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TRANSMISSION GRID EXPANSION CONSTRAINTS IN UGANDA: GOING BEYOND THE STANDARD SOLUTION

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Dissertation presented in fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

Department of Electrical Engineering

University of Cape Town

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Supervised by: Prof. CT. Gaunt

DECLARATION

I declare that this postgraduate dissertation is my own work. All sources that I have used or quoted have been indicated and acknowledged in the references. This work has not been submitted to any other university for any other degree or examination.

Stephen Mugisa

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DEDICATION

To

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ABSTRACT

There is a strong call for increase in transmission capacity to meet the increasing electricity demand and to interconnect new power generation plants. This requires a corresponding increase in transmission investment. In addition to being very expensive, transmission grid expansion is further hindered by environmental, social and political constraints. These constraints have slowed down transmission grid expansion in Uganda. This dissertation proposes the use of different transmission technology options as demonstrated elsewhere and quality decision making to minimize constraints faced by transmission grid expansion. In contrast to traditional planning that assesses alternative planning solutions by finding a solution with least cost, the proposed methodology considers all conflicting and multiple objectives faced by grid expansion by the use of a multi criteria decision making (MCDM) model. The method further acknowledges uncertainties that are usually ignored. The planning and decision making approach developed in the dissertation is tested with a practical example, by comparison with the literature and in discussions with Ugandan transmission planners. The results consistently indicated that the approach developed would have advantages and improve transmission planning.

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ACRONYMS

AC	Alternating Current
ACRS	Aluminum Conductor Steel Reinforced
AfDB	African Development Bank
AHP	Analytical Hierarchical Process
CBP	Corporate Business Plan
CIGRE	International Council on Large Electric Systems
DC	Direct Current
DMs	Decision Makers
EAPP	East African Power Pool
EIA	Environmental Impact Assessment
EMF	Electromagnetic Fields
EENS	Expected Energy Not Supplied
ERA	Electricity Regulatory Authority
FACTS	Flexible Alternating Current Transmission Systems
FV	Future Value
HV	High Voltage
HVDC	High Voltage Direct Current
GIL	Gas Insulated Line
GIP	Grid Investment Plan
GoU	Government of Uganda
GWh	Giga Watt Hours
HTS	High Temperature Superconducting
IGBTs	Insulated Gate Bipolar Transistors

KPLC	Kenya Power and Light Company
kV	Kilo Volts
LCC	Line commutated converter
MCDM	Multi-criteria Decision Making
MTN	Mobile Telecom Network
MoFPED	Ministry of Finance, Planning and Economic Development
MW	Mega Watts
NDP	Nation Development Plan
NEMA	National Environment Management Authority
OHLs	Overhead Lines
PFC	Power Flow Controlling
PSIP	Power Sector Investment Plan
PV	Present Value
RALF	Regression Analysis Load Forecast
REA	Rural Electrification Agency
RES	Renewable Energy Sources
ROC	Rank Order Centroid
ROW	Right Of Way
SMART	Simple Multi-Attribute Rating Technique
TA	Technology Assessment
TEP	Transmission Expansion Planning
TSO	Transmission System Operator
UEB	Uganda Electricity Board
UETCL	Uganda Electricity Transmission Company Limited

UBOS	Uganda Bureau of Standards
VSC	Voltage Source Converter
WB	World Bank

1 INTRODUCTION

1.1 OVERVIEW OF THE RESEARCH

The transmission system is one of the major parts of the electric power industry. It provides a linkage between the generation and distribution. As such, it is essential for a secure supply of electricity energy to the customer and enables a sustainable market for electrical energy. It also has to keep pace with the increase in demand and new generation. Investment to maintain and further develop the transmission grid is therefore required.

The electrical transmission industry in any country is highly capital intensive and involves investments of hundreds of millions of dollars. The developers of electricity transmission systems have to make investment decisions for an uncertain future. The investments have to meet various requirements, including flexibility, reliability and capacity for growth, and still yield an economic return. The decisions made in the planning and design stages determine how effectively these needs will be met. A good transmission plan is, therefore, always essential [Lee et al, 2006].

Technological progress over the last few decades has been so rapid that planners in the electricity supply industry are now confronted by an assortment of alternatives in their quest to accommodate growing demand for electricity. To compound this problem, it is no longer sufficient to limit consideration to the traditional primary objective of cost minimization and reliability of supply. Increasing concerns over political preference, social issues and environment issues have stimulated a paradigm shift in planning for the industry. Decision makers not only have to assess a wide range of transmission technology options, requiring extensive technical knowledge, but also have to deal with multiple, and often conflicting, objectives [Mills et al, 1996]. Achieving an optimal mixture of appropriate solutions for future electricity needs is a difficult and complex task. Traditional methods for determining choices are no longer adequate and a more powerful tool is required to cope with the paradigm shift [L'Abbate, 2010].

Currently, in Uganda, there is a strong call for increase in transmission capacity which directly implies increase in transmission investment [UETCL, 2012 and UETCL, 2008]. In addition to being very expensive, transmission grid expansion in Uganda is further troubled by environmental, social and political constraints. According to Buijs et al [2010] these constraints cause many transmission projects to be delayed or even cancelled. In fact, for the case of Uganda, there has been minimal transmission investment in the last three decades [UETCL, 2008].

AC overhead lines (OHL) are the standard solution for transmission grid expansion. It can be argued that different technology options can overcome or minimize many of the constraints that AC OHLs face. Additionally, it can be illustrated that the higher investment costs for some solutions can be offset with an increased benefit e.g. by accomplishing investments with shorter delays due to fewer constraints encountered [L' Abbate et al, 2010]. Therefore, choosing an appropriate transmission technology can be a solution to overcoming and/or minimizing constraints faced by grid expansion.

That said, a good transmission planning process that can deal with the multiple conflicting objectives and uses appropriate transmission technology would be vital. This is because it will avoid or minimize some of the constraints in the early stage of the process and thus improving project success.

1.2 UGANDA

Uganda, officially the Republic of Uganda, is a landlocked country in East Africa. Its beautiful and diverse landscapes make Uganda known as the pearl of Africa. Uganda is bordered on the east by Kenya, on the north by South Sudan, on the west by the Democratic Republic of Congo, on the southwest by the Rwanda, and on the south by Tanzania. The country is located between latitudes $4^{\circ}12'N$ and $1^{\circ}29'S$, and longitudes $29^{\circ}34'$ and $35^{\circ}0'E$ [UBOS, 2009].

According to the power system summary as monitored by Uganda Electricity Transmission Company Limited (UETCL) control centre for months of June and July 2012, the registered

maximum gross generation was 518 MW and the maximum domestic demand of 487 MW [UETCL, 2012].

In 2009, the demand had a 4% growth from the previous year and average load factor of 67% [UETCL, 2010].

According to ERA [2011], only 6-9% of the total population of Uganda has access to electricity, majority of whom live in urban areas. The system has 340,000 power customers, 4% transmission losses, 12% national access and 5% rural access.

Figure 1-1 shows the annual maximum demand from 1954-2012 [ERA, 2012]. From the graph, it is evident that Uganda has an increasing demand, and for the past 20 years the average load growth has been approximately 5.9%. This increase is largely driven by political stability, economic growth and population growth. The load values used to generate the graph are presented in Appendix A.

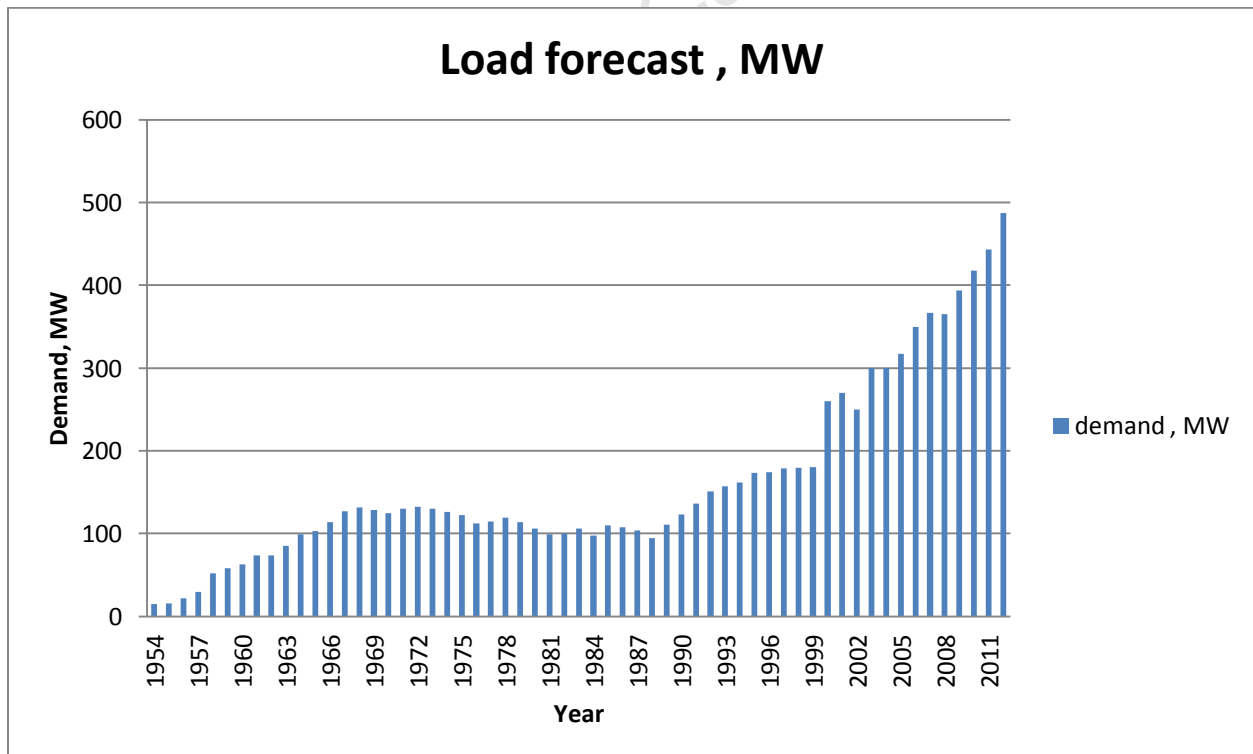


Figure 1-1: Annual maximum demand from 1954-2012

Limited access and use of electricity energy is also cited in the Uganda Nation Development Plan (NDP) for 2010/11-2014/15 as significantly slowing down economic and social transformation. The NDP focuses on increasing access and consumption of electricity by increasing power generation capacity, building new transmission lines, promoting renewable energy, accelerating rural electrification and promoting energy efficiency. In fact, Government of Uganda (GoU) has set a target of “electricity for all” by 2035 [GoU, 2010].

Uganda Electricity Transmission Company Limited (UETCL) released a 10-year Grid Investment Plan (GIP) 2008-2023 to meet the proposed programmes for system expansion, power evacuation from new power plants, re-investment projects and regional interconnection. The new power transmission plan aims at improving electricity transmission to meet national economic and social development objectives. The components of the projects include the construction of power transmission lines, construction of substations, resettlement and compensation and consultancy services [UETCL, 2010]. These investments are in line with the NDP 2010 and will contribute to the national vision of electricity for all by 2035.

Uganda in the last three decades has had minimal investment in transmission infrastructure and in fact in 2008, 80% of the overhead lines were more than 45 years old [UETCL, 2008]. Because of this, substantial new production is coming online as described in the GIP 2008-2023.

Table 1-1: Showing the 132kV transmission line network in Uganda, lengths and years when they were energized [ERA, 2009].

No.	Transmission line	Length, km	Year of commissioning
1	Nalubale-Kampala North	68.9	1954
2	Nalubale-Tororo 1	116.8	1954
3	Nalubale-Tororo 2	116.8	1954
4	Tororo- Kenya 1 (Uganda's part)	27	1954
5	Tororo- Kenya 2 (Uganda's part)	27	1954
6	Kampala North- Mutundwe	10.2	1959
7	Tororo-Opuyo	119.5	1963
8	Opuyo-Lira	141.2	1963
9	Mutundwe-Kabulasoke	84.7	1963
10	Kabulasoke-Nkongwe	78.5	1963

11	Kabulasoke- Masaka West	60	1963
12	Nkongge-Nkenda	138.9	1963
13	Masaka West-Tanzania	84.5	1991
14	Masaka West-Mbarara North	130.5	1995
15	Lugogo-Kampala North 1	5.7	1997
16	Lugogo-Kampala North 2	5.7	1997
17	Lugogo-Mutundwe	10.2	1997
18	Nalubale-Lugogo 1	70.2	1998
19	Nalubale- Lugogo 2	70.2	1998
20	Lugogo-Mutundwe	10.2	2008

A number of challenges to the grid investment plan (GIP) can be envisaged which could lead not only to delays but also cancellation of some projects. For example, the hydrological situation in Uganda (low water levels in Lake Victoria due the drought in 2005) led to substantial decrease in hydro generation and thus increases in power tariffs [UETCL, 2008]. UETCL was confronted with pressure from government to keep prices low thus having to postpone transmission investment because it did not have cost reflective tariffs. A summary of the challenges to grid expansion common to Uganda are:

- financial problems
- technical issues
- political issues
- environmental issues
- social opposition

The lack of transmission investment in the past and the need for it, have led to network congestions, which in turn lead to loss of reliability and network quality. This goes against one of UETCL's missions that is, "to dispatch, transmit quality and reliable bulk power in a viable and efficient manner [UETCL, 2011]." This has generally slowed down economic and social development of Uganda.

