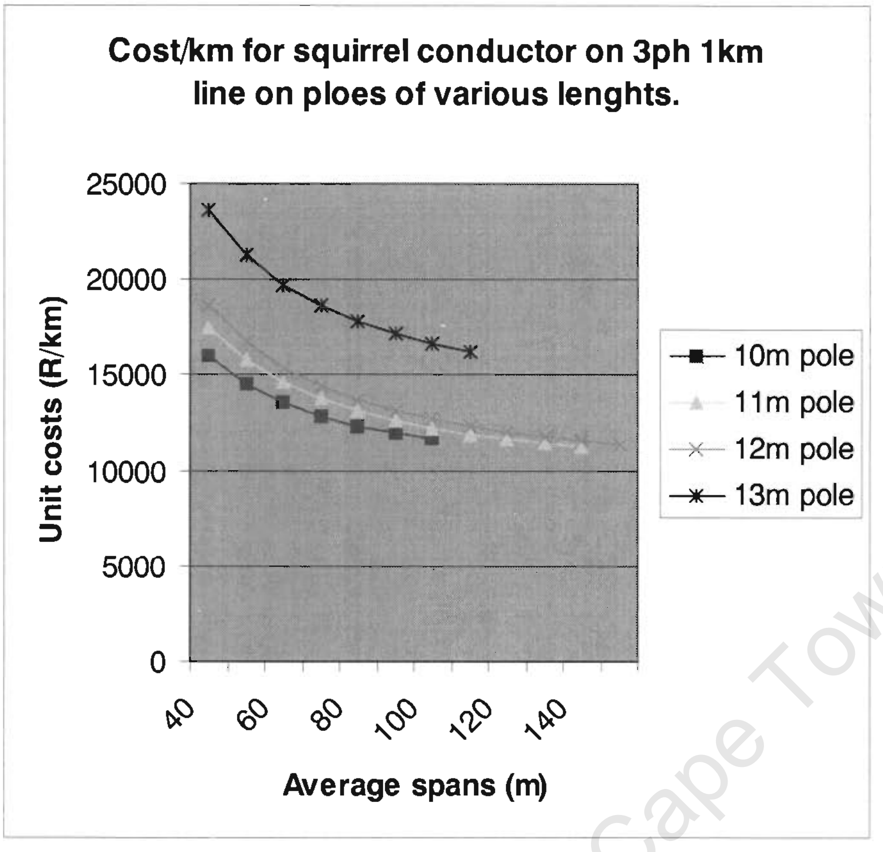

Figure 6.9: Cost/km for the squirrel conductor

Conductor choice on these 11m poles between the bantam and squirrel conductor will be based on conductor availability, power transfer capability, cost, and standardization.

With the bantam alternative it is possible to use fewer poles because of the longer spans. As a result insulators, cross arms, surge arrestors will be fewer in number and will cost less. Labour costs should also be lower.

Besides construction costs operational costs should also be low as less components are exposed to environmental stress.

This alternative (bantam conductor on 11m poles) is the least cost option for the tri-phase line.

However the squirrel conductor has a higher transfer capability (I rating 130A versus 69A) that can prove useful in the future if an additional source was found.

As the difference in cost is small (10862 for bantam and 11206 for squirrel) the squirrel conductor on 11m poles is recommended.

6.4.4 Conclusion (regarding the tri-phase line).

The voltage level of 30kV is used for this line, as this is the newly standardized voltage level for connecting rural areas from cities or from the grid and because it is a better alternative than 20kV as single-phase lines and particularly SWER lines are planned. It will be possible to use equipment of the three-phase systems on the single-phase lines.

For small conductors that are adequate for the connection of loads in rural areas, span lengths for ACSR conductors on poles of 9, 10, 11m are longer or similar to spans of copper conductors.
In addition, the cost structure and the theft threat associated with copper conductors favour the use of ACSR conductors.

For this three-phase line, costs/km are lower for the bantam and squirrel conductors on 11m poles. While the bantam alternative is the lowest cost the squirrel conductor has a better transfer capability that can prove useful if an additional source was found in the future.

6.5 LINE KIRUNGU-KALA (18km)

For this line the following technological options will be investigated: three-phase, phase-phase, phase-neutral and SWER.

6.5.1 Conductor selection

With a maximum demand of 100kVA the currents in line for each option are shown in table 6.18.

Option	Voltage (kV)	S (kVA)	I (A)
Φ-N	17.320	100	5.77
Φ-Φ	30.00	100	3.33
3Φ	17.320	100	1.92
SWER	17.320	100	5.77

Table 6.18: Currents in line for the 18km line under various configurations.

These currents are small and this explains that for voltage-drop calculations, investigation will be restricted to small size conductors. However for the SWER line the current shown consider only the line impedance.

The structure of the line in various options will be as follow:

- The three-phase line will be similar to the line from the hydro site to the main center.
- The phase-phase and phase-neutral lines will adopt the structure for the tri-phase line minus the bottom conductor. This means that the distance between the 2 identical conductors is again 1115mm.
- The SWER line will use a conductor placed at 300mm above the pole top for the intermediate structure.

As for impedance calculation the loop inductive reactance for the phase-phase or phase neutral line is given by: [Metha, 2003]

$$X = wL = w(1 + 4\ln\frac{d}{r}) \times 10^{-4}\,\Omega / km \qquad (6.\ 7)$$

For the SWER option, line impedances are calculated in appendix 3 and for the tri-phase options the same impedances than for the 30kV line hydro site-Kirungu will apply (same small size conductors).

For small size ACSR conductors and for each configuration line impedances appear in table 6.19 (the GMR of conductors is considered).

Conductor	R (Ω/km)	X (Ω/km)			Line impedance (Ω) on 18km		
		3Φ	Φ-Φ or Φ-N	SWER	3Φ	Φ-Φ or Φ-N	SWER
Bantam	4.303	0.4201	0.8371	0.9190	77.454 +j 7.5618	154.908+ j 15.0678	77.454+j 16.542
Magpie	2.707	0.4054	0.8079	0.9044	48.726+ j 7.2972	97.452+ j 14.5422	48.726+ j 16.2792
Squirrel	1.3677	0.4056	0.8119	0.9045	24.618+ j 7.3008	49.2372+ j 14.6142	24.618+ j 16.2810
Fox	0.7822	0.3881	0.7625	0.8870	14.079+ j 6.9858	28.1592+ j 13.7250	14.079+ j 15.9660

Table 6.19: Line (18km) impedance under each configuration.

Using the line characteristics above the voltage-drops in % under each option can be calculated and appear on table 6.20.

	Φ-N (I=5.77A)			Φ-Φ (I=3.33A)			3Φ (I=1.92A)			SWER (I=5.77A)		
	kV	ΔV (V)	ΔV (%)	kV	ΔV (V)	ΔV (%)	kV	ΔV (V)	ΔV (%)	kV	ΔV (V)	ΔV (%)
Bantam	17.32	806	4.65	30	464.89	1.55	30	134.05	0.70	17.32	430.144	2.48
Magpie	17.32	523	3.02	30	301.59	1.00	30	86.900	0.50	17.32	288.449	1.66
Squirrel	17.32	286	1.65	30	164.99	0.55	30	47.559	0.20	17.32	170.218	0.98
Fox	17.32	180	1.04	30	103.78	0.35	30	30.041	0.17	17.32	117.571	0.68

Table 6.20: Voltage-drops under various configurations.

For the SWER line the calculation shown consider only the line impedance. However as explained in appendix 3, the proper calculation should take into account the line impedance, the earthing resistances and transformers impedances.

Appendix 3 also shows that SWER lines with point loads can be extended at distances greater than 18km if a voltage drop limit of 10% is considered.

The bantam conductor can still be part of the investigation as the current involved is much lower than the limit of 25A.

It can be concluded that the transfer of 100kVA on 18km using bantam, magpie, squirrel and fox conductors, and under the various configurations does not lead to excessive voltage-drops. (However 10% voltage drop is considered for the SWER option)

6.5.2 Comparison system capacity and demand.

If the conductors above are operated at half their thermal capacity as recommended by SABS 0280, 2001 to limit conductor temperature and avoid excessive voltage drop, the capacity of the feeder with respect to the demand of 100kVA will be excessive as shown in table 6.21.

Conductor	½ I rating (A)	Feeder capacity (kVA)			
		Φ-N	Φ-Φ	3Φ	SWER
Bantam	34.5	597.55	1035	1792.67	400
Magpie	46	796.72	1380	2390	400
Squirrel	65	1125.80	1950	3377	400
Fox	85	14722.2	2250	4416	400

Table 6. 21: Comparison system capacity and demand for the 18km line under various configurations.

Table 6.21 shows that with respect to the long-term demand of 100kVA adopting configurations such as Φ-Φ, Φ-N, 3Φ may result in network capacity far exceeding the power available for distribution.

For the SWER line, as described in chapter 5 the system capacity is limited by safety requirements (such as the potential step and touch voltages for humans and livestock), protection purposes and sometimes by induction effects on nearby telecommunications networks.

The 400kVA capacity appearing in the table is the nominal capacity based on practice in other Southern Africa countries.

6.5.3 Construction characteristics.

Span lengths under each configuration will be calculated in order to assess the material cost in each case.

For spans calculations under the Φ-Φ or Φ-N configuration, as the third conductor is dropped the following changes from the 3-phase arrangement of figure 6.3 should be brought:

- The number of conductor is 2 and the center of gravity of wind load on 2 conductors is moved 300mm higher. This will affect the maximum wind spans.
- The lower conductor is 600mm higher than on the 3-phase structure. This modifies the maximum sags and will affect the ground clearance spans. In other words 600mm will be added to maximum sags. These become 1.15m, 2.05m, 2.95m, 3.85m, and 4.75m for poles of 9, 10, 11, 12, and 13m.

Under the above changes wind spans and ground clearance spans for the Φ-Φ or Φ-N line are as on tables 6.22 and 6.23.

	Wind spans (m) phase-phase 18km line														
	9m			10m			11m			12m			13m		
	140	160	180	140	160	180	140	160	180	140	160	180	140	160	180
Conductor															
Bantam	306	422	564	293	400	532	283	384	507	276	372	488	271	363	474
Magpie	242	334	447	232	317	421	224	304	402	218	295	387	214	287	375
Squirrel	243	335	448	233	318	422	225	305	403	219	296	388	215	288	376
Fox	184	253	339	176	240	319	170	231	305	166	223	293	163	218	285

Table 6.22: Wind spans for the phase-phase 18km line.