Buijs et al [2011], Albar et al [2007], and L'Abbate et al [2010], agree that the use of different transmission technologies other than AC overhead lines can minimize some constraints faced in transmission expansion. This could also find application in Uganda as discussed next.

1.3 TRANSMISSION TECHNOLOGIES

The dissertation discusses different transmission technologies that can boost transmission capacity and at the same time minimize transmission constraints. It goes further to discuss the possible application these technologies can find in Uganda. The focus lies on how they can contribute and how they are constrained in a country like Uganda. The following technologies will be considered:

- Installation of AC overhead lines
- Upgrading of existing assets
- Installation of underground cables
- Installation of controllable devices (FACTS)
- Installation of HVDC lines.

Knowing the technology option with the least obstacles, that is, not only cost effective but also fulfils the environment, technical, social, political and regulatory requirements, network planners can issue a quality decision. The choice will be made towards a more acceptable technology and this will lead to better timely project implementation. Therefore, the transmission expansion planning process in Uganda should include other transmission technologies as part of the alternative solutions and also ensure that all constraints are considered. In this light, a good transmission planning process will be essential. The next section gives an overview of transmission planning.

1.4 OVERVIEW OF THE PLANNING PROCESS

Willis and Scott [2000] defined planning as a process of identifying alternatives and selecting the best among them. They go further to segment the planning process into five steps as shown in the Figure 1-2.

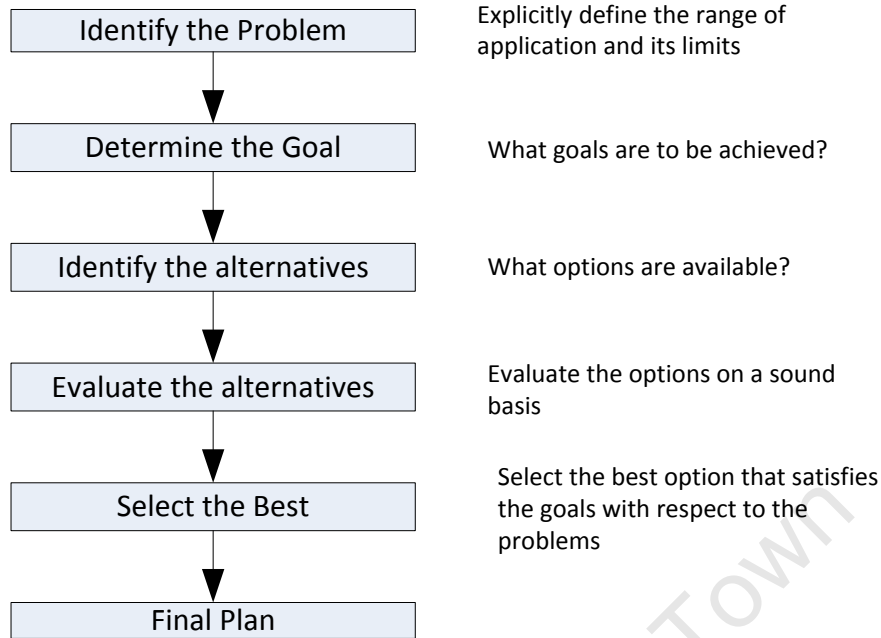


Figure 1-2: The general planning process [Willis and Scott, 2000]

Planning is a decision-making process that seeks to identify the available options and determine which is best. Applied to electric utility planning, the process seeks to identify the best schedule of future resources and actions to achieve the utility goal [Willis, 1997 and Gonen, 2000].

Transmission expansion planning is a complex decision making process and in addition to Figure 1-2, L'Abbate et al [2010] states that the transmission system operator (TSO) has to also plan the following:

- expansion of its network by minimizing transmission costs (investment and operation), overcoming bottlenecks and pursuing maximum social welfare,
- meeting static and dynamic technical constraints to ensure a secure and economically efficient operation,
- reliable integration of renewable energy sources (RES) that bring about additional uncertainties due to their rapid and less predictable flow changes,
- socio-environment constraints must also be taken into account,
- and must meet the requirement of the regulatory framework.

Therefore, the transmission planning process has to deal with multiple and often conflicting objectives. Each step and objective of the process is important and if poorly performed will lead to poor decision making, a poor plan and ultimately failure to attain the planning goals [Willis, 1997]. This calls for quality decision making.

1.5 QUALITY DECISION MAKING

The success of a project is directly related to the quality of the decision underlying the project. A quality decision can be defined as being, “well considered, justifiable and explainable” [Belton and Stewart, 2002]. Coherent and logical methodologies or approaches have been developed to aid project decision makers in making these quality decisions. These approaches should serve as intelligible, acceptable and exhaustive instruments of communication allowing conception, justification and transformation of the preference with the decision process [Roy, 1996].

Loken [2005] states that multi criteria decision making (MCDM) is a generic term for all methods that exist for helping people making decisions according to their preferences, in cases where there is more than one conflicting criterion. Using MCDM can be said to be a way of dealing with complex problems by breaking the problem into smaller pieces. After weighting some considerations and making judgments about smaller components, the pieces are then reassembled to present an overall picture to the decision makers. Therefore, this dissertation will use an appropriate MCDM model to assist in the planning process. The preceding discussions provoke the hypothesis defined in the next section.

1.6 HYPOTHESIS

The hypothesis that this dissertation addresses is:

Different transmission technology options as demonstrated elsewhere and quality decision making can be used to overcome or minimize constraints faced by transmission grid expansion in Uganda.

The research questions, listed below, are meant to lead to preliminary answers that will eventually be considered to test the validity of the hypothesis.

1.6.1 Research Questions:

1. What loads are expected in Uganda?
2. What technology options are being considered or used for grid expansion in Uganda?
3. What constraints are faced in the process of grid expansion in Uganda?
4. What other existing technology options can be used for grid expansion and how would they overcome these constraints?
5. How are the best choices identified?

The objective of this dissertation is to test the validity of the hypothesis.

1.7 RESEARCH METHODOLOGY

Research is an organized and systematic way of finding answers to the questions. In this dissertation, the following methodology is followed, with the aim of answering the research questions and eventually of course testing the validity of the hypothesis:

1) Search literature

This will be aimed at answering the research questions and is presented in Chapters 2 and 3. Chapter 2 identifies the loads expected, technology options being considered for grid expansion and the constraints being faced in Uganda. It goes further to identify how best choices are made to overcome or minimize these constraints. Chapter 3 identifies transmission technologies that will face fewer constraints and find application in Uganda as well.

2) Theory development

Chapter 4 describes the theory development by combining and applying techniques identified in the literature search. It proposes a process that can be used to improve on the comprehensiveness of the decision making and also uses different technologies that face fewer constraints in grid expansion as the alternative solutions.

3) Case study

Chapter 5 describes a case study on which the proposed process will be applied. In this case, an interconnection between Uganda and Kenya is analyzed.

4) Evaluation and results

Chapter 6 presents the evaluation process and the results. It also contains the interpretation of the results.

5) Evaluation of the planning process

Chapter 7 evaluates the proposed process based on some test questions used as a forum for discussion with power utility Engineers in Uganda.

6) Conclusion

Chapters 8 summarizes the answers to the research questions and assesses the validity of the hypothesis. It also states limitations of the dissertation and finally makes recommendations.

The next chapter is the literature review and it will focus on answering the research questions in line with what has been published.

University of Cape Town

2 LITERATURE REVIEW

2.1 BACKGROUND

Uganda is a developing country in East Africa. It has a population of approximately 30.7 million people and an annual population growth rate of 3.2%. In 2008, Uganda had a GDP of UGX 28 billion and a GDP growth rate of 8.3% per annum [UBOS, 2009]. Table 2-1 gives a summary of key characteristic of Uganda.

Table 2-1: Key characteristics of Uganda [UBOS, 2009]

Parameters	Value
Area	24,500.7 km ²
Population	30.7 million
Population Density	123 persons/km
GDP at market price	28,340 billion UGX
Capital city	Kampala
Official languages	English, Swahili
Urban population	14.80%
Life expectancy	50.4 years
Population growth	3.20%
GDP growth	8.30%
Inflation rate	12.10%
Currency	Uganda Shilling (UGX)
Agriculture	Cash crops: coffee, tobacco, cotton, corn, cassava (tapioca), potatoes, millet, cut flowers. Food crops: bananas, corn, cassava, potatoes, millet. Livestock and fisheries: beef, goat meat, milk, poultry, Nile perch, tilapia.
Natural Resources	Copper, Cobalt, hydropower, limestone, salt, phosphate, oil
Climate	Tropical: generally rainy with two dry seasons (December-February and June-August)

2.1.1 Overview of Uganda's power sector

In the past two decades, Uganda has had an increasing demand for power. This is evident from Figure 1-1 where the electricity demand has more than tripled (i.e. from 122.8 MW in 1990 to 487 MW in 2012).

Lavalin and Brinckerhoff [2011], as part of the ongoing Power Sector Investment Plan (PSIP) study, developed a demand forecast available for Uganda. The PSIP demand forecast projects demand for electricity over the period 2008 to 2038. The PSIP demand forecast is derived using PB's econometric based Regression Analysis Load Forecast (RALF) model. The base, high and low PSIP demand forecast is presented in Appendix B. From the forecast, although it is a bit inconsistent with the current demand, it is further evident that Uganda has an increasing demand for power.

This increase in the electricity demand can be directly linked to the increased rate of new connection in urban areas from 17,000 to 25,000 [UETCL, 2010] and rural electrification rate increased from 1% to 10% [REA, 2006].

Electricity demand in Uganda is further expected to increase due to intensified investment in industries that heavily rely on electricity. The Uganda Investment Authority (UIA) has indicated there are more than 62 projects especially in manufacturing that are in the pipe line and expect to be commissioned in 2013. Likewise, there is increased domestic and commercial connectivity as real estate businesses pick up. Agro processing is also on the rise and needs electricity to add value to the produces [Kasita, 2012].

Uganda is largely dependent on hydropower for its electricity needs. Drought in 2005 resulted in the deterioration in the hydrological condition in Lake Victoria, which in turn led to reduced generation. This created a power shortage in the country. To mitigate the problem Government of Uganda (GoU) introduced emergency power by using thermal generator [ERA, 2011]. According to the power system summary for the month of July 2012, the maximum average registered hydro power \approx 416 MW, thermal power \approx 70 MW and bagasse \approx 15 MW [UETCL, 2012]. Appendix C presents the installed capacities of current and future power options for Uganda.

Uganda also intends to keep renewable energy a substantial part of national energy consumption [ERA, 2009]. Uganda has considerable unexploited renewable energy resources for energy production and provision of energy services. For example it has a total hydro potential of approximately 2200 MW but currently only exploits 416 MW. These resources

include; biomass, geothermal, large scale hydro, mini/micro/pico hydro, wind, peat, and solar energy. The renewable energy potential of Uganda is shown in the Table 2-2 below [ERA, 2009].

Table 2-2: Renewable energy potential in Uganda [ERA, 2009]

Energy sources	Estimated Electrical Potential, MW
Hydro(mainly from the Nile)	2000
Mini Hydro	200
Solar	200
Biomass	1650
Geothermal	450
Peat	800
Total	5300

The limited access and use of energy is cited in the Uganda Nation Development Plan (NDP) for 2010/11-2014/15 as significantly slowing down economic and social transformation. The NDP focuses on increasing access and consumption of electricity by increasing power generation capacity, building new transmission lines, promoting renewable energy, accelerating rural electrification and promoting energy efficiency. In fact, GoU has set a target of “electricity for all” by 2035 [GoU, 2010].

2.1.1.1 Structure of the power industry

Prior to the power sector reforms, the Uganda Power sector was dominated by a public vertically integrated utility known as Uganda Electricity Board (UEB). In 1991, the GoU embarked on the power sector reform programme to unbundle UEB. The Electricity Act, 1999 CAP 145 provided legal frame work for the reforms. UEB was unbundled into 3 successor companies. These are:

- Uganda Electricity Generation Company Limited (UEGCL) that owns the generation assets
- Uganda Electricity Transmission Company Limited (UETCL) that owns and operates the transmission infrastructure

- Uganda Electricity Distribution Company Limited (UEDCL) that owns the distribution assets

An independent regulator, the Electricity Regulatory Authority was also established together with the Electricity Dispute Tribunal and the Rural Electricity Fund [ERA, 2010]. The following section discusses UETCL , the transmission system operator in Uganda.

2.1.1.2 Uganda Electricity Transmission Company Limited (UETCL)

UETCL is a Public Limited Liability Company established on March 26th 2001 as a result of the power sector reform and liberalization policy of the Government of Uganda that unbundled UEB into successor companies [UETCL, 2008]. The Company operates under policy guidance of the Ministry of Energy and Mineral Development and is owned by the Ministry of Finance, Planning and Economic Development (MoFPED).

Its vision is;

- to become a leading strategic business partner in the transmission and single buyer business and to support sustainable Energy Development in Uganda.