Ground clearance spans (m) phase-phase 18km line					
Conductor	9m (S=1.15m)	10m (S=2.05m	11m (S=2.95m)	12m (S=3.85m)	13m (S=4.75m)
Bantam	136	189	232	271	306
Magpie	136	189	232	271	306
Squirrel	88	133	170	204	234
Fox	88	133	170	204	234

Table 6.23: Ground clearance spans for the phase-phase 18km line.

As weight spans are much longer than the wind spans, they can be ignored.

And spans to be adopted are the smallest between wind spans and ground clearance spans.

Table 6.24 shows the spans to be adopted for the phase-phase or phase-neutral 18km line.

	Span length (m) for phase-phase 18km line.														
	9m			10m			11m			12m			13m		
	140	160	180	140	160	180	140	160	180	140	160	180	140	160	180
Conductor															
Bantam	136	136	136	189	189	189	232	232	232	271	271	271	271	306	306
Magpie	136	136	136	189	189	189	224	232	232	218	271	271	214	287	306
Squirrel	88	88	88	133	133	133	170	170	170	204	204	204	215	234	234
Fox.	88	88	88	133	133	133	170	170	170	166	204	204	163	218	234

Table6.24: Span lengths for the phase-phase (or phase-neutral) 18km line.

As for the SWER line, assuming a conductor placed 300mm above the pole top for the intermediate structure the shortest spans among wind spans, weights spans and ground clearance spans are shown in table 6.25 below.[5]

[5] The shortest spans are actually determined by the ground clearance criterion. Because there is only one conductor and despite being located at higher height, wind spans are very much longer than the ground

Span Lengths for the SWER line (m).					
	9m	10m	11m	12m	13m
Bantam	190	232	270	304	343
Magpie	190	232	270	304	343
Squirrel	137	174	207	237	265
Fox	137	174	207	237	265

Table 6.25: Span lengths for the 18km SWER line.

6.5.4 Cost Analysis.

With the knowledge of adequate conductors (and their cost) and span lengths in each technological alternative, line costs per km in each case can be calculated. However, as for the three-phase line the cost analysis will be restricted to conductor and pole costs.

Because of the restriction on conductor diameter due to safety concerns (not less than 5mm) a three-phase line of 18km long between the main center to the Kala community will have the same maximum spans and same cost/km as the tri-phase line from the hydro site to Kirungu. This means that to transfer 100kVA a line with 10-times capacity would be built.

As for the phase-phase alternative the cost analysis using the same conductor and pole costs is carried out on the following tables (6.26a to 6.26e)

			Cost/km on 9m poles ph-ph			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
50	361	90842.04	11047	12647	10827	12967
60	301	75743.64	10208	11808	9988	12128
70	258	64923.12	9607	11207	9387	11527
80	226	56870.64	9159	10759	8939	11079
90	201	50579.64	8810	10410		
100	181	45546.84	8530	10130		
110	164	41268.98	8293	9893		
120	151	37997.64	8111	9711		
130	139	34977.96	7943	9543		

Table 6.26a: Line unit costs in R/km on 9m poles (phase-phase option 18km length)

clearance spans for the three-phase and phase-phase line. The shortest wind span is equal to 333m and is related to the fox conductor on 9m, 140mm pole. As for the weight spans these are generally higher than the wind spans.

			Cost/km on 10m poles, ph-ph			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox.
50	361	104877.7	11827	13427	11607	13747
60	301	87446.52	10858	12458	10638	12778
70	258	74954.16	10164	11764	9944	12084
80	226	65657.52	9648	11248	9428	11568
90	201	58394.52	9244	10844	9024	11164
100	181	52584.12	8921	10521	8701	10841
110	164	47645.28	8647	10247	8427	10567
120	151	43868.52	8437	10037	8217	10357
130	139	40382.28	8243	9843	8023	10163
140	129	37477.92	8082	9682		
150	121	35152.92	7953	9553		
160	113	32828.76	7824	9424		
170	106	30795.12	7711	9311		
180	101	29342.52	7630	9230		

Table 6.26b: Line unit costs in R/km on 10m poles (phase-phase option18km length)

			Cost/km on 11m poles, ph-ph			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	63905.05	9550	11150	9330	11470
110	164	57900.2	9217	10817	8997	11137
120	151	53310.55	8962	10562	8742	10882
130	139	49073.95	8726	10326	8506	10646
140	129	45543.45	8530	10130	8310	10450
150	121	42719.05	8373	9973	8153	10293
160	113	39894.65	8216	9816	7859	9999
170	106	37423.3	8079	9679		
180	101	35658.05	7981	9581		
190	95	33593.75	7863	9463		
200	91	32127.55	7785	9385		
210	86	30362.3	7687	9287		
220	82	28950.1	7608	9208		
230	79	27890.95	7549			

Table 2.26c: Line unit costs in R/km on 11m poles (phase-phase option 18km length)

			Cost/km on 12m poles, ph-ph			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	72229.86	10013	11613	9798	11933
110	164	65445.84	9636	11236	9416	11556
120	151	60258.06	9348	10948	9128	11268
130	139	55469.34	9082	10682	8862	11002
140	129	51478.74	8860	10460	8640	10780
150	121	48286.26	8683	10283	8463	10603
160	113	45093.78	8505	10105	8285	10425
170	106	42300.36	8350	9950	8130	
180	101	40305.06	8239	9839	8019	
190	95	37910.7	8106	9706	7886	
200	91	36314.46	8016	9617	7797	
210	86	34319.16	7907	9507		
220	82	32722.92	7818			
230	79	31525.74	7751			
240	76	30328.56	7685			
250	73	29131.38	7616			
260	70	27934.2	7552			
270	67	26737.02	7485			

Table 2.26d: Line unit costs in R/km on 12m poles (phase-phase option 18km length)

			Cost/km on 13m poles, ph-ph			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	84708	10760	12306	10486	12626
110	164	76752	10264	11864	10044	12184
120	151	70668	9926	11526	9706	11846
130	139	65052	9614	11214	9394	11534
140	129	60372	9354	10954	9134	11274
150	121	56628	9146	10746	8926	11066
160	113	52884	8938	10538	8718	10858
170	106	49608	8756	10356	8536	
180	101	47268	8626	10226	8406	
190	95	44460	8470	10070	8250	
200	91	42588	8366	9966	8146	
210	86	40248	8236	9836	8016	
220	82	38376	8132			
230	79	36972	8054			
240	76	35568	7976			
250	73	34164	7898			
260	70	32760	7820			
270	67	31356	7742			

Table 2.26e: Line unit costs in R/km on 13m poles (phase-phase option 18km length)

It appears from tables 6.26a to 6.26e that:

- The phase-phase line is much cheaper than the three-phase line. For the squirrel conductor on 11m poles the cost of the 3-phase line varies from R17527 to R11206, while a phase-phase line costs varies from R 9330 to 7859 according to the average span.
- The bantam and squirrel conductors result in lower costs per km and the lowest minimum is associated with the 12m poles. However these costs are very close to the cost associated with the 11m pole (the difference is less than R100). For reasons advocated previously (standardisation, availability, low environmental impact, maximum sag limitation, easiness of maintenance) 11m poles should be used.

The cost analysis for the SWER alternative using the same costs for conductors and poles is carried out in tables 6.27a to 6.27e.

			Cost/km on 9m poles, swer			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	44547	5530	6275	5365	6435
110	164	41269	5293	6093	5183	6253
120	151	37998	5111	5911	5001	6071
130	139	34978	4943	5743	4833	5903
140	129	32461	4803	5603		
150	121	30448	4692	5492		
160	113	28435	4580	5380		
170	106	26674	4482	5282		
180	101	25416	4412	5212		
190	95	23906	4328	5128		

Table 6.27a: Line costs R/km for the SWER option on 9m poles 18km length.

			Cost/km on 10m poles, swer			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox.
100	181	52584	5921	6721	5811	6881
110	164	47645	5647	6447	5537	6607
120	151	43869	5437	6237	5327	6397
130	139	40383	5243	6043	5133	6203
140	129	37477	5080	5880	4970	6040
150	121	35153	4953	5753	4843	5913
160	113	32829	4824	5624	4714	5784
170	106	30795	4711	5511	4601	5671
180	101	29343	4630	5430		
190	95	27599	4533	5333		
200	91	26437	4469	5269		
210	86	24985	4388	5188		
220	82	23823	4323	5123		
230	79	22951	4275	5075		

Table 6.27b: Line costs R/km for SWER option on 10m poles 18km length

			Cost/km on 11m poles, swer			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	63902	6550	7350	6440	7510
110	164	57900	6217	7017	6107	7177
120	151	53311	5962	6762	5852	6922
130	139	49074	5726	6526	5616	6686
140	129	45543	5530	6330	5421	6490
150	121	42719	5373	6173	5263	6333
160	113	39895	5216	6016	5106	6176
170	106	37423	5079	5879	4969	6039
180	101	35658	4981	5781	4871	5941
190	95	33540	4863	5663	4753	5823
200	91	32128	4785	5585	4675	5745
210	86	30362	4687	5487		
220	82	28950	4608	5408		
230	79	27891	4549	5349		
240	76	26832	4491	5291		
250	73	25773	4432	5232		
260	70	24713	4373	5173		
270	67	23654	4314	5114		

Table 2.27c: Line costs R/km foe SWER option on 11m poles 18km length

			Cost/km on 12m poles, swer			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox.
100	181	72230	7013	7813	6903	7973
110	164	65446	6636	7436	6526	7596
120	151	60258	6348	7148	6238	7308
130	139	55469	6082	6882	5972	7042
140	129	51479	5860	6660	5750	6820
150	121	48286	5683	6483	5573	6643
160	113	45094	5505	6305	5395	6465
170	106	42300	5350	6150	5240	6310
180	101	40305	5239	6039	5129	6199
190	95	37911	5106	5906	4496	6066
200	91	36314	5017	5817	4907	5977
210	86	34319	4907	5707	4797	5867
220	82	32723	4818	5618	4708	5778
230	79	31526	4751	5551	4641	5711
240	76	30329	4685	5485		
250	73	29131	4618	5418		
260	70	27934	4552	5352		
270	67	26737	4485	5285		
280	65	25939	4441	5241		
290	63	25141	4397	5197		
300	61	24343	4352	5152		

Table 2.27d: Line costs R/km for SWER option on 12m poles 18km length

			Cost/km on 13m poles, swer			
Avrg Span	Pole nbre	Pole costs	Bantam	Magpie	Squirrel	Fox
100	181	84708	7706	8506	7596	8666
110	164	76752	7264	8064	7154	8224
120	151	70668	6926	7726	6816	7886
130	139	65052	6614	7414	6504	7574
140	129	60372	6354	7154	6244	7314
150	121	56628	6146	6946	6036	7106
160	113	52884	5938	6738	5828	6898
170	106	49608	5756	6556	5646	6716
180	101	47268	5626	6426	5516	6586
190	95	44460	5470	6270	5360	6430
200	91	42588	5366	6166	5256	6326
210	86	40248	5236	6036	5126	6196
220	82	38376	5132	5932	5022	6092
230	79	36972	5054	5854	4944	6014
240	76	35568	4976	5776	4866	5936
250	73	34164	4898	5698	4788	5858
260	70	32760	4820	5620	4710	5780
270	67	31356	4742	5542		
280	65	30420	4690	5490		
290	63	29484	4638	5438		

300	61	28548	4586	5386		
310	59	27612	4534	5334		
320	57	26676	4482	5282		
330	55	25740	4430	5230		
340	54	25272	4404	5204		

Table 2.27e: Line costs R/km for SWER option on 13m poles 18km length

From tables 6.27a to 6.27e it appears that:

- Average costs for the SWER alternative are much lower than costs in the phase-phase and three-phase alternatives. For the squirrel conductor and on 11m poles line costs vary from R6440 to R4675.
- The bantam and squirrel conductors result once again in lower line costs. The lowest minimum costs are associated with the 10m poles but the difference with figures for 11m poles are less than R100/km. Thus for same reasons than previously 11m poles will be used for the 18km SWER line.

Figures 6.10 and 6.11 compare line costs for bantam and squirrel conductors on 11m poles under different technology options (3phase, phase-phase and SWER)

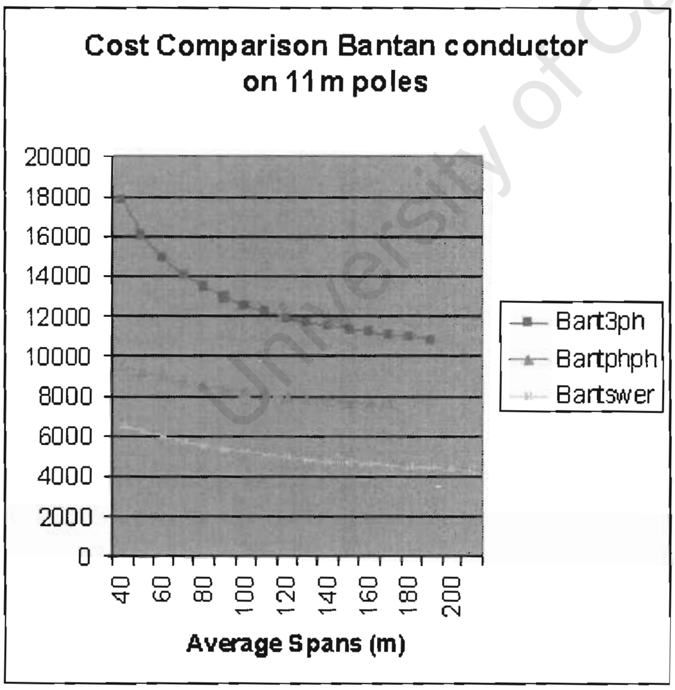

Figure 6.10; Comparison of line costs with bantam on 11m poles under various technologies, three-phase, phase-phase and SWER.

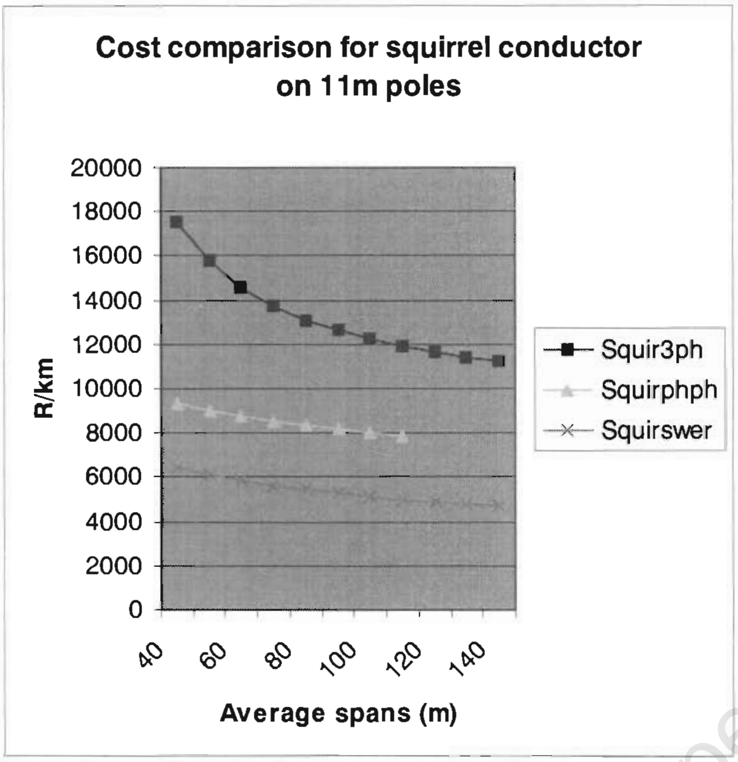

Figure 6.11: Cost comparison with squirrel on 11m poles under various technologies, three-phase, phase and SWER.

In conclusion, for the transfer of 100kVA capacity on 18km between the main center and the Kala community the SWER line with bantam conductor is the least cost alternative. For standardization reason and for reasons advocated in appendix 3 (lengths of SWER lines according to the conductor used), the squirrel conductor will be used without modifying significantly the line unit cost.

6.5.5 Constraints in the utilization of single phase supplies.

The major disadvantage associated with single-phase supplies in rural electrification is the inability to provide power for tri-phase motors. [Ferguson, 1998]

In the area such as the Kala community and in most of rural Congo, possible uses of electricity are as follow:

(1) lighting homes and small shops,

(2) powering small domestic appliances such as radios and cassette players

(3) agriculture processing mainly hulling and milling grain or oil and juice extraction.
(4) water pumping.
(5) Lighting administrative buildings, clinics and possibly schools.

If the single-phase supplies can solve such problems, the objective of providing electricity at low cost for socio economic development will be achieved[6].
However in Congo single-phase motors of more than 5kW are hardly available and in order to take into account the vital requirements of agriculture processing and water pumping, a supply strategy for single-phase motors of adequate capacity or electronic converters is of the utmost importance.
Single-phase motors of capacity up to 20kW and electronic converters are available in other countries including South Africa.
The cost of these motors and electronic converters are certainly much less than the costs of a tri-phase distribution network.

If such equipment is made available (at a cost) the SWER line connecting the Kala community is not only the least cost option but also a cost-effective way of electrifying that community.

6.6 LINE KIRUNGU-MOBA (6km)

For the connection of the Moba community an investigation into different options is also recommended.
In this case current in line under the different supply options are as follow: 6.7A for the phase-phase 30kV line, 3.85A for a tri-phase 30kV line. For the SWER line the distance involved is much lower than the distance shown in appendix 3 using squirrel conductor.

[6] Adjidjonu, (2000) reports the rejection of single phase supplies by communities in rural Ghana. As single-phase motors were not available or were of low capacity, cornmills, palm kernel extractors and palm kernel crackers with motors up to 10kW could not be used.

These currents are still very low and it can be shown that the use of bantam, magpie, squirrel, and fox conductors do not result in excessive voltage drop.

A three-phase line would be of the same structure and unit cost than the three-phase line from the hydro site to Kirungu.
A phase-phase or a SWER line would also have the same physical characteristics and same unit costs than the 18km phase-phase and SWER lines connecting Kala to the main center Kirungu.

Given economic activities that can probably develop at the harbour level, conservative planning might propose a phase-phase line extendable to three-phase.
In this case the phase-phase line should use the spanning lengths of a three-phase line although the third conductor would not be installed initially.
In other words a line with characteristics of a three-phase line should be built and investment in the 3rd conductor postponed.

However this conservative approach to planning contradicts the primary objective of implementing low cost electrification. Under conditions of scarce capital and the limited capacity of the power station, the over design of the "conservative" option must be disregarded.
Instead, the balance (what would have been spent in a "conservative" approach) can be used to connect other small communities in the vicinity.

Thus another SWER line will be built to connect Moba from the main center.

6.7 CONCLUSION (regarding the case study)

As communities such as Kala and Moba with characteristics of small loads (long-term maximum demands in the range of 100-200kVA) are typical of Congo rural areas there is substantial scope for the application of lower cost distribution technologies than the present standards in the country.

This chapter has shown that for loads of 100-200kVA encountered in rural areas, MV single-phase networks are cheaper to build (than the three-phase alternative).
The low cost of such networks is a consequence of using conductors of small size (as a result of higher voltages and low loads, but safety requirements dictate a minimum size to be used) and fewer conductors in number.
Besides the use of conductors resulting in greater spanning lengths (ACSR instead of copper conductors), lead to reduced number of poles to be erected.

If three-phase networks were systematically used, with the safety restriction to conductors (of at least 5mm diameter), the capacity of the networks would be far greater than the capacity needed by the 3 rural communities and even greater than the capacity available for distribution.
In order words, such networks with considerable excess capacity, built at high costs, will not be fully utilized.
However with single-phase supplies capacity of the networks can be matched more closely with the demand.

It is evident that adoption of a conventional or conservative planning approach, which makes provision for possible future load center requiring the supply capacity of three-phase lines, is not appropriate where the supply capacity is restricted and capital can be used better in extending a network to more communities from the station.

Application of lower cost technologies to extend existing networks with sufficient unused capacity will allow the connection of communities in the vicinity.
In addition, as a number of mini and small hydro sites (500kW-10MW) have been identified in the country, replication of experience such as in the Moba area can result in isolated networks operating separately up to the time connection to other networks become financially possible.

CHAPTER 7

FINANCIAL ANALYSIS

7.1 INTRODUCTION

In order to determine the conditions that lead to the viability of the electrification project of chapter 6, a financial analysis based on the net present value will be carried out.