Its mission is:

- to dispatch, transmit quality and reliable bulk power in a viable and efficient manner
- to be an efficient and commercially focused single buyer actor
- to mitigate emergency power situations in Uganda

Some of the key stakeholders include:

- Government(Ministry of Energy, Ministry of Finance, REA, ERA, Parliament of Uganda)
- Donors(WB, NORAD, AfDB)
- Banks(Stanbic Uganda, CitiBank Uganda, Standard Chartered)
- Customers(UMEME, KPLC, Electrogaz, MTN Uganda and Uganda Telecom)

UETCL is a key national player in the power sector. It has the operational mandate that is divided into the single buyer business and transmission system operator. It therefore

undertakes bulk power purchases and sales, import and export of energy, operation of the High Voltage Transmission Grid and plays the national system operator role.

2.1.2 State of Uganda's transmission system

The transmission system is the backbone of the Uganda power system. The grid serves to transport electricity energy from the main generation sources located at Jinja to the load centre of Kampala (capital city) where approximately two thirds of the consumption is concentrated, and to the main district towns[UETCL,2012].

The transmission system consists of 1376 km of 132 kV, 38 km of 66 kV and 18650 km of 33 kV and 11 kV grid length and related substations [ERA, 2011]. The system is interconnected within the EAPP (East African Power Pool) with Kenya through its eastern part and will be interconnected with Rwanda through its south western part. The system also provides power to Bukoba in northern Tanzania. The single line diagram of the 132kV network is shown in Appendix D.

2.1.3 Transmission grid expansion in Uganda

The growth projection (i.e. demand growth) in Uganda justifies construction of new infrastructure like dams, substations and new power lines. Appendix E presents a map of Uganda showing the present and proposed future transmission network.

UETCL released a 15-year Grid Investment Plan (GIP) 2008-2023 to meet the proposed programmes for system expansion. The new power transmission plan aims at improving electricity transmission to meet national economic and social development objectives. The components of the projects include the construction of power transmission line, construction of substations, resettlement and compensation, and consultancy services [UETCL, 2008]. The GIP 2008-2023 projects were categorized as follows:

- Interconnection to new power plants
- System extension
- Regional interconnection projections
- Reinvestment projects

The objective of these projects is to build a robust network, enhance transfer capacity, improve reliability and quality of power supply, and provide capacity for regional power trade. This will in turn, contribute towards the GoU's strategic objective (i.e. economic and social development).

These projects will provide a back bone for the distribution and rural electrification extensions and will also enable East African Community member countries to exploit the enormous energy resources potential in the region.

UETCL intends to invest 419.4 million USD in grid expansion to provide adequate transmission infrastructure to meet to meet the load demand requirements in the coming years. This is hoped to lead to approximately doubling of the current transmission grid from the current 1400 km to approximately 2800 km of high voltage (HV) grid in regards to the corporate business plan (CBP) and to meet the company's mission and vision. This investment is also in line with the National Development Plan and will further contribute to the national vision of electricity for all by 2035[UETCL, 2012].

Uganda's power system grid expansion is inevitable because of increase in quality of life (due to increased use of technology and economic growth), population growth and government policy. This in turn has led to increased demand for electricity (evident in Figure 1-1), increase in generation and the finally need for transmission grid expansion.

The transmission system is one of the major parts of the electricity power industry. A good transmission plan is, therefore, always essential [Lee et al, 2006].

2.2 TRANSMISSION EXPANSION PLANNING

Electricity power transmission lines were initially built to link remote generating plants to load centres, thus allowing power plants to locate in regions that are more economical to do so. As systems grew, a meshed network of transmission lines emerged, providing alternative paths for power flows from generators to loads that enhance the reliability of continuous supply. In regions where generation resources or patterns of load demand are different, transmission interconnection eases the need for generation addition. Transmission addition is justified

whenever there is a need to connect cheaper generation to meet growing load demand, enhance system reliability, or both. The traditional primary objective of transmission expansion was linking generation to load and enhancing reliability in a cost effective manner [Wu et al, 2005].

Technological progress over the last few decades has been so rapid that planners in the electricity supply industry are now confronted by an assortment of alternatives in their quest to accommodate growing demand for electricity. To compound this problem, it is no longer sufficient to limit consideration to the traditional primary objective of cost minimization and reliability of supply. Increasing concerns over political preference, social issues and environment issues have stimulated a paradigm shift in planning for the industry. Decision makers not only have to assess a wide range of transmission technology options, requiring extensive technical knowledge, but also have to deal with multiple, and often conflicting, objectives [Mills et al, 1996].

2.2.1 Traditional transmission expansion planning

Traditionally, the transmission expansion algorithm is least cost planning. The primary objective of transmission and or grid expansion planning is to invest in transmission expansion technologies for purposes of cost effectively maintaining secure and efficient energy supply [Gross, 2005]. Bhowmick et al [2007] states that the purpose of transmission grid expansion planning is to identify a flexible, robust and implementable transmission system that reliably facilitates commerce and serves all loads in a cost effective manner. Keith et al [2008] writes that the major concerns of planning are; financial considerations, service quality and reliability. The transmission expansion has to comply with the electric energy demand and satisfy quality and reliability at a minimum cost [Kiessling et al, 2003]. It should also be robust and flexible to different future generation and load growth scenarios.

Reliability of meeting load demand is a constraint that must be fulfilled in transmission expansion, and the selection among those alternative expansion plans that meet reliability requirement is based on costs. Hence, transmission expansion planning may be formulated formally as an optimization problem, with cost minimization as its objective function and

reliability as a constraint. This is notwithstanding that both reliability assessment and cost evaluation involve complex analysis over the lifetime of the proposed expansion.

In summary, traditional transmission expansion planning faced mainly two constraints, financial and technical constraints. They are discussed in more details below.

2.2.1.1 Financial constraints

Several authors have written that the most cost effective alternative for transmission grid expansion must be selected. That is to say, the planning solutions that satisfy the basic electrical criteria are evaluated in a cost and present worth of investment analysis and annual losses are determined in order to obtain the most economical option. Economic feasibility and sensitivity analysis are carried out on the planning solutions, taking into account a cost-benefit evaluation comprising of investment, maintenance, availability of energy, load market and revenues, and losses and reliability benefits [Kiessling, 2003].

Transmission system operators (TSO) responsible for network expansion plans are required to minimize transmission costs (investment and operation). In fact, one of the UETCLs objectives is to promote least cost projects for power system development [UETCL, 2012].

Transmission infrastructure is highly capital intensive, and the returns are uncertain, so investors are reluctant to invest in the industry. Gross [2005] writes that one of the problems is that transmission is a regulated service and, as such, tariffs are cost based and not value based. Thus, there is uncertainty about the recovery of transmission investments due to factors, such as, the need for long-term revenue streams, lack of clarity in the regulatory policy and often-conflicting goals of federal and state regulators.

This is typical for Uganda since domestic sales price (bulk tariff) is set by the regulator (ERA) and approved by MoFPED [UETCL, 2008]. In a normal situation the tariffs should reflect the purchase and operating costs of UETCL, but this is not the case. For example, during the drought in 2005 that led to the increased use of thermal diesel generators, which in turn led to a substantial increase in the purchase cost. But UETCL has to keep prices low because of

pressure from government and thus not being able to cover the purchase costs. It therefore receives state subsidies to cover up the deficit [UETCL, 2008].

In this light, UETCL has to rely on funding from government and donors to maintain and further develop the transmission grid. In addition, Uganda being a developing country, government is more willing to fund cheaper projects because of limited financial resources, so, least cost projects are most desirable.

2.2.1.2 Technical constraints

Some of the technical barriers are a result of the objectives of transmission grid expansion. These objectives have already been described above. So these dictate that the transmission system expansion should maintain quality of supply, should also maintain or improve system reliability, should also be secure, and finally should be robust and flexible to meet the uncertainty that is involved.

The technical impact of the transmission expansion plan is assessed using detailed engineering models of the transmission system under worst-case scenarios to ensure that the system can perform reliably. Both steady-state and dynamic responses of the future power system are analyzed, usually under the assumption of the worst heavy loading conditions. Most serious disturbances on the system, such as three-phase short circuit faults and loss of generation, are postulated. Stability analysis is conducted, using detailed models of generators, transmission network and loads. The effect of loss of any single equipment (the so-called N-1 criterion) on power flows is assessed [Wu et al, 2006].

According to Kiessling [2003], the basic electrical design of an AC system involves the following technical studies: power flow requirements, system stability and dynamic performance, selection of voltage level and optimization studies, voltage and reactive power flow control, conductor selection, losses, corona performance (audible and television noise), electromagnetic field effects, reliability evaluation, insulation and overvoltage design, switching arrangements, circuit breaker duties and short circuit and protective relaying.

It is the role of UETCL as the TSO in Uganda to ensure that the technical requirements of the network are met and this is evident from the company mission.

2.2.2 Changing planning environment and new challenges to TEP

Transmission network planning is a very complex process and recent trends and challenges make it even more complicated. For the case of Uganda, before the electricity market liberalization, in a centrally managed power system the system operator (UEB) controlled the whole power system. The transmission network was then expanded with the aim to minimize both generation and transmission costs, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

Nowadays, in a liberalized environment, UETCL (i.e. the TSO in Uganda) is solely responsible for transmission, and plans the following:

- expansion of its network by minimizing transmission costs (investment and operation), overcome bottlenecks and pursuing maximum social welfare,
- meeting static and dynamic technical constraints to ensure a secure and economically efficient operation,
- reliable integration of renewable energy sources (RES) that bring about additional uncertainties due to their rapid and less predictable flow changes,
- socio-environment constraints must also be taken into account,
- and must meet the requirement of the regulatory framework.

UETCL being government (i.e. MoFPED) owned faces additional political interference thus making transmission planning in Uganda even more complex.

While traditional optimization and simulation models have been applied successfully for a variety of generation expansion planning and integrated resource planning studies, it is now gradually being recognized that identifying a minimum-cost plan under a particular series of constraints is not sufficient [Millis, 1996]. Many other aspects, such as environmental impact and social-political concerns, may be of equal importance as the cost minimization objective. Furthermore, the influence of various uncertainty factors on the outcomes of different planning

strategies must be carefully examined because these may significantly affect the system performance if the plans are not designed with adequate level of flexibility or robustness to the possible changes from the base assumptions.

Kiessling et al [2003] stated that land use and availability of right of way, availability of licenses and legal obstructions, environmental factors, new technologies and financial aspects would assume greater importance for transmission projects in the future. Keith et al [2008] also includes environmental impact and public image as major concerns of planning. These new challenges are discussed below:

2.2.2.1 Political or institutional barriers

Political and institutional barriers encompass the barriers caused by the TSO, regulators, donors, investors and government.

Regulatory controls vary from country to country but they generally present common features and similarities regarding obtainment of approvals and licenses. So, depending on the country, these authorizations procedures and legal frame works take too long and are considered as barriers [Buijs et al, 2011]. Some of the reasons underlying the failing procedure and legal frame work are; problems of convincing the public of the usefulness of a project and procedures can be badly designed. These can inherently result in long delays. For the case of grid interconnection projects, delays will be brought about by lack of harmonized procedures and technical requirements. The process is furthermore a time consuming process because the decision makers are spending tax payers' money and so, public processes are used to try to arrive at the best decision.

In developing countries, services like electrification are often treated as commodities to be used as rewards to politically friendly communities and denied those that are politically hostile. Therefore, in this case, political support is very crucial for project support otherwise the project may not be approved [Bekker and Gaunt, 2006]. UETCL being wholly owned by government falls victim to a kind of political interference. For example, due to the current hydrological situation in Uganda, there has been a substantial increase in tariffs. UETCL has been confronted

by government to keep prices low, meaning that it doesn't have cost reflective tariffs, thus having to postpone transmission investment. In addition to this, whoever controls the funding, that is, either government or donors influence which projects are accepted and can also further influence the consultants and contractors used for the projects. That said, political and/or donor support is very essential especially in developing countries.

Akampurira et al [2009] identified; corruption, protracted negotiations, withdrawal of project developers, non-transparent processes, low level of skill in the public sector and lengthy bureaucratic processes as being among the factors constraining the implementations of projects in Uganda electricity sector.

2.2.2.2 Environmental impact assessment (EIA)

Currently, environmental aspects are becoming more and more important, thus leading to more opposition from environmentalist bodies. They also increase cost and implementation time of transmission projects [Abbate et al, 2010].

Buijs et al [2010] continue to say that environmental issues are some of the barriers that need to be overcome in the process of grid expansion. Studies carried out by Cigre show that practically all countries require environmental impact studies for constructing a new overhead line [Cigre SC22 WG 14, 2000]. Environmental constraints cover statutory requirements, utility policy with regard to environmental matters and also public and private views and concerns [Kiessling, 2003].

When planning the construction of new transmission lines, several environmental aspects have to be taken into account. Lavalin and Brinckerhoff [2011], identified some potentially significant environmental risks and impacts, and these are: soils and geology, water environment, air quality, ecology, noise, land use, socio-economic, health and safety, cultural heritage and electromagnetic fields.