The Net Present Value (NPV) is "*the algebric sum of initial costs and discounted future costs and incomes. A positive NPV is associated with a viable project and the highest NPV with the most profitable project".* [NRS 034-1: 1997]

7.2 ASSUMPTIONS FOR THE FINANCIAL ANALYSIS.

The following assumptions will be made.

- In line with section 4.3.2 the investment cost of the hydro station will be estimated at $1000/kW or R 7000/kW, leading to a total of R 7000 000. This low cost scenario is adopted taking into account the fact that community labour and transportation will be used. The total amount can be invested at the same time when the project starts or in 2 steps. In the first option R 5000 000 is invested at year 0 for 0.5MW capacity and when this capacity is reached, a further investment of R 2000 000 is made. In the second option the whole amount of R7000 000 is invested at year 0.

- Operating, administrative and maintenance costs are low and estimated at R15600/year (185$/kWh)
- According to 6.3.2 a peak load of 300kW can be adopted at start with a load factor of 0.25 (typical in rural areas). The peak load will grow at about 15% for the first 5 years then 10, 5, and 2,5% in the future.
- Losses are not significant and all the energy produced is sold.
- The project will be evaluated over 20 years and the net discount rate is 10%.

- For the capital investment cost of lines, a first option considers the construction of a three-phase line between the power station and the main center and two SWER lines of 18km and 6km. In the second option, all lines are of tri-phase construction. It is assumed that the total cost of a line is about 6 times the conductor cost regardless of the technology used. The costs to be considered are as in the table 7.1 (squirrel conductor is considered).

Line length (km)	Line Option I			Line Option II		
	Technology	Conductor cost	Line cost (Rands)	Technology	Conductor cost (Rands)	Line cost (Rands)
11	3-phase	95370	572220	3-phase	95370	572220
18	SWER	52020	312120	3-phase	156060	936360
6	SWER	17340	104040	3-phase	52020	312120
Total			988 380			1 820 700

Table 7.1: Total costs of lines according to investment options.

7.3 NET PRESENT VALUE CALCULATION

The NPV will be calculated according to the formula:

$\sum NPV = CF_0 + CF_1/(1+i)^1 + CF_2/(1+I)^2 + \ldots + CF_n/(1+I)^n$

Where: CF_I is the cash flow in year i (income and expenditure), i being the net discount rate and n the investment period considered. [Source: www.prenhall.com] (24/03/2004)

7.4 EXAMPLE OF CALCULATION

The spreadsheet (table 7.2) shows the calculation of $\sum$NPV for the following case:

2 stages investment for the power station (R 5000 000 invested at year 0 and R2000 000 at year 6), line investment according to option 1 (a tri-phase line and 2 SWER lines), a tariff of 40 cents/kWh. The resulting $\sum$NPV is −1 271 736 Rands, meaning that under the conditions of investment and tariff described the project will not be viable.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Station Exp (R)	5000000	0	0	0	0	0	2000000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Line Exp (R)	988000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Maintenance (R)	0	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	
Peak Load	0	300	350	400	450	500	550	600	650	700	750	785	820	860	900	915	925	935	945	950	950	
Load factor	0.24	0.25	0.26	0.27	0.28	0.29	0.3	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.4	0.41	0.42	0.43	0.44	
Energy/Year (kWh)	0	657000	797160	946080	1103760	1270200	1445400	1629360	1822080	2023560	2233800	2406810	2585952	2787432	2995920	3126006	3241200	3358146	3476844	3578460	3661680	
Revenue (R)	0	262800	318864	378432	441504	508080	578160	651744	728832	809424	893520	962724	1034381	1250402	1198368	1250402	1296480	1343258	1390738	1431384	1464672	
Total cash (R)	-5988000	247200	303264	362832	425904	492480	-1437440	636144	713232	793824	877920	947124	1018781	1234802	1182768	1234802	1280880	1327658	1375138	1415784	1449072	
Discounting factor	1	0.909	0.83	0.75	0.68	0.62	0.56	0.51	0.46	0.42	0.38	0.35	0.32	0.29	0.26	0.24	0.22	0.2	0.18	0.16	0.15	
Net Present Value	-5988000	224704.8	251709.1	272124	289614.7	305337.6	-804966	324433.4	328086.7	333406.1	333609.6	331493.4	326009.9	358092.7	307519.7	296352.6	281793.6	265531.7	247524.8	226525.4	217360.8	-1271736

Table 7.2: Spreadsheet for the calculation of a ∑NPV in alternative A.

7.5 VIABILITY OF THE ELECTRIFICATION PROJECT

A further investigation into the conditions of viability of this project is carried out in table 7.3. It shows a record of results obtained by varying investment options for the station and the line, and the tariff applied, keeping the peak load and load factor as in the previous example (because this pattern is typical for rural areas).

	Line Option 1		Line option 2	
	Station Opt 1	Station Opt 2	Station Opt 1	Station Opt 2
Tariff	A	B	C	D
0.4	-1271736	-2151736	-2104436	-2984436
0.41	-1122519	-2002519	-1955219	-2835219
0.42	-973301	-1853301	-1806001	-2686001
0.43	-824084	-1704084	-1656784	-2536784
0.44	-674867	-1554867	-1507567	-2387567
0.45	-525649	-1405649	-1358349	-2238349
0.46	-376432	-1256432	-1209132	-2089132
0.47	-227215	-1107215	-1059915	-1939915
0.48	-77997	-957997	-910697	-1790697
0.49	71220	-808780	-761480	-1641480
0.5	220437	-659563	-612263	-1492263
0.51	369655	-510345	-463045	-1343045
0.52	518872	-361128	-313828	-1193828
0.53	668089	-211911	-164611	-1044611
0.54	817307	-62693	-15393	-895393
0.55	966524	86524	133824	-746176
0.56	1115741	235741	283041	-596959
0.57	1264959	384959	432259	-447741
0.58	1414176	534176	581476	-298524
0.59	1563393	683393	730693	-149307
0.6	1712610	832611	879911	-90
0.61	1861828	981828	1029128	149128
0.62	2011045	1131045	1178345	298345
0.63	2160262	1280262	1327562	447562
0.64	2309480	1429480	1476780	596780
0.65	2458697	1578697	1625997	745997
0.66	2607914	1727914	1775214	895214

Table 7.3: Record of ∑NPV results according to the 4 investment patterns.

The various alternatives can be labeled as follow:

A: 2-stage investment for the power station; a three-phase line plus 2 SWER lines.

B: 1-stage investment for the power station; a three-phase line plus 2 SWER lines.

C: 2-stage investment for the power station; 3 three-phase lines.

D: 1-stage investment in the power station, 3 three-phase lines.

From this table (6.30) the following lessons can be drawn:

- For a given tariff the NPV associated with the investment option A is the highest while the NPV associated with the investment option D is the lowest.
- A tariff of 49 cents is enough to make the investment option A viable but a tariff of 61 cents is needed to reach the viability in the investment option D.

Investment option A brings a major advantage with respect to the tariff that is an important issue in rural areas.

Keeping the tariff low while the project is viable leads to the sustainability of the project. These findings are illustrated in figure 7.1 below.

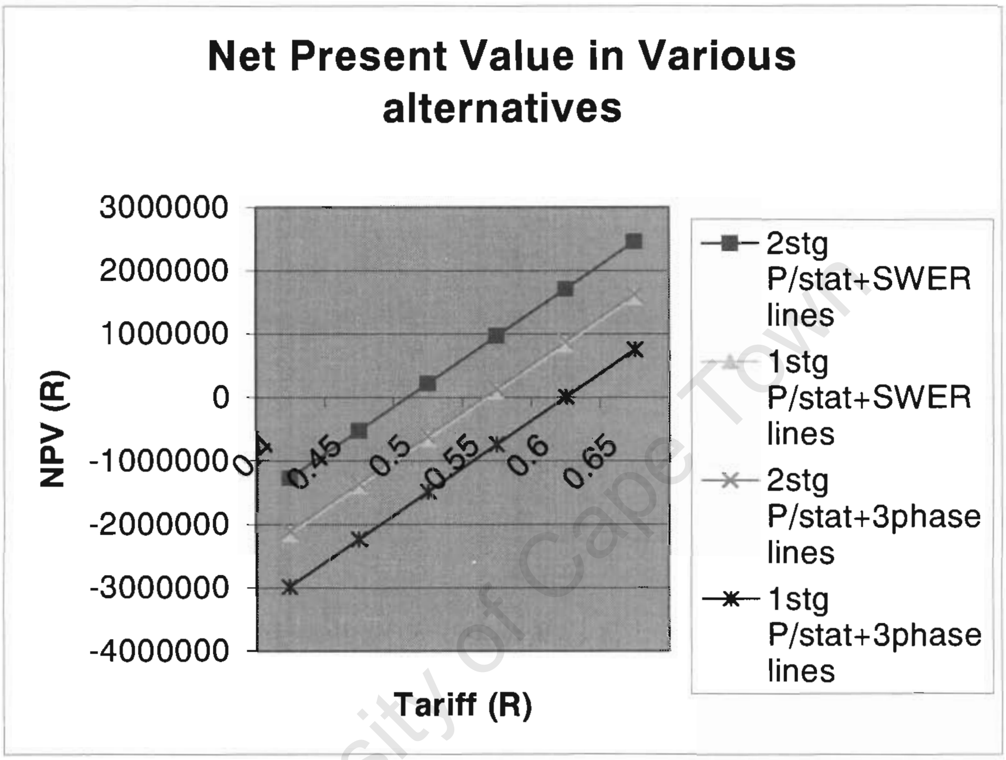

Figure 7.1: Graphs of ∑NPV in alternatives A, B, C, and D

7.6 CONCLUSION

It can be concluded that the adoption of single-phase supplies where applicable can contribute to the viability of rural electrification schemes and allow a lower tariff to be applied.

In other words, building tri-phase lines systematically can undermine the viability of the electrification project or require application of high tariffs in order to reach viability.

The resulting high connection costs and tariffs make electricity unaffordable to some customers.

CHAPTER 8

RECOMMENDATIONS

8.1 INTRODUCTION

In this chapter recommendations outlining actions that should be taken or policies that should be followed in order to expand electricity in Congo are given. Based on the findings of previous chapters these recommendations will be grouped according to the major obstacles to electrification.

8.2 EFFICIENCY IMPROVEMENT

As written in section 4.2, poor technical and operational performance (in particular reduced plant availability, unreliability of power supply, high overall losses and poor collection) are depriving the Congo utility of the capacity to expand networks and of investments funds.
In order to improve performance the following recommendations are made.

Because the overall plant availability is currently under 50%, as shown by table 3.1, the rehabilitation program should be considered with high priority, such that the capacity is recovered, making electricity expansion possible.
In this respect it is recommended that skills and capabilities be enhanced to improve the maintenance of power plants.
Joint partnership or technical assistance with more experienced power companies can help to improve skills in order to achieve more effective maintenance of power plants.
In addition to depriving the utility of financial resources, the extent of non-payment and energy losses probably contribute significantly to the reluctance of lenders to commit investments funds.

Besides, given difficulties to repair or replace obsolete credit meters the utility largely resorts to flat tariffs and estimated readings.
In order to reduce losses and make electricity available for distribution it is recommended that the use of prepaid meters be investigated and a costs/benefits analysis be implemented.
This is justified by the fact that in the specific case of Congo, beside the investment required in the acquisition of the whole prepayment equipment (as described in figure 4.1), in staff training and marketing, additional investment in infrastructure such as telephone lines may be needed.
Fixed telephone lines do not always exist in Congo and where existing are not always reliable. As a result efficiency in exchange of information and data among various units of the prepayment system may be reduced. The mobile vending technology is probably more expensive.
However, the culture of paying in advance of consumption has already been introduced by other utilities including cellular phone companies.

Given the environment of high non-technical losses and non-payment, it is not realistic to recommend unmetered supplies in Congo.

With only 6% electricity access, the electrification of the country is a major challenge facing the electricity sector in Congo and one of its primary objectives.
The literature review has shown that the restructuring process as advocated by international organisations may not be effective in electricity expansion especially towards rural areas.
Taking into account these two reasons (the necessity of electrifying the country and the limited benefits shown elsewhere by restructuring), it is recommended that the restructuring route be disregarded and minimum reform measures in the framework of public utility be taken.

The liberalization of small-scale production and distribution is among such minimum measures as it creates the necessary conditions for expansion.

The expectation is that under standards defined by the government, small operators such as local industries, missions, and NGOs are encouraged to develop local networks powered by diesel sets, micro hydro plants (below 0.5MW) or by agro processing residues.

For example palm-oil industries generally generate steam and electricity from agriculture residues. If such local companies or organisations, generally located in remote areas, are allowed to sell their electricity surplus to others, liberalization will contribute to expand electricity in the country. Currently only missionaries are able to obtain exemptions for electricity production and limited distribution.

To illustrate the expected results of the liberalization process the table below presents 2 realisations in rural Congo.

Location	Initiator	Capacity (kW)	Load connected
Kaziba(40km from Bukavu, eastern Congo)	Missionaries	125	Hospital, nursery school, local administration, street lighting, 50 households, 150 other planned.
Ifwanzondo (120km from Kikwit, southwest Congo)	Missionaries	100	Mission needs, local hospital, local school, 45 households.

Table 8.1: Two examples of local production and distribution systems developed outside the utility.

Source: [Jensen and Beheim, 1999] for the Kaziba Project and personal communication with missionaries of Ifwanzondo, August 2003.(ilocosta@yahoo.fr)

In addition to the liberalization of local production and distribution in remote areas it is recommended that more authority be given to the utility to impose sanctions for non-payment.

With more authority, improved collection and skills the utility should be in better position to generate or attract external funds and tackle the challenge of electrification.

8.3 STRATEGY AND TECHNOLOGY FOR ELECTRIFICATION

The analysis of successive master plans has shown that the strategy of extending electricity from existing systems failed to deliver the expected results because of the high cost of transmission lines, long distances and low loads.
It is recommended that an off-grid development program complement this traditional approach.
As the major economic activities are concentrated in mining areas and towns such as Kinshasa and Lubumbashi, elsewhere loads are generally small and made of some of the following: residential loads, administrative and health buildings, water utilities, small commercial and entrepreneurial activities and agro-processing machinery.
Most of such demands can be met by off-grid developments that better match limited resources.

However experience in diesel units managed by the utility has not been successful in Congo because of " *technical and managerial deficiencies*" [World Bank, 1986] or "*difficulties in fuel and spare parts acquisition and transport*" [SNEL, 2000].
Viable substitutes to thermal based power should be found with special consideration to small and mini hydropower. As explained in section 2.6 because of limited resources and deficiencies in production and transport systems, oil and coal are not likely to play a major role in electricity production in Congo.
Thus, it is recommended that the utility give equal attention to extending existing networks and to isolated systems powered by small and mini hydropower (0.5MW to 10MW).

The objective should be to develop small independent grids that will be connected to existing systems at a later stage.

Given the current financial situation in Congo and within the utility, economic and socio economic electrification should be emphasized.

In other words the extent to which electrification contributes to socio economic development should be the main consideration in planning electricity expansion.

The basis of this recommendation is that the productive use of power will increase income and improve the ability to pay for electricity. As a result the utility will be in a better position to undertake new projects and attract funding from development organisations.

However in order to attract popular attention that can be useful in gaining political support, some social electrification can still be implemented.

The common standard of distribution technology in Congo is the tri-phase construction irrespective of load size and type (single-phase or tri-phase).

In order to reduce electrification costs it is recommended that the Congo utility be receptive to low-cost technological alternatives that have been tested and successfully applied in other countries.

As shown by the case study, single-phase supplies (phase-phase and SWER at the MV level) are adequate to meet electricity needs in rural areas in a cost-effective manner despite some minor inconveniences.

However application of shield wire systems are currently limited to the western and southern system where HV lines under voltage levels higher than 115kV ($V \geq 115kV$) are concentrated, as shown by table 3.2.

Most communities not connected in these areas are generally close to distribution networks and other technologies may be cheaper than the shield wire systems.

The three-phase construction is sometimes adopted in low-load areas as a precaution measure to avoid upgrading the network at a later stage.

As a result of this conservative planning, some networks with capacity high enough to meet many years of demand growth are built while other communities are not connected, because the three-phase network to connect them is too expensive. At the same time capacity is idle in the network already built.

The financial impact assessment (in chapter 7) showed that building three-phase lines systematically could undermine the viability of a project or require the application of a high tariff in order to reach viability. Such high tariff may become unaffordable to other customers. This contradicts the objective of expanding electricity to most possible customers.

It is recommended that to connect the highest possible number of customers with limited financial resources, the above planning approach be replaced by the predominance of low-cost electrification.

At the customer level, ready boards that include isolators, protection, (fuses or circuit breakers) socket outlets and switches and are cheaper than the traditional distribution boards are recommended in order to reduce the initial cost of connection to electricity.

Because single-phase motors of capacity higher than 5kW are hardly available in Congo, the utility should find a strategy to make such motors or electronic converters available at the same time single-phase networks are introduced.

As for conductors, as long as copper conductors have to be imported (in which case they are always more expensive than ACSR conductors) it is recommended that networks be built with ACSR conductors. A shown by the case study, ACSR conductors are associated with longer spans (thus less number of poles).

Finally in order to dismiss perceptions that single-phase technologies are not efficient or can undermine public safety it is recommended that the utility provide training to its staff and adequate information to the public prior to their introduction.

8.4 STANDARDIZATION

Standards from Belgium are still in use in Congo particularly the old editions where special reference was made to "tropical areas". Standards from donor countries are also used in some particular projects.

As it is difficult to change existing equipment the up coming rehabilitation and expansion program offer a chance to standardize network voltages and equipment.

It is recommended that Congo take advantage of standards existing in the region through organisations such as PIESA and UPDEA.

In particular MV distribution voltages that currently comprise 6.6, 10, 15, 20 and 30kV should be reduced to a minimum in order to reduce electrification costs in the long term.

8.5 CONCLUSION

The major recommendations are listed below:

- Consider plant rehabilitation as a priority and enhance skills to improve plant maintenance.
- Investigate the introduction of prepaid meters to reduce non-technical losses and improve collection.
- Initiate minimum reform measures such as liberalization of local production and distribution. Allow more authority to the utility in the framework of public utility in order to implement the electrification of the country even in rural areas.

- Give equal consideration to extending existing systems and to off-grid developments based on the identified hydropower resources.
- Emphasize economic and socio economic electrification with limited social electrification.
- Introduce low-cost technological alternatives (such as MV singe-phase supplies) tested and successfully applied in other countries instead of the exclusive reliance to three-phase construction.
- In rural areas, avoid the conservative planning approach that favours tri-phase networks as a measure to avoid upgrading later. This keeps other customers unconnected while capacity is idle in three-phase lines. This approach is not appropriate when financial resources or capacity are limited.
- Make single-phase motors available, train staff, and inform the public when introducing single-phase technologies.
- Standardize MV voltages and network equipment by taking advantage of existing standards.

APPENDIX 1

The purpose of this appendix is the determination of the wind span of an overhead line. It is the maximum allowable span length such that the pole supporting conductors will have sufficient strength to counter the effect of expected wind forces and moments.

The figure A.1.1 shows an intermediate structure supporting 1 conductor on 2 span lengths.

Forces and moments arising from the pressure of the wind against conductors and poles depend on the speed of the wind.

If V (m/s) is the basic wind speed in a country or an area, the design wind speed Vs (m/s) is given by: [Bayliss, 1999]

$$Vs = V \times S_1 \times S_2 \times S_3 \qquad \text{(A.1. 1)}$$

S_1, S_2, and S_3 are factors defined as follow:

S_1 depends on the topography and is equal to 1.1 for exposed sites, 0.9 for sheltered spots, and 1.0 for normal conditions.

S_2 is the ground roughness and is equal to 0.5 to 1.3 depending on structure size height and location.

S_3 is a statistical factor depending on the level of security required and is normally taken as 1.0 [Bayliss, 1999]

The maximum design wind pressure is given by: [Bayliss, 1999]

$$DWP = k \times (V_s)^2 \qquad \text{(A.1. 2)}$$

(with k=0.613)

Assuming that the wind blows horizontally across the projected area of the conductor and the pole, wind action on the conductor results in a total force F_c that creates a moment M_c on the pole.