EIA is a process of analyzing the positive and negative effects of a proposed project, plan, or activity on the environment. This may include studies on the weather, flora and fauna, soil, human health including physical, social, biological, economic and cultural impacts. It is one of

those measures taken to ensure that development is sustainable. An EIA should be conducted before the commencement of a project. By studying the possible impact that the project may have on the environment, it is possible to eliminate or avoid adverse impacts or costs that would be met after damage by either redesigning the project or by taking mitigation measures. EIA must be exhaustive and comprehensive and must give due consideration to all alternatives including the "no action" alternatives [Kakuru et al, 2001].

Ingredients of the "environment" as reflected in most legislation include [Gilpin, 2000]:

- all aspects of the surrounding of human beings, whether affecting human beings as individuals or in social groupings
- natural resources including air, land, and water
- ecosystems and biological diversity
- fauna and flora
- social, economic and cultural circumstances
- infrastructure and associated equipment
- any solid, liquid, gas, odour, heat, noise, vibration, or radiation resulting directly or indirectly from the activities of human beings
- identified natural assets such as natural beauty, outlooks, and scenic routes
- identified natural historical and heritage assets
- aesthetic assets
- public health characteristics
- identifiable environmental planning, environmental protection, environmental management, pollution control, natural conservation, and other mitigation measures.

This is consistent with its categorization as natural environment and social environment [Harunari et al, 2002]. Natural environment includes influence on precious animals and plants, while social environment includes cultural property, community development and environmental issues from the residents. For the natural preservation, there is need to carry out the influence evaluation about plants, birds, amphibians, insects, the quality of water and tree restoration in the construction site. For the social environment preservation, there is need

to carry out the influence evaluation about noise from helicopter and construction work, obstacle to radio wave, wind noise, corona, and electromagnetic fields.

Grid expansion incorporates construction through open spaces and potentially populated areas. High voltage transmission lines will require construction of: foundations, suspension towers, conductors and insulators, together with associated fittings, accessories and diagnostics. Transmission lines have the nature to affect the environment in many ways and impacts differ greatly between projects and sites. The length of a transmission line will depend upon the requirements of supply and delivery of electricity and therefore the zone of influence will be project specific with regard to the environment and social impact assessment.

This usually calls for specialists to carry out an accurate and objective environment impact assessment and present it in due time to authorities in charge for approval. Good industrial practice would see the EIA done early in the planning stage such that the mitigation of any potential significant impact can be, as far as is practical, incorporated into the project design.

In Uganda, the National Environment Management Authority (NEMA) is a semi-autonomous institution, established in May 1995 under the National Environment Act CAP 153 and became operational in December 1995, as the principal agency in Uganda, charged with the responsibility of coordinating, monitoring, regulating and supervising environmental management in the country. NEMA advises Government and spearheads the development of environmental policies, laws, regulations, standards and guidelines; and guides Government on sound environmental management in Uganda [NEMA, 2011]. NEMA requires an 'Environmental Impact Assessment '(EIA) for electrical infrastructure i.e. generation stations, transmission lines, electrical substations and manufacturing storage schemes [UETCL, 2008; Kakura et al, 2001].

In addition to this, the Third Schedule of the National Environment Act, Cap 153 (section 10(a), (b), (c): "Electrical infrastructure including electricity transmission lines and substations.") requires transmission projects to undertake an EIA. In addition, national laws (Constitution, 1995; Land Act; 1998) require that the impact on private property should be compensated and affected persons resettled before commencing project development. Systematic implementation of this requirement necessitates a Resettlement Action Plan (RAP). Against this

background, UETCL contracted SMEC international limited in association with AWE environmental engineers to undertake EIA and RAP studies for the proposed power line [AWE and SMEC, 2008].

Due to the population growth and environmental restriction particularly due to the forest coverage, right of way (ROW) for the construction of transmission lines is gradually becoming more and more difficult. Akampurira et al. [2009], identified 'resistance from environmental groups' as being among the top constraints to development and implementation of private public partnerships in the Uganda electricity sector.

2.2.2.3 Social barriers

These are characterized by opposition from the locals to construction of new transmission projects. They are brought about by fear of EMF effects on health, visual impact of the transmission lines, depreciation of land and limitation of land use. These lead to the NIMBY (Not In My Backyard) phenomenon. The European Transmission System Operators (ETSO¹), identified that most projects encountered obstacles related to NIMBY phenomenon in the Priority Interconnection Plan (PIP) in 2007 and that they impeded new investments in transmission lines [Buijs et al., 2011].

For the case of HV transmission lines that serve an entire zone or country, the locals further oppose their constructions because they don't directly benefit from them. HV lines transmit bulk power to distant areas and there are cases where lines pass through areas that are not receiving grid power. In Uganda, some of the electricity transmission equipments are vandalized by the locals as a means of opposing construction of transmission lines [UETCL, 2012]. This slows down project implementation and can also lead to project failure.

These new challenges (constraints) bring out the need for compromise among conflicting objectives; the need to satisfy financial, reliability and environment constraints and uncertainty acknowledgement. Therefore, the transmission expansion problem now has multiple conflicting objectives or attributes and there is no single solution that simultaneously optimizes all of

¹ recently transformed to ENTSO-E

them. A compromise is usually achieved that represents a reasonable trade-off among the attributes. The problem requires a model that can cope with the complexity of this decision making process. The model needs to be able to evaluate different options against a number of performance measures and according to a range of objectives.

Achieving an optimal mixture of appropriate solutions for future electricity needs is a difficult and complex task. Traditional methods for determining choices are no longer adequate. On top of this, there is a strong call for increase in transmission capacity but the transmission grids are facing investment challenges, public opposition, a complex regulatory framework, environmentalist opposition, political interference and technical limitations. These complexities and constraints faced in the process lead to delays and sometimes cancellation of transmission grid projects. This further leads to a mismatch between generation and demand growth and transmission grid expansion i.e. the grid expansion is not able to keep pace with the increase in demand and new generation. In reality, transmission investments specifically in Uganda are lagging behind.

In this respect, the dissertation looks into the possibility of minimizing these constraints faced in transmission grid expansion by using transmission technologies that minimize constraints and improving on the decision making process by considering all the constraints faced. Buijs et al [2011], Albar et al [2007], and L'Abbate et al [2010], agree that the use of different transmission technologies other than AC overhead lines can be a solution to minimizing constraints faced in transmission expansion planning.

2.3 TRANSMISSION TECHNOLOGIES

AC overhead lines are the standard solution for grid expansion; it can be argued that different technology options can overcome many obstacles that proposals for OHLs face. Additionally, it can be illustrated that the higher investment costs for some solutions can be offset with an increased benefit e.g. by accomplishing investments with smaller delays due to fewer obstacles encountered. To overcome or minimize some of the obstacles faced, selection of an appropriate technology would be vital in the transmission planning process [Buijs et al, 2011].

Chapter 3 has a detailed discussion of transmission technology that can be used to enhance transmission capacity, the constraints they minimize in the process of transmission grid expansion and their possible application in Uganda.

2.3.1 Technology Assessment

Technology assessment (TA) would enable the network planner to know the technology option that faces least obstacles, that is, not only cost but also environment, technical, social, political and regulatory requirements. Therefore, making a proactive decision towards a more acceptable technology and this will lead to better timely project implementation [Buijs et al, 2011]. The best technology will be one with least barriers to grid expansion. It is also highly important to make decisions in the early stage of technology development since there are many uncertainties.

Technology assessment is a concept that offers opportunities for the improved public policy and decision-making. Emilio Q. Daddario [1967] articulated this concept about 40 years ago. He described technology assessment as;

A form of policy research that provides a balanced appraisal to the policymaker. It identifies policy issues; assesses the impact of alternative courses of action, and presents findings. It is a method of analysis that systematically appraises the nature, significance, status, and merits of the technological program. It is designed to uncover three types of consequences- desirable, undesirable, and uncertain. The focus of technology assessment will be those consequences that can be predicted with a useful degree of probability [Daddario, 1967].

From the above definitions, TA is a comprehensive analytical strategy to achieve more effective public management of technological changes.

The objective of conducting a TA is to assess holistically the potential short-term impacts and longer term consequences of emerging technologies on society. This holistic analysis would include, for example, effects of the proposed technology on the economy, the physical environment, institutions, culture, the social structure, mores, values, and the law. The larger objective of the new research strategy is to enable policy and decision-makers to determine

how they might more effectively employ various public policy interventions during the R&D phases of a prospective technology to better assure its societal desirability [Arnstein, 1977].

TA is an attempt to anticipate the social implication of technology choices. The difficulty with TA, is that choices are based on compromises that reflect and affect individual values and preferences. Such compromises are very difficult to make and are essentially political. Nevertheless, TA with all its flaws and shortcomings, makes an important contribution to the bargaining that eventually leads to compromise [Christakis et al., 1980].

Gonen [2000] defines planning as a decision making process that seeks to identify the available options and determine which the best is. From the preceding discussion of TA, it is clear that it is a decision-making process that is characterized by multi- dimensions and uncertainty. Willis [1997] continues to say that an important aspect of effective planning is analysis of uncertainty in the future events and planning for their possibility. Willis and Scott [2000] state that planning is a process of identifying alternatives and selecting the best among them. Therefore, base on these planning definitions, TA can be looked at as part of the transmission planning process, where the different transmission technologies are assessed to find the best option.

The general planning process as described in Willis [1997] and Willis and Scott [2000] illustrated in Figure 1.2 of this dissertation, can be segmented into five steps. This process is normally a general approach that has been used in many fields e.g. engineering, management, computing and business. Each step is an important part of the process of accomplishing the goals of any type of planning. Any step poorly performed, will lead to poor decision-making, a poor plan and ultimately failure to attain the planning goals.

2.4 QUALITY DECISION MAKING

The success of a project is directly related to the quality of the decision underlying the project [Belton and Stewart, 2002]. Therefore, for better transmission project success, TA and transmission planning both being decision making processes prior to the projects, call for quality decision making in the processes. High quality decision making results in decisions that lead to the achievement of the project's primary objectives.

A quality decision can be defined as being, “well considered, justifiable and explainable” [Belton and Stewart, 2002]. The broad characteristics as summarized by Bekker [2010] include;

- Objectives, alternatives and risks should be well-considered, acknowledging the multi-dimensional nature of most decision making problems

The process should be informed with accurate, adequate and unbiased data, and take past lessons learned into account

- The process should be inclusive, taking a wide range of stakeholder opinions into account
- The process should be transparent, with an audit trail to ensure that the decisions can be explained and justified.
- The process should be flexible and able to adapt to the context of the process through built-in iterative feedback loops. The process should result in detailed implementation, monitoring and contingency plans
- The processes should acknowledge both soft and hard uncertainties.

Coherent and logical methodologies or approaches have been developed to aid project decision makers in making these quality decisions. These approaches should serve as intelligible, acceptable and exhaustive instruments of communication allowing conception, justification and transformation of the preference with the decision process [Roy, 1996].

As already mentioned above, transmission expansion problem has multiple conflicting objectives or attributes and there is no single solution that simultaneously optimizes all of them. A compromise is usually achieved that represents a reasonable trade-off among the attributes. The problem requires a model that can cope with the complexity of this decision making process. The model needs to be able to evaluate different options against a number of performance measures and according to a range of objectives.

There are many decision making models that can be used to improve decision making. For example multi-criteria decision making models, spatial choice models, decision making tree,

influence diagram, game theory, linear programming, cost/benefit analysis and trial and error. The most appropriate solution for this is the use of MCDM models [Millis et al, 1996].

2.4.1 Multi-criteria Decision Making (MCDM)

MCDM is a well-known branch of decision-aiding. It is a branch of a general class of operations research models which deals with decision problems under the presence of a number of decision criteria [Pohekar and Ramachandran, 2004]. The process involves “making preference decisions (such as evaluation, prioritization, and selection) over the available alternatives that are characterised by multiple, usually conflicting criteria”.

Zionts, [1979] defines multiple criteria decision-making (MCDM) as decisions that involve conflicting objectives. Loken [2005] states that MCDM is a generic term for all methods that exist for helping people making decisions according to their preferences, in cases where there is more than one conflicting criterion. Using MCDM can be said to be a way of dealing with complex problems by breaking the problem into smaller pieces. After weighting some considerations and making judgments about smaller components, the pieces are then reassembled to present an overall picture to the decision makers. The MCDM process generally consists of three steps:

- The structuring of the decision making problem
- The acquisition of preference information
- The aggregation of preferences to obtain a unified value across multiple criteria

It should be noted that the MCDM models are meant to unfold decisions through a process of learning, understanding, information processing, and defining the problem and its circumstances. The emphasis must be on the process, not on the act or the outcome of making a decision. In other words, the focus of the models is on supporting or aiding decision-making, it is not on prescribing how decisions “should” be made, nor is it about describing how decisions are made in the absence of formal support. The analysis helps to structure the problem, hence serves to complement and to challenge intuition, acting as a sounding –board against which ideas can be tested, it does not seek to replace intuitive judgment or experience. The process

leads to better considered, justifiable and explainable decisions i.e. the analysis provides an audit trail for a decision [Belton and Stewart, 2002].

According to Bekker [2010], MCDM improves the quality of the decision making process in a number of ways:

- By focusing on the need to “make explicit and manage (the) subjectivity” which exists in the various stakeholders’ objectives and value systems, the likelihood of well considered and informed decisions is increased
- By using “explicit but not necessarily completely formalized models” decision aiding provides a flexible structure to the decision making process
- By trying to “obtain elements of the responses to questions posed by a stakeholder” decision aiding helps to clarify the decision problem, and increases the likelihood of a feeling of process ownership amongst the stakeholders, identified as important during the preceding discussion on inclusivity and transparency

2.4.1.1 MCDM methods

According to Rossi and Freeman [1993], there is no single method of evaluation capable of dealing consequently with many programs of different content, planning or policies that concern development planning and the corresponding decision-making. There are many different MCDM methods based on different theoretical foundations such as optimization, goal aspiration, outranking or a combination of these different theoretical foundations. Some of the different methods are:

- Weighted sum method(WSM)
- Weighted product method(WPM)
- Hierarchical decision making (HDM)
- Analytical hierarchy process (AHP)
- Preference ranking organisation method for enrichment evaluation (PROMETHEE)
- The elimination and choice translating reality (ELECTRE)

- The technique for order preference by similarity to ideal solutions (TOPSIS)
- Compromise programming (CP)
- Simple multi-attribute rating technique (SMART)

Pohekar and Ramachandran [2004] has a detailed description of these methods.

The majority of these methods belong to the two main schools of multi-criteria methods, the American and the European. The American school proposed various practical methods based on MAUT (multiattribute utility theory), such as the family of smart methods. The American approach focused on weighting methods, which reduce a multidimensional evaluation to a one-dimensional one via the formulation of a composite utility (or value) function, with which the criteria between them are balanced. The determination of the composite utility function presupposes that utility functions will be determined for each criterion, as well as weights for each function. The decision maker formulates his preferences with regard to the alternatives with the single utility functions, and the composite utility function provides indicators, that express the total value of alternatives [Valiris et al., 2005].

The European school, with the work of French B. Roy and contributions by several European scientists, has developed families of methods, such as ELECTRE, PROMETHEE and Regime analysis, in which the balance of criteria is limited. The philosophy of the European school is completely different from the American one since the proposed methods firstly, aim to help the decision-making and not to find the optimal choice, while, secondly, they are not based on a powerful axiomatic foundation, but their pragmatic character allows the incorporation of many dimensions of real decision-making processes [Valiris et al., 2005].

The MCDM methods have different strengths depending on the decision to be made. Choosing among all the MCDM methods that exist can be a multi-criteria problem by itself. Each of the methods has its own advantage and drawbacks, and it is not possible to claim that any of the methods is generally more suitable than the others are. Different decision makers (DM) will always disagree about which methods are most appropriate and valid. The choice of the method mostly depends on the preferences of the DM and the analyst. It is important to

consider the suitability, validity and user-friendliness of the methods. It is also important to realize that use of different methods will most probably give different recommendations. This should not lead to conclusion that there is anything wrong with any of the methods; it just means that the different methods work in different ways and are also used to solve different types of problems [Loken, 2005].

For this research project, the MCDM chosen is the SMART which is introduced in the next section. The main reason for choosing SMART is that, it has been used in numerous fields and its strength resides in its ability to structure a complex, multi-personal, multi-attribute, and multi-period problem hierarchically. It has also been applied in electricity network planning [Wang and McDonald 1994; Espie, 2003].

2.4.1.2 Simple Multi-Attribute Rating Technique (SMART)

According to Edwards and Barron [1994], the SMART is “by far the most common method actually used in real, decision-guiding multi-attribute utility measurements”. For the SMART technique, ratings of alternatives are assigned directly, in a natural scale of the criteria where available. The advantage of the smart model is that it is independent of the alternatives. Since the ratings of alternatives are not relative, changing the number of alternatives considered will not in itself change the decision scores of the original alternatives. This characteristic is particularly useful when new alternatives or features are added to the existing comparison. Any further evaluations necessary need not begin right from the start but the process can continue from the previous scores obtained. The linear utility function used by SMART is

$$V(\mathbf{a}) = \sum_{i=1}^m w_i v_i(\mathbf{a}) \quad 2-1$$

where w_i is the scaling value (weight) assigned to the i^{th} of m criteria, and $v_i(\mathbf{a})$ is a partial value function reflecting alternative \mathbf{a} 's performance on criterion i . The partial value function must be normalized to some convenient scale (e.g. 0–100). Using Eqn. 2.1, a total value score $V(\mathbf{a})$ is found for each alternative \mathbf{a} . The alternative with the highest value score is preferred. SMART is a pretty simple and user-friendly approach where the DM—in cooperation with the analyst—

only needs to specify value functions and define weights for the criteria to get very useful help with his decision [Belton and Stewart, 2002].

The overall preference values of the alternatives depend on weights assigned to criteria. Many different methods have been proposed for assessing criteria weights which are then used explicitly to aggregate criterion specific priority scores. Subjective methods determine the weights solely according to the preferential judgments of the decision-maker, which include simple multi-criteria rating technique by swing (SMARTS) [Edwards and Barron, 1994] and analytic hierarchy process (AHP) [Saaty, 1980]. On the other hand, objective weighting methods determine the weights by solving mathematical models without any consideration of the decision-maker's preferences, for example, the entropy method [Abbas, 2011]. Given criteria ranks, specific functions for assigning weights have been suggested by several authors. For example, rank reciprocal, rank sum, rank exponent, rank order centroid weight (ROC), rank order distribution and linear rank weight function. Abbas [2011], Edwards and Barron [1994] and Seaver and Edwards [1981] have detailed discussions of these methods. In general, weighting of criteria is a difficult task and is open to criticism, as it includes a strong subjective component and results are often not replicable.

The analytical hierarchy process (AHP) developed by Saaty [1980 and 1992] has many similarities to the SMART because they use the same model. Belton and Stewart [2002] described AHP "as an alternative means of eliciting a value function". However, they pointed out that the two methods rest on different assumptions on value measurements, and that AHP is developed independently of other decision theories. Of these reasons, many of the proponents of AHP claim that AHP is not a value function method. However, both SMART and AHP present their results as cardinal rankings, which mean that each alternative is given a numerical desirability score. Consequently, the results from the two methods are directly comparable.

In comparison, AHP is often a more time-consuming process than SMART and for managerial decision making "time" becomes a crucial factor. Another potential drawback of AHP is that of "rank reversal". Judgments in AHP are relative by nature and changing the set of alternatives

may change the decision scores of all the alternatives. Even if a new and very poor alternative is added to a completed model, those alternatives with top scores sometimes reverse their relative ranking. Since business performance measurement decision-making has become more and more complex with the passage of time, the overall complexity of selecting from a set of alternative measures has greatly increased. The dynamic nature of performance measurement systems suggests that new measures are likely to be introduced. As such the “rank reversal” problem might prove to be acute in this type of application and therefore SMART can be recommended as a better method in this situation [Valiris, 2005].

There is no doubt that if properly applied MCDM can be a very useful tool for planning, which is known to be complex in nature. The MCDM framework creates an environment where alternatives or options are evaluated on an equal footing. The SMART is a multiple criteria decision making technique that utilizes a number of discrete evaluation criteria within a MCDM environment to examine and assess the trade-offs between alternative solutions. The technique has benefited from the long standing interests of psychologists, engineers, management scientists and mathematicians who have brought a continuing awareness of behavioural and social issues as well as underlying theory [Belton and Stewart, 2002].

2.4.2 Uncertainty in decision making

For a quality decision making, uncertainties need to be acknowledged. Bekker [2010] identified, *“lack of uncertainty acknowledgement in the decision-making process as one of the major causes of electrification project failure in developing countries.”*

Loosemore et al [2006] identified four useful criteria to distinguish between what is an uncertainty (or risk), and what is not:

- Uncertainties imply unpredictable outcomes: *“(It is) the absence of information about future events which makes them unpredictable. A certain future event which is predictable is not a risk but is a problem which needs resolving.”*

- Uncertainties relate to events, not impacts or consequences. This criterion highlights the danger of focusing on the consequences of risk events rather than on the risk events themselves.
- Uncertainties relate to the future: “...past events are not examples of risks, but are actual problems or crises that need to be resolved. Risk management is therefore a proactive process of looking forward and is fundamentally different from crisis management, which is reactive and backward looking.”
- Uncertainties are closely linked to project objectives. If a potential future event has no way of affecting the objectives of a project negatively, the future event is not an uncertainty within the context of the specific project.

Young [2001] notes that the modes of uncertainty identified in literature is generally confined within the first conception of reality: *risk*, which has an objective probability distribution, and *uncertainty*, which in this context refer to subjective probabilities. Loosemore et al [2006] presents a distinction between risk and uncertainty which is also restricted to the perspective of an immutable reality, as shown by the fact that both risk and uncertainty are defined by probability (see Figure 2-1 below).

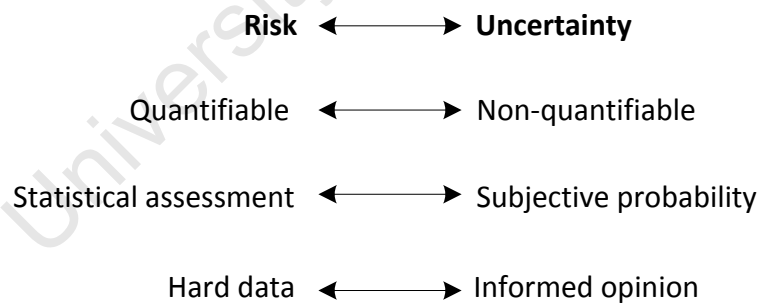


Figure 2-1: The risk–uncertainty continuum, based on Loosemore et al [2006]

Young [2001] defined two types of uncertainty, hard and soft, based on Davidson’s conceptions of reality and previous work by a variety of authors. He then applied these definitions within the context of environmental policy decision making, using a nonprobabilistic decision aiding approach developed by Shackle.

In *hard uncertainty* 1) the set of all possible outcomes of an action is unknown and can only be hypothesized, or 2) if all the outcomes are known, the probability distributions of all the outcomes are unknown or not fully definable. The definition of hard uncertainty encompasses both the subjective probability area of immutable reality and transmutable reality, as shown in Figure 2-2.

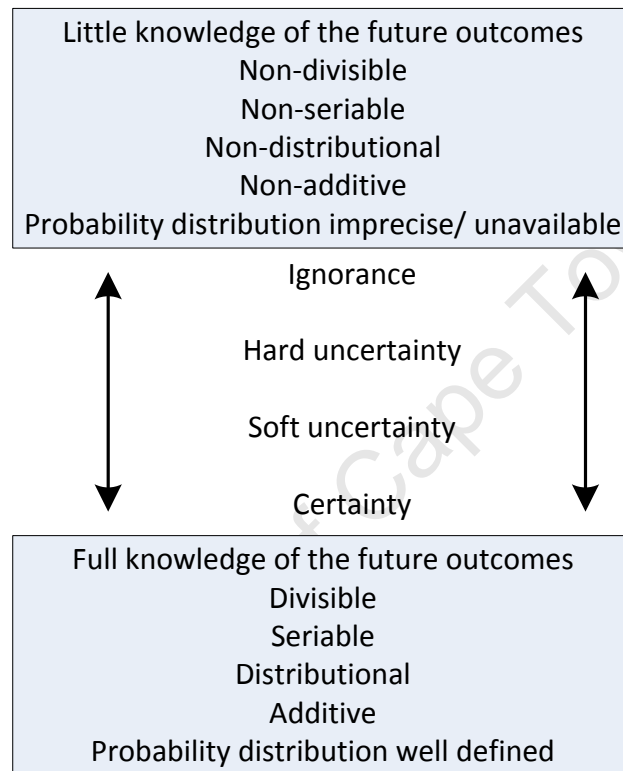


Figure 2-2: The types of uncertainty and their relation to the Davidson's concepts of reality, as proposed by Young [2001]

Soft uncertainty or risk is used to define situations where all the possible outcomes of an action, as well as the outcomes' probability distributions, are known, and therefore fall within the area of immutable reality.

This recognition of uncertainty as occurring both within the immutable and transmutable realities, through the concepts of soft and hard uncertainty, potentially allows a much wider range of uncertainties to be modelled (and therefore acknowledged in the decision making

process) than if only probability-based uncertainties were included. Refer to Young [2001] and Bekker [2010] for more detailed descriptions of hard and soft uncertainty.

From the definition of soft uncertainty, the technical, financial and environmental (i.e. ROW) constraints, fall under soft uncertainty. The decision aiding approach will acknowledge (evaluate) the soft uncertainties (i.e. project cost and timing, technical reliability) as described in section 2.5. However, political and social constraints have hard uncertainty, because humans and other stimuli create the future. Thus making modelling using probability meaningless [Young, 2001]. Examples of hard uncertainties include effectiveness of institution, corruption, human inertia to change, and political uncertainty.

From Equation 2.1, as earlier stated, $vi(\alpha)$ is a partial value function reflecting alternative α 's performance on criteria i . $vi(\alpha)$ is then normalized to a convenient scale (e.g. 0-1). The next section discusses the evaluation criteria that will be used to calculate of the performance of each planning solution (or alternative).

2.5 EVALUATION CRITERIA

To allow each possible planning solution to be assessed a number of evaluation criteria must be specified. Therefore, based on current literature, the sub sections below discuss different criteria that can be used to quantify the identified transmission planning constraints.