F_c (N) is given by: [SABS 0280, 2001]

$$Fc = DWP \times dc \times L \times K \times 0.6 \qquad \text{(A.1. 3)}$$

Where:

- F_c is the horizontal force on the conductor due to the wind.
- DWP is the design wind pressure.
- L is the wind span or the sum of the adjacent half spans on each side of the supports as illustrated on figure A.1.1, ($L = (L_1+L_2)/2$), $d_c \times L$ being the projected area of the conductor.
- K is the shape factor for conductors and 0.6 is the gust factor. (It takes into account the fact that the wind is not uniform over the entire span length. The wind is made of a steady component on which an alternating gust component is superimposed. [SABS 0280, 2001])

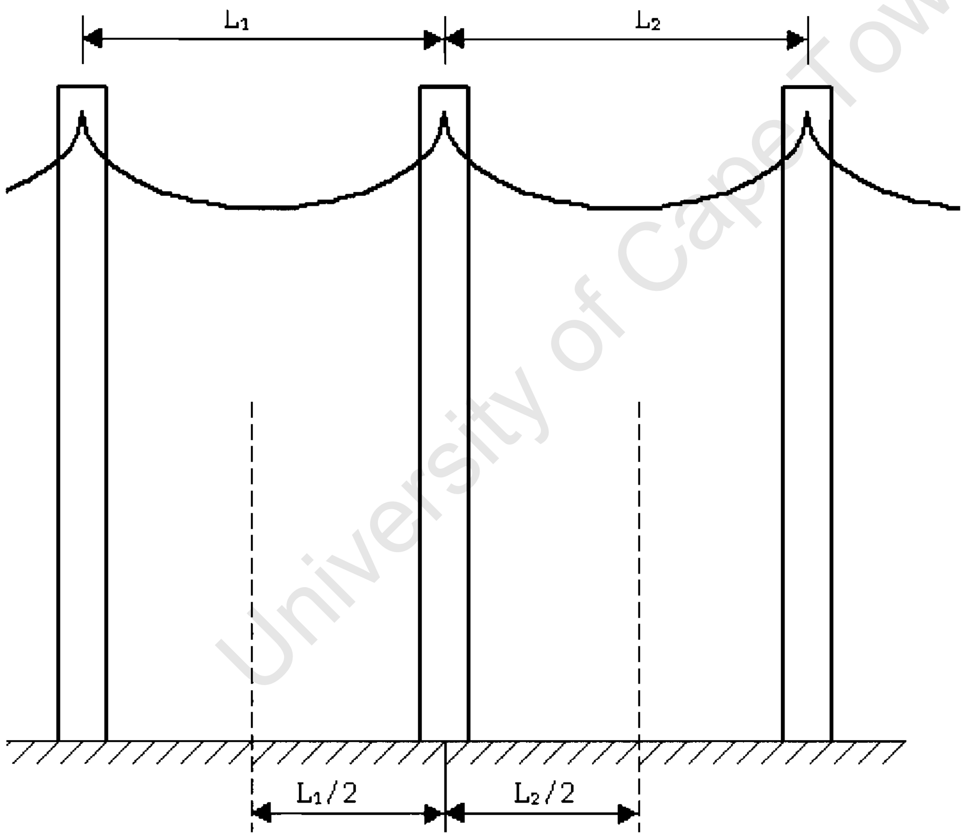

Figure A.1.1 Span length on an overhead line.

If h_c is the conductor height, a bending moment on the pole M_c results from the wind effect on the pole. M_c (Nm) is given by:

$$Mc = Fc \times hc \qquad \text{(A.1. 4)}$$

Using equation (A.1.3), this can be written as

$$Mc = DWP \times dc \times K \times 0.6 \times L \qquad \text{(A.1. 5)}$$

If the line has n conductors the resulting moment becomes:

$$Mc = DWP \times dc \times K \times 0.6 \times L \times n \qquad \text{(A.1. 6)}$$

For the action of the wind on the pole it is assumed that the gust will affect the entire structure, thus no gust factor will be applied. [SABS 0280, 2001]
The resulting force on the pole is Fp (N) and is given by:

$$Fp = K \times A \times DWP \qquad \text{(A.1. 7)}$$

(where K is the shape factor for round poles and A, the projected area of the pole).

If d_g is the pole's ground line diameter, and $h_{FP}$the height out of ground, the projected area is:

$$A = (dg + dt) \times \frac{hp}{2} \qquad \text{(A.1. 8)}$$

Inversin, (2000b) has shown that the bending moment M_p (Nm) can be obtained by assuming that the force is applied at a height of

$$\frac{hp}{3} \times \frac{(dg + 2dt)}{(dg + dt)}$$

Thus $Mp = K \times A \times DWP \times \frac{hp}{3} \times \frac{(dg + 2dt)}{(dg + dt)}$ (A.1. 9)

To resist effects of the previous bending moments on it, the pole will create a resisting moment M_r.

According to Chard (1976) for a pole of ground line diameter dg the resisting moment Mr (Nm) is given by:

$$Mr = \frac{f \times Z}{SF} \qquad \text{(A.1. 10)}$$

(where f (N/m^2) is the ultimate fiber stress of the pole, Z (m^3) is the section modulus at diameter dg (m), and SF a safety factor).
With respect to the pole's moment of inertia I, the section modulus Z is expressed as:

$$Z = \frac{2I}{dg} \qquad \text{(A.1. 11)}$$

and, for circular sections $I = \frac{\pi \times dg^4}{64}$ (A.1. 12)

. This leads to $Z = \frac{\pi \times dg^3}{32} = 0.0982 \times dg^3$

And the resisting moment can ultimately be written as:

$$Mr = \frac{0.0982 \times f \times dg^3}{SF} \qquad \text{(A.1. 13)}$$

As shown in figure A.1.2, to resist the wind effect the condition on moments is:

$Mr \geq Mc + Mp$ or

$$Mc \leq Mr - Mp \qquad \text{(A.1. 14)}$$

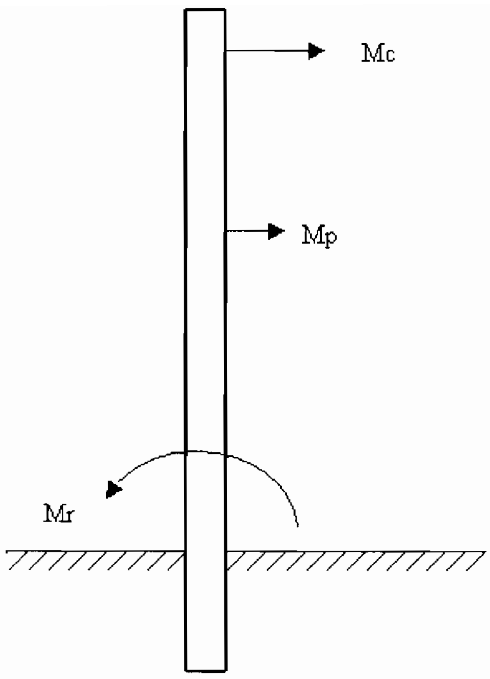

Figure A.1.2: Moments on an overhead line's pole as a result of wind.

Using the previous equations for M_c (A.1.6), M_p (A.1.9) and M_r (A.1.13) this equation becomes:

$$K \times 0.6 \times DWP \times dc \times n \times hc \times L \leq \frac{0.0982 \times f \times dg^3}{SF} - K \times A \times DWP \times \frac{hp}{3} \times \frac{(dg + 3dt)}{(dg + dt)}$$

Solving this equation for L gives:

$$L \leq \frac{0.0982 \times f \times dg^3}{SF \times (K \times 0.6 \times DWP \times dc \times n \times hc)} - \frac{K \times A \times DWP \times hp \times (dg + 2dt)}{(K \times 0.6 \times DWP \times dc \times n \times hc) \times 3(dg + dt)}$$

It can be shown that the last term is small compared to the middle term and can therefore be neglected.

Thus the approximate maximum span L (m) of an overhead line under design wind pressure DWP is given by:

$$L \leq \frac{0.0982 \times f \times dg^3}{SF \times (K \times 0.6 \times DWP \times dc \times n \times hc)} \qquad \text{(A.1. 15)}$$

The maximum wind span is mostly set by the wind action on the conductors.

APPENDIX 2

This appendix provides equations for the calculation of the ground clearance span of an overhead line.

A conductor suspended between 2 supports at the same level takes the shape of a catenary, but if the sag S is small compared to the span length L, (as is generally the case for distribution lines, with practical order of $S \leq 10\%L$), the shape approaches a parabola.

Under this assumption, it can be established that at any physical condition (temperature, wind loading,), the maximum sag (S) and conductor length (l) are given by: [Guile and Paterson, 1981] [Chard, F, 1976]

$$S = \frac{wL^2}{8T} \qquad \text{(A.2. 1)}$$

And $$l = L + \frac{8S^2}{3L} \qquad \text{(A.2. 2)}$$

Where:

- T is the tension in the conductor
- w is the load on the conductor and is made of w_c (conductor weight) and w_w (wind load, in the presence of wind). These quantities are linked by the equation $w = \sqrt{w_c^2 + w_w^2}$ (If there is no wind $w=w_c$)

Changes in conductor temperature (from t_1 to t_2) and in tensions (from T_1 to T_2) result in the extension or the contraction of the conductor. These can be expressed by:

$l \times \alpha \times (t1 - t2)$ and, $l \times \frac{(T1 - T2)}{AE}$ where A is the conductor total area (mm^2), E is the Young's modulus of elasticity and α the coefficient of linear expansion.

Guile and Paterson (1981) showed that these changes are linked to tensions and loads on an overhead conductor suspended on span of length L by the following relation:

$$\frac{L^2}{24}[(\frac{w_1}{T_1})^2 - (\frac{w_2}{T_2})^2] - \frac{(T_1 - T_2)}{AE} - \alpha(t_1 - t_2) = 0 \qquad \text{(A.2. 3)}$$

The subscript 1 refers to an initial set of conditions generally specified in regulations, So w_1, t_1 and T_1 are the load on the conductor, the conductor temperature and the tension in the conductor at this particular condition.

The subscript 2 refers to another set of conditions (temperature, wind pressure, tension) for example erection conditions or the conditions leading to the maximum sag.

In particular, this equation can be used to calculate the ground clearance span of an overhead line by specifying conditions as follow:

- Condition 1 is taken according to specifications (minimum temperature, no wind and $T_1 \leq$ 25% of UTS of the conductor) [SABS 0280, 2001]
- Condition 2 corresponds to the maximum sag requirements (maximum temperature and no wind). At this temperature, the increased sag should not reduce line clearance to a dangerous point.

In the purpose of calculating the ground clearance span, equation (A.2.3) can be modified as follow:

As the maximum sag is expected to be reached at maximum temperature with no wind, w_2=w_c (conductor weight), and, $S = \frac{wc \times L^2}{8T_2}$ or

$$T2 = \frac{wc \times L^2}{8S} \qquad \text{(A.2. 4)}$$

.

Thus the expression $(\frac{w_2}{T_2})^2$ in equation (A.2.3) becomes $(\frac{8S}{L^2})^2$

And the equation (A.2.3) can be written as

$$\frac{L^2}{24}[(\frac{w_c}{T_1})^2 - (\frac{8S}{L^2})^2 - \frac{(T_1 - \frac{w_c L^2}{8S})}{AE} - \alpha(t_1 - t_2) = 0 \qquad \text{(A.2. 5)}$$

For a particular overhead line wc, α, A, E, and T1 are conductor characteristics. The maximum sag S is related to the pole arrangement.

It is the vertical distance between the lower conductor and the minimum height imposed by regulations.

Solving this equation using Matlab or Excel gives the maximum ground clearance.

A program for calculating the ground clearance span and an example of calculation for a 3/3.0 copper conductor on 10m pole with maximum sag of 1.45m is shown at the end of this appendix.

For ACSR conductors of the same composition (example 6/1 conductors: 1 steel core and 6 aluminum strands) the ratio $\frac{w_c}{A}$ (N/m/mm^2) is constant and equal to 0.0341 for 6/1 conductors and 0.055 for 3/4 conductors (Bantam, Magpie).

At low tensions in the conductor (such as 25% UTS) the aluminum strands are slightly loose on the steel core and the conductor stretches as if it consisted of the steel core alone. [Cissna, 1969]

In order words at low tensions most of the load is on the steel strand.

The fibre stress $f_1 = \frac{T_1}{A}$ is thus approximately same for such conductors

Equation (A.2.3) can be further modified using the stress in the conductor instead of the tension T_1.

The expression $(\frac{w_1}{T_1})^2$ becomes $(\frac{w_c}{Af_1})^2$

Introducing $T_2 = \frac{w_c L^2}{8S}$ in the expression $\frac{T_1 - T_2}{AE}$ and taking $T_1 = Af_1$ leads to

$$\frac{T_1 - T_2}{AE} = (\frac{f_1}{E} - \frac{w_c L^2}{8AES}) \qquad \text{(A.2. 6)}$$

And finally the general equation can be written as

$$\frac{L^2}{24}[(\frac{wc}{A \times f1})^2 - (\frac{8 \times S}{L^2})^2] - (\frac{f1}{E} - \frac{wc \times L^2}{8 \times A \times E \times S}) - \alpha(t1 - t2) = 0 \qquad \text{(A.2. 7)}$$

Solving this equation for L and for conductors of the same composition gives the maximum ground clearance span for all conductors of that composition.
An example of program and calculation for ACSR 6/1 conductors on 11m poles and maximum sag of 2.35m are given at the end of this appendix.

<u>Matlab program and results of the calculation of the ground clearance span for a 3/3.0 copper conductor on 10m pole with maximum sag of 1.45m.</u>

Program

```
T1= input ('enter tension value:');
omega1=input('enter load1 value:');
t1=input('enter temperature1:');
t2=input('enter temperature2:');
s=input('enter maximum sag:');
omega2=input('enter load2 value:');
alpha=input('enter coefficient of linear expension:');
E=input('enter initial modulus of elasticity:');
A=input('enter total area:');
accuracy=0.00001;
Max=input('enter maximum lenght:');
disp(['    L' '    value'])
for L=10:1:Max
   value=((L^2)/24)*((omega1/T1)^2-(8*s/L^2)^2)-alpha*(t1-t2)-(T1-
(omega2*L^2)/(8*s))/(E*A);
   disp([L value])
   %if value <= accuracy
     % disp([L value])

     %end
end
disp('fin du programme')
```

Results

```
>> span2
enter tension value:2146
enter load1 value:1.8639
enter temperature1:6
enter temperature2:60
enter maximum sag:1.45
enter load2 value:1.8639
enter coefficient of linear expension:0.000017
enter initial modulus of elasticity:124000
enter total area:21.20
enter maximum lenght:200
   L    value
  10.0000   -0.0560

  11.0000   -0.0462

  12.0000   -0.0388

  13.0000   -0.0331

  14.0000   -0.0285

  15.0000   -0.0248

  16.0000   -0.0218

  17.0000   -0.0193

  18.0000   -0.0172

  19.0000   -0.0154

  20.0000   -0.0139

  21.0000   -0.0126

  22.0000   -0.0114
```

Calculations continue up to L=200m

Matlab program and results of the calculation of the ground clearance span for ACSR 6/1 conductors on 11m poles and maximum sag of 2.35m

Program

```
Omega = input('Omega:');
A = input('A:');
f1 = input('f1:');
S = input('S:');
E = input('E:');
Alpha = input('Alpha:');
t1 = input('t1:');
t2 = input('t2:');
Max = input('Max:');
disp('     L')
for L=10:Max
   value = ((L^2)/24)*((Omega/(A*f1))^2-(8*S/L^2)^2)-((f1/E)-
(Omega*L^2)/(8*A*E*S))-Alpha*(t1-t2);
   disp([L value])
end
```

Results

```
>> span3
Omega:0.8358
A:24.48
f1:77.29
S:2.35
E:80400
Alpha:0.00001931
t1:6
t2:60
Max:200
    L
  10.0000   -0.1472

  11.0000   -0.1216

  12.0000   -0.1022

  13.0000   -0.0871

  14.0000   -0.0750

  15.0000   -0.0654
```

16.0000	-0.0574
17.0000	-0.0509
18.0000	-0.0454
19.0000	-0.0407
20.0000	-0.0367
21.0000	-0.0333
22.0	-0.0303

Calculations continue up to L=200m

APPENDIX 3

This appendix gives equations and values for the inductance and the capacitance of a SWER line built with small size conductors (bantam, squirrel, magpie, fox and hare). It also considers the length of SWER lines under different values of voltage-drop limit.

SWER Inductance.

For a transposed tri-phase overhead line with aluminum or copper conductors, under a supply frequency of 50 Hz, the inductive reactance is given by:

$$X = 314 \times (0.5 + 2\ln\frac{GMD}{GMR}) \times 10^{-7}\,\Omega / km \qquad \text{(A.3. 1)}$$

Where: (GMD) is the mean interphase distance and (GMR) is the conductor mean radius.

For a SWER line there is only one conductor and the GMD generally equal to $\sqrt[3]{d_{12} \times d_{23} \times d_{31}}$ is determined by the distance between the overhead conductor and the earth return imaginary conductor (d_{12}, d_{23}, d_{31} are the distances between conductors in the case of a tri-phase line).

Guile and Paterson, (1981) showed that this distance is function of the soil type and, for a supply frequency of 50 Hz, the distance is approximately equal to:

$$De = 93\sqrt{\rho} \qquad \text{(A.3. 2)}$$

(where ρ is the soil resistivity in Ω-m and can be taken at 1200 Ω-m for the worst soil conditions). [Eskom, 2001]

This leads to the distance “De” being 3222m.

It follows that the inductive reactance per phase is:

$$X = 314 \times (0.5 + 2\ln\frac{De}{GMR}) \times 10^{-4}\,\Omega/km \qquad \text{(A.3. 3)}$$

Using the data above, inductive reactance for some ACSR conductors can be calculated as in table A.3.1

Conductor	Radius (m)	GMR (m)	2lnDe/GMR	X (Ω/km)	R (Ω/km)
Bantam	0.002515	0.0018241	28.7688	0.9190	4.303
Magpie	0.003175	0.0023028	28.3027	0.9044	2.707
Squirrel	0.003165	0.0022962	28.3085	0.9045	1.3677
Fox	0.004185	0.0030362	27.7498	0.8870	0.7822
Hare	0.007080	0.0051365	26.6982	0.8540	0.2733

Table A.3.1: Inductances of a SWER line using small size conductors.

<u>SWER Capacitance.</u>

Guile and Paterson (1981) showed that the capacitance C (F/m) of an air insulated conductor to a perfectly conducting plane located h meters below it is given by

$$C = \frac{2\pi \times \varepsilon o}{\ln\frac{2d}{r}} \qquad \text{(A.3. 4)}$$

(where d is the distance between the conductors and εo the permitivity of free space).

This can be applied to the SWER case if the earth is considered as a perfectly conducting plane.

The permitivity of free space being 8.885×10^{-12}, the capacitance per km is equal to:

$$C = \frac{55.606 \times 10^{-9}}{\ln\frac{2h}{r}}$$

And the capacitive reactance

$$Xc = \frac{1}{wC} = \frac{\ln\frac{2h}{r}}{55.606\times10^{-9}}\times\frac{1}{2\pi f} \qquad \text{(A.3. 5)}$$

For the SWER line, the knowledge of the charging current is more important, thus it is adequate to state the line admittance instead of the capacitive reactance.

Table A.3.2 below gives the admittance B (in micro mho/km) for different ACSR conductors and different attachment heights.

Conductor	Radius (m)	Admittance(micro-mho/km)		
		9m	10m	11m
Bantam	0.002515	1.967	1.944	1.923
squirrel	0.003165	2.019	1.995	1.973
magpie	0.003175	2.020	1.995	1.974
fox	0.004185	2.086	2.060	2.038
hare	0.007080	2.226	2.197	2.171

Table A.3.2: Admittances of a SWER line using small size conductors

<u>SWER Impedance and line length</u>

The resistance of a SWER circuit is of significant importance for voltage-drop calculation. This allows the determination of the line length under a given voltage drop limit.

The proper calculation takes the following elements into account:

- The line impedance (resistance and inductance)
- Earthing resistances at the isolation transformer and at the customer (distribution) transformer
- Impedances of the isolation transformer and the customer (distribution) transformer.

According to Gatta et al (2002) the return path of a SWER line has a much lower resistance than the resistance of usual distribution conductors and it can be calculated at $10^{-4}\times\pi^2\times f(\Omega/km)$. At 50 Hz this is equal to 0.05 (Ω/km) and can be neglected in many cases.

Using appropriate tools, Ferguson (1998) has shown that SWER line under 19.1kV with point loads of 25A (maximum) can be extended as shown in the table below.