2.5.1 Environmental constraint criteria

The word environment includes; both natural environment and social environment. Natural environments includes the impact the line will have on precious animals and plants, while social environment includes the impact the line will have on cultural property, community development, and any other environmental issues from the residents. EIA must be exhaustive and comprehensive and must give due consideration to all alternatives. This usually calls for specialists to carry out an accurate and objective environment impact assessment and present it in due time to authorities in charge in due time for approval. Good industrial practice would see the EIA done early in the planning stage such that the mitigation of any potential significant impact can be, as far as is practical, incorporated into the project design.

For this dissertation and in case of the OHL, the term environmental impact (land use) can be referred to as the surface area occupied by the tower footing and the span, while for cables this term quantifies the surface area over the underground cable run. For both span and the surface area of cables run, the usability is only constricted after the construction of the line. For HVDC the terminals and reactive compensation the term also refers to the area occupied by the facility building as well [L'Abbate et al, 2010].

Espie et al [2003] adopted a methodology for this criterion and that was to consider the total circuit length (and ROW) of new or modified network circuit. For each new or modified circuit, the length (and ROW) is weighted to represent the likely environmental impact associated with the visual obstruction and implementation of each circuit type and route. This weighted length (or area) is then summed over all new or modified circuits to determine a weighted value for each planning solution.

The author acknowledges that EIA involves more than just surface area occupied by the lines (as already discussed) and requires specialists to carry out this assessment but the surface area is used to give a scale of the impact the technology will have on the environment in comparison to other technologies. The EIA also depends on the type of land use (socially sensitive sites, ecologically sensitive sites and archeologically sensitive sites), so the impact will vary depending on the proximity to these key features of environment. This can be captured by assigning environment a higher weight depending on the type of land use.

2.5.2 Technical constraints criteria

A key criterion within any planning methodology is the impact of each solution on the network reliability. Quantitative reliability estimation is being recognized as necessary and is becoming feasible in the planning of electricity distribution systems [Allan and Silva, 1995].

The improvement in the network reliability level, or the decrease in interruptions cost, usually leads to increase in investment cost. According to Neiman [2001], there exist well developed methods for approximate reliability assessment for distribution networks, which are suitable for planning purposes, since they allow for compelling reliability estimation for each state of

the network. The next section gives a brief description of Reliability analysis with respect to distribution planning.

2.5.2.1 Basic Reliability Indices

Billiton [1995] notes that at distribution level, basic power supply reliability is defined by two sets of indices, namely, the load-point indices and the system performance indices. The primary reliability indices at a customer point are:

- Expected frequency of failure λ ;
- The average duration of a failure r ;
- The average annual outage time (Unavailability), U .

These indices depend on many factors such as reliability of individual items of equipment, circuit length and loading, network configuration, load profile and availability transfer capacity.

In radial distribution systems the calculations of reliability indices involves a system consisting of series components from source to load. Supposing there are n components in series the system failure rate, λ_s will be:

$$\lambda_s = \lambda_1 + \lambda_2 + \lambda_3 + \dots \dots \dots \lambda_n \quad \mathbf{2-2}$$

And the system failure duration, r_s will be;

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \dots \dots \dots \lambda_n r_n}{\lambda_1 + \lambda_2 + \lambda_3 + \dots \dots \dots + \lambda_n} \quad \mathbf{2-3}$$

The system interruption time, U_s will be;

$$U_s = \lambda_s r_s = \lambda_1 r_1 + \lambda_2 r_2 + \dots \dots \dots \lambda_n r_n \quad \mathbf{2-4}$$

Equipment failure rates and failure durations are the data obtained from statistics and their values vary in certain ranges. Even for the same equipment there are many types and sizes. These values depend also on age of the particular piece of equipment.

2.5.2.2 Customer Interruption Cost

Reliability has been recognized as an important part of the system planning task. But it is also important to take into account the market value of a particular customer [Allan and Silva, Chen et al 1995, and Neiman 2001]. It could be done through Customer Interruption Cost (CIC), which is defined as a measure of the monetary losses for customers due to an interruption of electric service. Customer Interruption Cost reflects the service value provided by a utility to the customer and the inconvenience or damage experienced by its customers if a power failure occurs.

For many types of customers the issue of service reliability is simply a question of whether the supply is available or not. Other customers have quality requirements more stringent. Therefore, in the nearest future the utilities will face the problem of providing differentiated levels of reliability for different customers [Neiman, 2001].

2.5.2.3 Reliability as Planning Attribute

Thus the value, which combines network utility unavailability data with customers view on availability of supply, can be used as reliability criterion in planning tasks (Chen et al, 1995). The corresponding attribute is calculated according to the following equations:

$$C_{Reliab} = \sum_{i=1}^m IC_i = \sum_{i=1}^m \left(\sum_{j=1}^m (\lambda_j r_j P_i CIC_i(r_1)) \right) \quad 2-5$$

Where the reliability criterion, C_{Reliab} is calculated as a sum of load node interruption costs IC_i

The interruption costs is calculated for each node in the network as a sum of interruption cost due to possible failure of each upstream element $m(j)$ from the node to the feeding point. Finally, λ_j is a failure rate of the element j , r_j is its average outage time, P_i is average load at point i and $CIC_i(r_1)$ is customer interruption cost due to failure of duration r_i , the energy not supplied is given as ;

$$ENS = \text{total energy not supplied by the system} = \sum P_i U_i \quad 2-6$$

$$ENS = \sum_{i=1}^m \left(\sum_{j=1}^m (\lambda_j r_j P_i) \right) \quad 2-7$$

Where unavailability is calculated for each node in the network as a sum of interruption durations due to possible failure of each upstream element $m(j)$ from the node to the feeding point, λ_j is failure rate of element j , r_j is its average outage time, P_i is the load at point i

The reliability attributes must be calculated for each load node. Moreover, the economic principle must be taken into the consideration even in case of Equation 2-7 despite the fact the ENS is an energy value. Thus the annual value of **ENS** must be multiplied by $K = (1 + i)^{-t}$, where K is the value of future amount in the year t and i is the interest rate.

2.5.3 Financial constraints criteria

Capital cost is an important factor when assessing alternative planning solutions. With the proposed methodology this is a summation of the costs involved in implementing each of the options selected for each identified problem plus any ongoing costs related to implementation or the other operational aspects associated with the network (Khatib, 1996 and Espie et al, 2003).

The cost of each option (and solution) should be expressed either as the current cost of implementation or as the future-worth equivalent at the end of the planning period (horizon year), converted using present-worth calculations.

According to Neiman [2001], Present value (or worth) analysis is a method of measuring and comparing costs and savings that occur at different times on a consistent and equitable basis for decisions making. To convert the single payments at some year, t in the future into equivalent amount at present and vice versa the Present Value method can be described as:

$$PV = \frac{1}{\left(\frac{1+d}{1+i}\right)^t} FV \quad 2-8$$

$$FV = \left(\frac{1+d}{1+i}\right)^t PV \quad 2-9$$

Where, **FV** is a value of future amount in the year, t ; **PV** is the value of the same amount at time zero; d is the discount rate and i is the interest rate.

If there are uniform series of the annual payments from today through T years, the present worth of these payments can be found by using the Annuity methods:

$$PV = \left(\frac{(1+i)^T - 1}{i(1+i)^T} \right) \cdot A \quad \mathbf{2-10}$$

Where, A stands for value of annual payments, which is considered constant and

T corresponds to the planning period.

In network planning tasks, different alternatives are usually analyzed over a longer period of time corresponding to the life time of the equipment. However, the life time of different units of the equipment may differ considerably. One solution to the problem of the dynamic allocation of assets is to use one of the accounting depreciation methods. Depreciation may be defined as lessening in value of a physical asset with the passage of time. Thus, the alternative investment, which do not coincide in time, can be compared based on the Present Value of the investments and the salvage value. Another, conceivable more general approach is to reduce a single investment to a series of annualized costs [Neiman, 2001 and Khatib, 1996]

$$A = \left(\frac{i(1+i)^T}{(1+i)^T - 1} \right) PV \quad \mathbf{2-11}$$

If one defines the lifetime of the particular unit of the equipment as depreciation time and assign the planning period, the following cases may need to be compared with each other:

- Planning period is shorter than the unit depreciation time and the investment is made at present time. The planner is only interested in payments to be made during the planning period. A series of annualized costs can be found from the following equation

$$A_{Depr} = \left(\frac{i(1+i)^{T_{Depr}}}{(1+i)^{T_{Depr}} - 1} \right) PV \quad \mathbf{2-12}$$

The present value of the investment during the planning period may be found applying the Equation 2.10.

- Planning period may be shorter than (or equal to) the unit depreciation time, but the investment is postponed by a number of years more than $T_{Depr} - T_{Pt}$.

In this case, a series of annualized casts to be found from Equation 2.12 and used to find the future investment value as follows:

$$FV_{pt} = \left(\frac{(1+i)^{T_{pt}-T_0}}{i(1+i)^{T_{pt}-T_0}} \right) \cdot A_{Depr} \quad 2-13$$

Where, T_0 is the time of delay of the investment in comparison to the present time. The present value of the investment can be obtained either from Equation 2.13 applying 2.8 or directly from the physical value of investment according to:

$$PV = (1+i)^{-T_0} \left(\frac{1-(1+i)^{T_{pt}-T_0}}{1-(1+i)^{-T_{Depr}}} \right) \cdot PV \quad 2-14$$

Equation 2.14 is obtained from Equations 2.8, 2.12 and 2.13,

- Unit depreciation time is shorter than (or equal to) planning period. In this case, the present value of the investment is equal to its physical value, but annuity can be calculated using Equation 2-12.

2.5.4 Political and social criteria

Political and social constraints have hard uncertainty, because humans and other stimuli create the future. Bekker B [2010] defines hard uncertainty as, a type of uncertainty in which the set of all outcomes of an action is unknown and can only be hypothesized, or if all the outcomes are known, the probability distributions of all these outcomes are unknown or not fully definable. This subjectiveness and lack of prediction, makes modelling using probability meaningless [Young, 2001]. Examples of hard uncertainties include effectiveness of institution, corruption, human inertia to change, vandalism of transmission infrastructure and political uncertainty.

The Shackle model, published in the 1940s, steps entirely outside the probability framework and proposes a solution to modelling hard uncertainty. It replaces probability as a measure of uncertainty with the measure of the degree of surprise. Young [2001] has a more detailed description of the model.

Bekker and Gaunt [2007], used an uncertainty checklist as a means of making uncertainties explicit in electrification projects, thus increasing the quality of decision making, and ultimately the success of the project. This makes potentially hidden project uncertainties explicit without resorting to subjective numerical methods.

2.6 IN SUMMARY

This chapter set out to answer the research questions that will ultimately test the research hypothesis. The following answers were found to the research questions:

What loads are expected in Uganda?

From the literature above, it is clear that Uganda is in need of power system grid expansion, that is, there is increasing demand for electric power that has led to increased generation and finally need for transmission grid expansion.

Recent studies show that, the average rate of demand growth (i.e. rural electrification and new connections in urban areas) is approximately 4% at a load factor of about 58.6% [UETCL,2010]. In fact, based on the historic load data (Figure 1-1), it is clear that Uganda is having increasing demand for power. In the last two decade, the demand has increased at a rate of approximately 5.9% per annum. If factors remain constant, the demand is expected to continue increasing in the years to come.

To meet this growing demand, Uganda has considerable unexploited renewable energy resources for energy production and provision of energy services. For example it has a total hydro potential of approximately 2200MW but currently only exploits 416MW. These resources include; biomass, geothermal, large scale hydro, mini/micro/pico hydro, wind, peat, and solar energy. The renewable energy potential of Uganda is shown in the Table 2-2 below [ERA, 2009]

Clearly, there is an increasing demand for power in Uganda and the energy potential to satisfy this demand is available.

What technology options are being considered or used for grid expansion in Uganda?

From the current state of Uganda's power system [ERA, 2011 and PB, 2010] and the Grid investment plan 2008-2023 [UETCL, 2008], the technology being used and/or proposed is the AC OHL lines at 33, 66, 132, 220 and 400kV. Further discussions of this are in chapter 3.

What obstacles are faced in the processes of grid expansion in Uganda?

From literature (Kiessling et al [2003], Gross [2005], Bhowmick et al [2007], Keith et al [2008] Buijs et al [2011], UETCL [2008], UETCL [2001], NEMA [2011], Akampurira [2009] and Kakura et al [2009]), the constraints to transmission grid expansion in Uganda are:

- Financial constraints
- Technical constraints
- Environment constraints
- Political constraints
- Social constraints

These constraints lead to delays and cancellation of some projects in the process of transmission grid expansion. In turn, the transmission grid is not able to keep pace with the increasing demand and new generation.

What other technology options can be used for grid expansion and how would they overcome these obstacles?

Chapter 3 of this dissertation has the detailed discussion on transmission technologies.

How are the best choices identified?

From the literature, it is evident that transmission expansion planning is experiencing a paradigm shift due to increasing concerns over political preference, social issues and environmental issues. Network planners now have to deal with multiple and often conflicting objectives.