Conductor	Point Load	
	5%ΔV	10%ΔV
Bantam	8	15
Magpie	14	28
Squirrel	27	53
Fox	41	82

Table A.3.3: Maximum lengths of SWER lines with point loads under 19.1kV.
[Source: Ferguson, 1998]

In rural areas up to 10% voltage drop can be allowed.

REFERENCES

Aberdare Power Cables (2003): Conductor costs. Private communication Tel: 021 555 2919.

Adjidjanou S (2000): "Rural electrification in Ghana" Proceedings of a rural electrification seminar in Libreville-Gabon, October.

Bartle A (2002): "Hydropower potential and development activities" Energy Policy, Volume 30 p1231-1239.

Bayliss CR (1999): "Transmission and Distribution, Electrical Engineering" Newness, Oxford.

Birol F and Malyshev T (2002) "Electrification against Poverty" Published by IEA (International Energy Agency), June.

Bisengo K (1992): "Energy in Central Africa, with special reference to Zaire" MSc Thesis, Energy Development and Research Center, University of Cape Town,

Chapman N (2001): "When one wire is enough" in Transmission and Distribution World, April. (www.tdworld.com) (08/09/2002)

Chard F (1976): "Electricity supply" Longman, London.

Cissna VJ (1969): "AC Power transmission" in Standard Handbook for Electrical Engineers, Fink, GD editor, 10th edition, Mc Graw Hill Book Company, New York.

Dingley CE (1988): "A Review of Electrification in Six Countries" University of Cape Town, Department of Electrical and Electronic Engineering, September

Eberhard A (2001): "Restructuring of the Electricity supply industry in South Africa: Building on international experience" Proceedings of the 18th Congress World Energy Council, Buenos Aires, October.

Eskom Statistical Yearbook (1995), published by Eskom Communications Services, Johannesburg

Eskom Statistical Yearbook (1996), published by Eskom Corporate Communication, Johannesburg

Eskom (2001): "Distribution Standard, Part 4: MV Reticulation, section 6; 19kV Single-wire earth return overhead reticulation, reference SCSASABBG"

Esterhuysen P (1997): "Africa at a glance" Africa Institute of South Africa, Pretoria.

Esterhuysen P (1998): "Africa A-Z, Continental and Country profiles" Africa Institute of South Africa, Pretoria.

Ferguson I (1998): Guide for the Use of SWER & MV Single-Phase Technologies. Eskom Training manual, Johannesburg.

Gatta FM, Iliceto F, Lauria S and Masato P (2002): "Analysis of unsymmetrical transmission-distribution systems. Application to Insulated Shield Wire Schemes" L'Energia Elettrica, Volume 79 No 5 September-October.

Gaunt CT (2003): "Electrification Technology and processes to meet economic and social objectives in Southern Africa" PhD Thesis, Department of Electrical Engineering, University of Cape Town, May.

Geldenhuys H (2003): "Single phase MV, SWER and LV electrification of rural areas" Energize, PIESA Special Issue, October, Johannesburg.

Girod J and Percebois J (1998): "Reforms in sub-Saharan Africa's power industries" Energy Policy Volume 26 No1 p21-32.

Gonen T (1988): "Electric Power Transmission System Engineering. Analysis and Design" John Wiley and Sons, New York.

Gourou P (1998): "The Democratic Republic of Congo Physical and social geography" in Africa South of the Sahara, 28th edition Europa Publications, London

Gower AH and Strachman MA (1991): "Maintenance of Cost-effective Electricity Reticulation in Townships" Proceedings of the Electrification of Developing Communities Workshop, SAIEE, 11-12 November.

Guile AE and Paterson W (1981): "Electrical Power systems" Vol 1 Pergamon Press, London.

IAE (2002): "World Energy Outlook 2002" Published by IEA (International Energy Agency) and OECD (Organization for Economic Co-operation and Development) Paris.

Inversin (1994): "New designs for rural electrification. Private sector experiences in Nepal" (www.panasia.org.sg/nepalnet/technology. 11/08/2002)

Inversin (2000a): "Reducing the cost of Grid Extension in Rural Electrification" World Bank, Report no 227/00, September.

Inversin (2000b): "Mini-grid design manual" World Bank Report 21364, September.

Jensen T and Beheim E (1999): "Congo, DRC, The Kaziba Project" in: The challenge of Rural Energy Poverty in Developing Countries, Case studies, World Energy Council, 1999, London.

Karekezi S and Kimani J (2001): "Power Sector reform in Africa", Proceedings of a Regional Policy Seminar, Afrepren, Nairobi, 24th-25th April.

Karekezi S and Kimani J (2002): "Status of power sector reform in Africa, impact on the poor". Energy Policy Volume 30 p 923-945, September.

Karekezi S and Kithyoma W (2002): Renewable Energy Strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa? Energy Policy Volume 30 p1071-1086, September.

Karekezi S and Majoro L (2000): "Improving modern energy services for Africa's urban poor" Energy Policy Volume 30 p1015-1028, September.

Karlson V and Mc Dade E (2000): "Sustainable Energy and Women", in Generating Opportunities, Case Studies on Energy and Women, UNDP, Publication E.00.III.B.2, New York. April

Kotze IA (2000): "The South African National Electrification Program, Past lessons and future prospects" Department of Mineral and Energy, Pretoria.

Kristoferson LA and Bokalders V (1991): "Renewable Energy Technologies, Their Applications in Developing Countries" The Royal Swedish Academy of Sciences and the Beijer Institute, Intermediate Technology Publications.

Kutelama D (2004): "Technology for an isolated network in Congo, a case study" Paper presented at Saupec-04 Stellenbosch, 22-23 January 2004

Lamech R and Saeed K (2003): "What international Investors look for when investing in developing countries. Results from a survey on International investors in the power sector".
World Bank, Energy and Mining Sector Board Discussion Paper No 6, May.

Mehta VK and Mehta R (2003): "Principles of Power Systems" Chand and Company, Ltd, New Dehli-110055.

Menke C and Fazzari PG (1994): "Improving Electric Power Utility Efficiency, Issues and Recommendations" World Bank Technical Paper No 243, Washington, May.

Misser F (1998): "Economy of the Democratic Republic of Congo", in "Africa, South of the Sahara", 1999, 28th edition, Europa Publications, London.

NRS 033 (1996): "Guidelines for the application design, planning and construction of medium voltage overhead power lines up to and including 22kV using wood pole structures and bare conductors"

NRS 034-1 (1997): "Guidelines for the provision of electrical distribution networks in residential areas. Part 1: Planning and design of distribution systems".

Paish O (2002): "Small hydropower: technology and current status" Renewable and Sustainable Energy Reviews, Volume 6, Issue 6, p 537-556, December.

Pachauri RK (1991): "The role of electricity in economic development" Proceedings of Electrification of Developing Communities Workshop, SAIEE, 11-12 November.

Pachauri RK (2001): "Measuring and managing power sector reforms" in The Economic Times, 3 September (www.teriin.org 20/02/2004)

PIESA 001: (2001) "Specification for wood poles, cross arms and spacers blocks"

Ranganathan V (1992): "Rural Electrification in Africa" Zed Books Ltd, London.

SABS 753: (1994): "Pine poles, cross-arms and spacers for power distribution, telephone systems and street lighting" Published by the South African Bureau of Standards, Pretoria,

SABS 0280: (2001): "Overhead power lines for conditions prevailing in South Africa", Published by the South African Bureau of Standards, Pretoria, May.

Sanhvi A and Barnes D (2001): "Rural Electrification; Lessons Learned" World Bank, Report 22058, February.

SNEL (Societe Nationale d'Electricite), (2000) "1970-2000: 30 ans"
Published by SNEL for its 30th anniversary, Kinshasa.

Steyn G (1995): "Restructuring the South African electricity supply industry, Appropriate Governance in a Newly Democratised South Africa". Utilities Policy Volume 5 No 2 p95-108.

Tewari D and Shah T (2003): "An Assessment of South African prepaid electricity experiment, lessons learned, and their implications for developing countries". Energy Policy Volume 31 p 911-927.

Tremolet S and Neale J (2002): "Emerging Lessons in Private Provision of Infrastructure Services: Water and Electricity Services in Gabon" World Bank report no 8524, September.

Turkson J and Wohlgemuth N (2001): "Power sector reform and distributed generation in sub-Saharan Africa" Energy Policy Volume 29 p135-145

Turkson J (1998): "The Electric Utility Industry: Path to Restructuring in Sub-Saharan Africa" Proceedings of 17th Congress of World Energy Council, Houston, September.

UNDP (1999): "Energy as a tool for sustainable development for African, Caribbean, and Pacific countries" The United Nations Publications, Report no 99-III-B-45, New York.

Vellut JL (1983): "Mining in the Belgian Congo" in History of Central Africa, Volume 2, Longman, London.

Wamukonya N (2003): "Power Sector Reform in Developing Countries: Mismatched agendas", Energy Policy Volume 31, p 1273-1289.

WEC (World Energy Council) (2001): Survey of Energy Resources 2001/Hydropower" 19th Edition London.

Woodline Timber Industries (2004): Wood pole costs. Private communication Tel: 021 903 2181.

World Bank (1975): "Rural Electrification", Report No PUB-517, Washington, October.

World Bank (1986): "Zaire, Issues and Options in the Energy sector". Report of the joint UNDP/World Bank Energy Sector Assessment Program; Report no 5837-ZR, Washington, May.

World Bank (1989): "Burundi, Rwanda, Zaire: Evaluation of L'Energie des Pays des Grands Lacs" Report No ESM 9889, February.

World Bank (1992): "Burundi, Issues and Options in the energy sector" Report No 9215-BU, Washington, January.

World Bank (2001): “Peri-urban electricity consumers. A forgotten but important group: What can we do to electrify them?” Energy Sector Management Program, Report No 249/01, Washington, October.

World Bank (2002a): “Bangladesh Rural Electrification and Renewable Energy Development” Project No BDPE 71794. Washington, June.

World Bank (2002b): “Congo, DRC Emergency Multisector Rehabilitation and Reconstruction Program”. Report No T7551, Washington, June.

World Bank (2002c): “Mozambique, Energy Reform and Access” Project MZPE69183, Washington, April.

World Bank (2003) “Congo (DRC), Private Sector Development and Competitiveness”. Project P071144, Washington, June.

Zomers AN (2001): Rural Electrification” PhD Thesis, University of Twente, Netherlands.