Coherent and logical methodologies or approaches have been developed to aid project decision makers in making quality decisions. These approaches should serve as intelligible, acceptable and exhaustive instruments of communication allowing conception, justification and transformation of the preference with the decision process. MCDM is a well-known branch of decision-aiding so will be used in this dissertation. There are numerous MCDM methods and they have different strengths depending on the decision to be made. For this dissertation, SMART MCDM model is used. The main reason for choosing SMART is, its ability to structure a complex, multi-personal, multi-attribute, and multi-period problem hierarchically.

The literature further identified that political and social constraints have hard uncertainty, meaning that humans determine their outcomes, thus making modelling using probability meaningless. The literature also states that for better project success, these hard uncertainties also need to be acknowledged.

Uganda being a developing country, politicians and donors control the funding to major projects. Therefore, it is key to have their support before any project in order to ensure continuous financial backing. This will in turn better transmission project success.

This chapter provides evidences of the relevance of this research, which rest on the assumption that Uganda's transmission grid expansion is lagging behind due to the poor (or less comprehensive) consideration of the constraints faced in the process of transmission grid expansion.

3 APPLICATION OF TECHNOLOGIES SPECIFICALLY FOR UGANDA

3.1 INTRODUCTION

AC OHLs are the standard solution for grid expansion; it can be argued that different technology options can overcome many obstacles that proposals for OHLs face. Additionally, it can be illustrated that the higher investment costs for some solutions can be offset with an increased benefit e.g. by accomplishing investments with smaller delays due to fewer obstacles encountered. Different transmission technologies other than AC overhead lines have been used as a solution to minimize constraints faced in transmission expansion planning as discussed in Buijs et al [2011], Albar et al [2007] and L'Abbate et al [2010].

To overcome or minimize some of the obstacles faced, selection of an appropriate technology would be vital in the transmission planning process. Therefore, to enhance transmission capacity, two approaches can be identified, building new lines or installing devices which increase the flow through existing assets or even by combining both approaches. The different technologies that can be considered are; installation of AC OHLs, uprating of existing assets, installation of underground cables, installation of controllable devices(FACTS), installation of HVDC lines, upgrading AC lines to DC, over building AC OHLs, battery energy storage systems, generation closer to load centres, enhanced wide area measurement systems, communication technologies, robust state estimator, software tools performance, real time automated load forecasting and generation tools, advanced substations and software tools for online real time dispatch operations.

This chapter answers the fourth research question. It discusses different transmission technologies that can boost transmission capacity and at the same time minimizing transmission constraints. The chapter goes further to discuss the possible application these technologies can find in Uganda. Next is a brief overview of the technologies being applied and proposed in Uganda for transmission grid expansion.

3.2 TECHNOLOGY OPTIONS CURRENTLY BEING USED IN UGANDA

Currently, Uganda uses AC OHL for power transmission. It has 1376 km of 132 kV, 38 km of 66 kV and 18650 km of 33 kV and 11 kV grid length [ERA, 2011]. In the GIP 2008 -2023 [UETCL, 2008], projects are categorized as power interconnection to new plants projects, reinvestment projects, system extension projects and regional interconnection projects. The document only proposes the use of AC OHL lines at voltages of 400, 220, and 132 kV for power evacuation, system extension and regional interconnection projects. It also proposes construction of new substations, substations upgrades, and substation extension.

Based on the GIP 2008-2023, Uganda is planning to continue using AC OHLs for grid expansion. The only difference is that, it is planning to use higher voltage levels of 220 kV and 400 kV for some interconnection and power evacuation from some new plants. Clearly, AC overhead lines still have a wide application in Uganda.

3.3 AC OVERHEAD LINES (AC OHLs)

The traditional approach in transmission system reinforcement is the three-phase AC OHL. AC OHLs are well established and much experience has been gained over the years [Buijs et al, 2011]. Their fundamental purpose has been to transmit power from generating units to the distribution system that ultimately supplies the loads. AC OHLs have also been used to interconnect various areas to the transmission network and interconnect one electric utility with another.

This planning solution is very cost effective and robust, uses technology that is known and has been used for decades. There are currently few technologies that can compete with OHL when taking only investment cost into account, especially in rural areas.

However, AC OHLs have high visual impact, are possibly hazardous by public opinion due fears of EMF, lead to loss of property value, also require a significant right-of-way (ROW) and so, are considered not appealing. As discussed in the preceding chapter, AC OHLs have negative impact on both natural and social environment. According to Buijs et al [2011], this results in tough sitting opposition and long permitting processes.

Transmission system design involves the selection of the necessary lines and equipment which will deliver the required power and quality of service for the lowest cost over service life. The system must also be capable of expansion with minimum changes to existing facilities [Fink D et al, 2006]. These designs include:

- The electrical design of the ac systems involves; power flow requirements; system stability and dynamic performance; selection of voltage levels; voltage and reactive power flow control; conductor selection; losses; corona- related performance; electromagnetic field effects; insulation and over voltage design; switching arrangements; circuit breaker duties; and protective relaying.
- Mechanical design includes; sag and tension calculations; conductor composition; conductor spacing; type of insulators; and selection of conductor hardware.
- Structural design includes; selection of the type of structure to be used; mechanical loading calculations; foundations and; guys and anchors.
- Finally, the miscellaneous features of transmission-line design are; line location; acquisition of the ROW; profiling; locating structures; inductive coordination (considers line location and electrical calculations); means of communication; and seismic factors.

Over the years and from the experience gained, standards have been established in voltage levels, conductor selection, electrical properties of the conductors, line insulation, line configuration and structure location, types of towers, line accessories, environmental effects, line operation and maintenance, and foundations. The Table 3-1 below shows some of the standards that are being used today.

Kiessling et al [2003] discusses more of these standards, that is, voltage levels, conductor types, electrical properties, insulator types and tower types that are being used in practice today.

As a continued application of AC OHLs overbuilding the lines can help overcome some of the constraint faced because it is generally cheaper per mega-watt of capacity to build larger transmission lines as discussed in the subsection below.

Table 3-1: Nominal voltage and corresponding highest system voltages according to IEC 60 038 [Kiessling et al, 2003].

Nominal voltage, kV	Highest system voltage, kV	Nominal voltage, kV	Highest system voltage, kV
3	3.6	90	100
6	7.2	110	123
10	12	132	145
15	17.5	150	170
20	24	220	245
30	36	225	245
45	52	275	300
50	72.5	380	420
60	72.5	400	420
63	72.5	480	525
66	72.5	700	765
70	82.5		

3.3.1 Overbuilding AC OHL

Overbuilding can be defined as building a line to match a longer term forecast than the short term or the current forecast. Overbuilding a line now will reduce long-term costs by avoiding the much higher costs of building two smaller lines. It will also further reduce the delays and opposition associated with transmission-line sitting by eliminating these costs for the now unneeded second line [Hirst et al, 2001].

Economies of scale in transmission investment argue for overbuilding, rather than underbuilding, transmission. It is substantially cheaper per GW-mile to construct a higher-voltage line than a lower voltage line [Hirst et al, 2001].

Table 3-2: Typical costs and thermal capacities of transmission lines [Hirst et al, 2001]

Voltage, kV	Capital cost, k\$/mile	Capacity, MW	Cost, million \$/GW-mile
230	480	350	1.37
345	900	900	1
500	1200	2000	0.6
765	1800	4000	0.45

It is also generally cheaper per mega-watt of capacity to build larger transmission lines. This is illustrated in Table 3-2. For example, the cost per MW-mile (marginal cost) of a 500kV transmission line is about half that of a 230-kV line. Higher voltage lines also require less land per MW-mile than lower voltage lines. This is illustrated in the Figure 3-1 [Hirst et al, 2001].

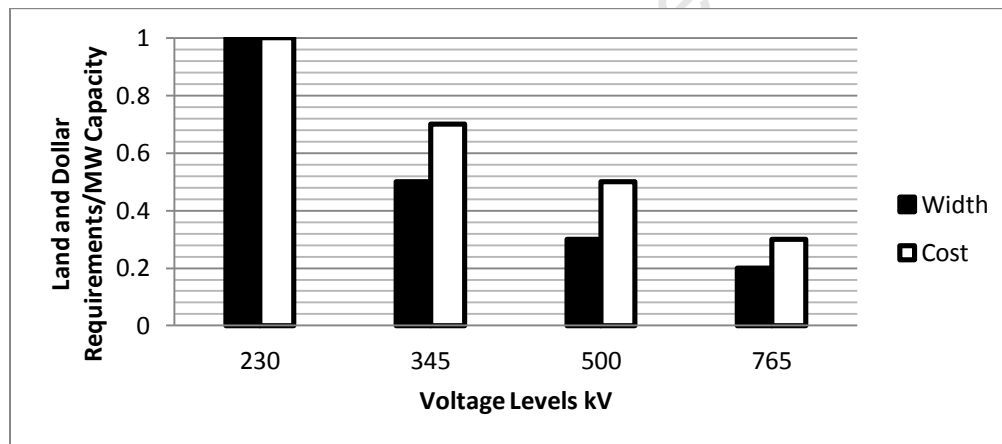


Figure 3-1: Per- megawatt capital cost and land requirements for transmission lines relative to a 230kV line [Hirst et al, 2001].

Both these factors argue for overbuilding lines rather than trying to size lines to exactly match current and short term forecast needs. Therefore, it reduces the regulatory delays, opposition from local landowners and opposition from environmental bodies by eliminating these costs for the now unneeded second line. On the other hand, a large transmission line may impose more of a reliability burden on the system than several smaller lines. Indeed, if a new, large line becomes the largest single contingency, contingency-reserve requirements might increase in the country.

3.3.2 Application of AC OHL in Uganda

AC OHLs are generally expensive but are very cost effective compared to the alternatives. For example the technology is cheaper than underground cables (about 3 times cheaper) and also cheaper than HVDC for short distance (i.e. <400km) bulk power transmission. The technology is robust and has been used for decades enabling the technology to be well known. There are currently few technologies that can compete with OHL when taking only investment (especially in rural areas grid electrification) or technical experience into account.

Therefore, AC OHL will continue to have a competitive edge especially in a country like Uganda with financial constraints as the major constraint faced as already described in the preceding chapter. However, other alternatives maybe better when it comes to environmental constraints and also depending on the project, technically and financially better.

Overbuilding can find application in Uganda with population and economic growth, suitable land on which to build transmission lines can only become less available in the future and become more expensive. Environmental bodies too are getting stronger thus resulting into increasing opposition from them. That said, for a country with financial and environmental constraints, this is an option because it is cheaper per GW-mile, it is also cheaper in the long run than to build two different lines and it also requires less land per MW-mile or less than two lines.

3.4 UPRATING OF EXISTING CIRCUITS

As the load growth and system development continue to be significant, the need for new lines and also the need to adopt higher voltages, to increase transmission capacity has always existed. However, obtaining new servitude and corridors is becoming increasingly difficult and expensive. Therefore, taking advantage of existing overhead lines and improving their transmission capacities, has been an extensively used tool. In turn, new servitude is not required. This can be achieved by uprating.

Upgrading is generally understood as increasing the transmission capacity of existing transmission lines [Cigre WC B2.13, 2008]. As discussed in Simpson [1990], Buijs et al [2011] and Fink et al [2006], the options available for upgrading are as follows:

- Increasing the voltage, or
- Increasing the current

Increasing the current can be practically accomplished by increasing the design temperature of the existing conductors, or by using bigger conductor cross section area, or other conductor types with higher current rating. Voltage upgrading consists of increasing the insulation levels if feasible, or by compacting the line that will eventually operate with lower insulation levels.

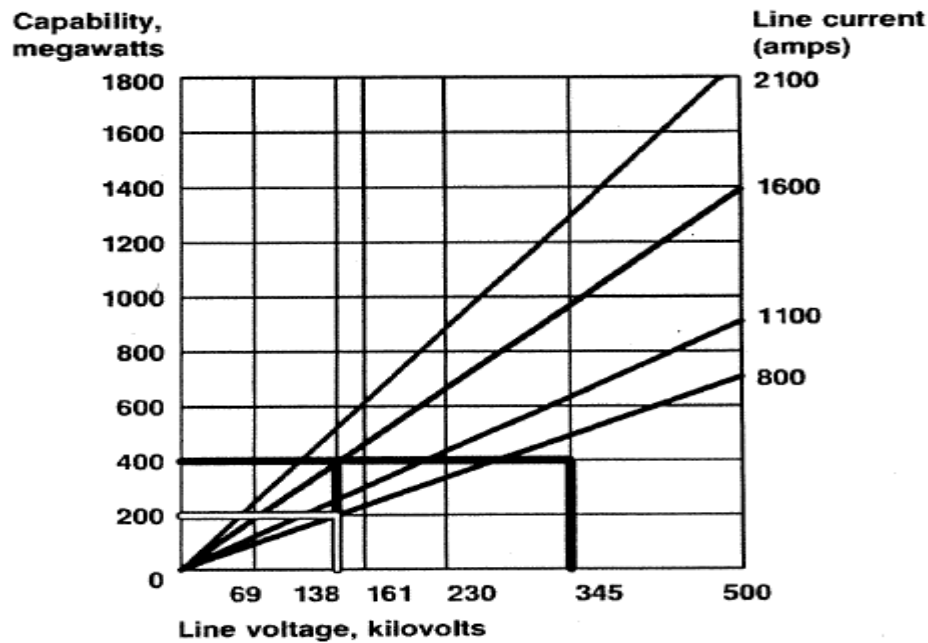


Figure 3-2: Power transfer capability [Simpson, 1990]

As illustrated in Figure 3-2, the capacity of a 138kV circuit with current of approximately 800A could be increased from 200MW to 400MW by either increasing the voltage to 345kV or the current to about 1600A. Choosing either of these options would typically result in conditions that are electrically or structurally beyond the capabilities of the existing line components.

Examples of the increase of the conductor section (increasing current) are described in Kiessling et al [1998] and Sanchez et al [2004] and are shown in Table 3-3. Examples of voltage uprating are described in Kiessling et al [1998], Broschat [1971] and Hanson [1991] and are shown in Table 3-4. In both these cases, they achieve higher transfer capacity and make significant saving and less environmental impact as compared to new AC OHL.

Table 3-3: Cases of increase of conductor section

Case	Voltage, kV	Original Conductor	New conductor
S1 [Kiessling et al,1998]	380	2 ACSR 560/50	4 ACSR 265/35
S2 [Sanchez et al, 2004]	132	1 ACSR Hen	2 ACSR Hawk

Table 3-4: Cases of increase of line voltage

Case	Original Voltage, kV	New Voltage, kV	Original Conductor	New Conductor
V1 [Broschat,1971]	115	230	1 ACSR 266,8 kcmil 26/7	1 ACSR 795 kcmil 24/7
V2 [Hanson,1991]	115	230	1 ACSR 954 kcmil 54/7	Igual
V3 and V4 [Hanson ,1991]	230	345	1 ACSR 1272 kcmil 45/7	2 ACSR 1272 kcmil 45/7
V5 and V6 [Kiessling et al,1998]	220	380	2 ACSR 240/40	3 ACSR 240/40

Transmission engineers are often faced with the challenge of increasing the power capacity of existing transmission lines by uprating, as it requires system upgrades. This is because electrical and structural capabilities requirements exceed the capabilities of the existing facilities. This calls for a detailed feasibility study to determine a viable uprating method preferably with minimal upgrade requirements.

To determine if uprating a transmission line is cost effective, the transmission planners must carefully evaluate the proposed utilization of the existing facilities. An uprating that involves

increased mechanical loads or electrical clearance generally requires structural modifications. A number of factors should be considered that minimize these modifications.

Uprating can be very attractive in terms of getting smaller costs, however, before starting the uprating task, it is important to evaluate some feasibility issues, as well as to choose the most appropriate type of uprating for a specific transmission line. As discussed in Simpson [1990], Buijs et al [2011], Fink et al [2006] and Daconti et al [2003], the uprating feasibility issues are summarized below.

3.4.1 Uprating feasibility issues

Technical feasibility: It is important to consider at least the following points:

- System load requirements. This will involve evaluating how long the uprated line will satisfy the load requirements
- Assessment of current conditions and life expectancy of transmission line materials. It is crucial to make this kind of evaluation for the main transmission line components, such as towers, foundations, conductors, insulators, and hardware
- Potential margins of uprating. It is also necessary to check electrical clearances, mechanical strengths, ROW width, as well as the possibility of compliance with the requirements of safety codes(NESC), regulatory bodies and government agencies (e.g. navigable streams, public lands, air lanes)
- Utility considerations. Sometimes electric utilities are not allowed to take the transmission line out of service to perform the necessary uprate services. In this case it is very important to check if the mentioned services can be done with the line in service

Economical/ Financial Feasibility; for this kind of analysis it is important to consider at least the following points:

- Uprating cost versus new line costs. It is crucial to remember that technical analysis of old lines usually requires data gathering and this can be very expensive and time consuming. Besides that, it is necessary to estimate what will be the need of the uprated line in terms of additional ROW. Other costs that can be relevant are related to

construction (i.e. material and labor), maintenance and operation of the upgraded line. Environmental costs are usually higher for new lines

- Upgrading cost versus upgrading benefits

Environmental feasibility; for this analysis, the following issues should be considered:

- Environmental considerations. Usually not so critical when compared to new lines. However, it may be necessary to deal with historical societies, environmental groups and concerned neighbors.
- ROW easements. If significant changes will be made to the original line, it is necessary to check the validity of the previous ROW terms of use. It can be difficult to get licensing for the modified line. It is also important to check the existence of ROW encroachments and line crossings that would be unacceptable by the upgraded line.

Adding capacity to existing transmission paths can be done by adding an additional circuit to existing transmission tower or by increasing voltages if possible. If voltage is increased, there has to be care of insulation and clearances (both vertical to the ground and internal to other parts of the transmission line). Alternatively, the existing conductors may be replaced by new conductor types with higher ampacity. New materials are constantly developed, which allow higher temperatures, and consequently higher permissible currents for equal cross-section. Another approach is to look at materials that reduce the sag of the line. Most new developments focus on the tension wire made from a material with high strength over weight ratio, and a minimum resistance over weight ratio for the conducting material [Buijs et al, 2011].

On the other hand, upgrading requires a detailed assessment of the existing lines which can be both time consuming and very costly as well. It also introduces new structure and electrical challenges which have to be carefully attended to [Hanson, 1991]. There computer softwares which have been made to effectively assist transmission engineers in both preliminary and detailed evaluation schemes. Examples include TLCADD, UPSTUDY and TLOPGR [Simpson, 1990].

As compared to construction of new OHL, uprating provides a fast and economic way of increasing capacity or improving reliability. The slow costly environmental processes are greatly reduced in scope and time. Also, it may not be environmentally possible to acquire a new ROW.

3.4.2 Application of AC OHL Uprating in Uganda

Transmission expansion in Uganda has been limited by financial and environmental constraints which have resulted into old transmission systems that are about 40 - 50 years. Uprating can be a solution to this problem by providing a more economic and environmentally friendly way of increasing capacity.

Smaller costs and less environmental impact when compared to a new transmission line is very attractive for the case of Uganda with financial and environmental constraints. Besides that, it can postpone the need of new transmission lines, reduce congestion costs and avoid unnecessary load shedding during contingencies. However, before starting the uprating task, it is important to evaluate the most appropriate type of uprating for a specific transmission line.

It should be noted that original designs used were overly conservative design methods, and more stringent code requirements than currently were used. Also consideration of the available types of insulator assemblies and special conductors, computer software is also available, some compact line design techniques may be applied, as well as configuration of the uprating circuits can minimize the impact of the uprating on the existing structures.

Barthord et al. [2008] said that uprating a circuit from one system voltage to the next is feasible mainly at lower voltages because older circuits (110,115 and 138 kV) were often conservatively designed. As a result a number of North America utilities have uprated circuits from 115 or 138 kV to 230 kV without serious modification. Therefore, Uganda with mainly lower voltage lines (66 and 132 kV) and old lines (40-50 yrs) can take advantage of these conservative designs as well. In this respect, the dissertation assumes a successful voltage feasibility studies for the analysis.

3.5 UNDERGROUND CABLE CONNECTION

Underground cable systems are usually installed in urban or suburban areas where overhead lines are not approved, in locations such as airport approaches because of safety issues, or water crossings where OHLs are not feasible. Other applications include substation gateways, crossings under major overhead line conductors and insulations where technical considerations favor underground cables [Fink et al, 1987]. Submarine cables offer a valuable alternative to OHL transmission for interconnection of electric systems physically separated by water [Gazzana-Priaroggia et al, 1971]

In order to avoid most of the visual impact, underground transmission assets are considered the ideal solution. However, technically and economically this is not necessarily the case. Next to being several times more expensive than OHL, with respect to material cost and installation, high voltage transmission systems act as capacitors, requiring large compensation units and complicating system operations [Kiessling et al, 2003]. Cable systems for transmission system voltages are limited in length due to charging current. Underground cables have been successfully installed in 400kV transmission system; however the line length is generally limited to a few kilometers. In Table 3-5 a summary of international investment data is presented, according to a survey carried out by Cigre SC21/22 in 1997.

Table 3-5: Summary of international investment data of OHLs and underground cables [Cigre SC21/22, 1997]

Voltage range, kV	110 to 219	220 to 362	363 to 764
Mean power MVA/ circuit	220	600	1800
Mean overhead line investments EUR/(km.MVA)	820	390	185
Mean underground cable investments EUR/(km.MVA)	6100	4900	3700
Mean ratio	7	13	20

Transmission of electricity at high voltages by underground cables is significantly more costly than by overhead lines. The disparity in investments increases with the voltage as shown in the table above.

A special type of cable is the gas insulated line (GIL), which allows longer lengths, higher transmission voltages and power ratings. The conductor core is placed in an isolating gas within a metal tube. At this moment there are no long distance connections using installed GIL. GIL is more expensive than underground cables. Serious advances are also being made in the field of high temperature superconducting (HTS) cables, which promise high rating lower losses. At the moment, HTS technology is not ready for use in the transmission system [Exposito et al, 2007].

Underground connections are several times more expensive than overhead lines, while less troublesome concerning permitting and social requirements. Therefore, often a compromising solution is found, where part of the connection is overhead and part underground. The combined solution requires a substation at each transition. Each transition also comes with a change in the characteristic impedance, requiring additional equipment to protect it from voltage surges in the transmission system.

Underground cable transmission is good when it comes to overcoming environmental constraints, but remains too expensive compared to AC OHL. They will only find application in Uganda in niche situations of, probably totally no ROW.

3.6 FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS) OR POWER FLOW CONTROLLING DEVICES

FACTS is a generic term for installations, which allows controlling the power flow. Therefore, they are sometimes called power flow controlling devices (PFC). According to IEEE, FACTS are “Alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability [Cole et al, 2005].”

FACTS can be defined as highly engineered power electronic based systems, integrating the control and operation of advanced power semiconductor based converters with software-based information and control systems, which produce a compensated response to the

transmission network that is interconnected via conventional switchgear and transformation equipment. FACTS technologies can deliver the following benefits; rapidly implemented installations, increase system capacity, enhance system reliability, improve system controllability and seamless system interconnections [Reed et al, 2004].

In addition to transmission application and the benefits offered by FACTS, they are also extremely beneficial when implemented for the interconnection of certain renewable energy sources (RES) to the grid. RES (e.g. wind) do not universally provide a steady and continuous interconnection to the electric power transmission grid. For example, due to the nature of the source of wind power, a continuous and steady supply from wind generation units is difficult to achieve. Therefore, extra measures are needed to stabilize the RES outputs for seamless interconnection to the transmission grid. FACTS can be used for this purpose by ensuring a reliable, steady, and secure connection to the transmission grid [L'Abbate et al, 2010].

In comparison with the solutions proposed above all add capacity by adding new paths or strengthening existing paths. FACTS offer a completely different approach as they consist of devices placed at specific points in the grid. As such they can be connected to existing lines, influencing the flow through that line. The additional space required is limited; they can be placed in existing substations. This makes the permitting process relatively straightforward. Controlling the power flow, PFCs can redistribute the line flows in the system, alleviating stress on the heavily loaded lines, and thus increasing the overall transfer capability of the grid. As this technology presents a single investment in a single device, the solution is relatively easier to install compared to other ones. PFCs receive lots of attention of TSOs that are looking for increased transmission capacity without having to build new lines.

Distinction has to be made between different types of controllable devices. The technology used for the construction of power flow controlling devices can be divided into three main categories, based on their switching method: mechanically switched; thyristor controlled switching and; fast switching, power electronic converter based.

The main difference between these technologies is speed. Mechanical switches, such as mechanical tap changers, are used for phase shifting transformers which can be used for

regulating steady-state power flow, but too slow to provide additional dynamic control. The phase shifting transformer can set the power flow through a transmission line, avoiding unidentified loop flows and sharing the power flow over parallel lines. Transformers equipped with tap changers and phase shifting transformers are very efficient, reliable and installed all over the world [Van Hertem et al, 2005].

Thyristor based controllers can switch much faster, typically within a few periods of system frequency. A lot of these devices are installed, mainly Static Var Compensators (SVC) and HVDC systems. Fast switching valves e.g. Insulated Gate Bipolar Transistors (IGBTs), allow a straightforward construction of voltage source converters (VSC), making practically instant control possible. Both thyristor based and IGBT based controllable devices can provide additional dynamic control and damping to the power system, increasing the security and loadability of the system.

FACTS are system specific and definitely postpone network reinforcement. But, implementation of FACTS and their full utilization may require considerable changes in the operation of power systems (e.g. change from preventive to corrective mode of operation). It would also require major developments in the communication and computer. Therefore, from an economic point of view, FACTS are expensive and system reinforcement is more attractive [Mutale and Strbac, 1999; Van Hertem et al, 2005]. They will also only find application in Uganda in niche situations of totally no ROW or stability complications.

3.7 HIGH VOLTAGE DIRECT CURRENT (HVDC)

An alternative way of providing additional transmission capacity is the installation of an HVDC link. An HVDC system consists of a rectifier, a DC conductor and an inverter. DC links are mainly used for transportation of bulk power over long distances or for undersea transmission. DC conductors have lower losses per kilometer than AC conductors. However, the converters exhibit high losses. Therefore, there exists a certain distance, the break- even distance, where the total cost of an AC line (AC terminal and line cost plus losses) is equal to the total cost of the HVDC system (DC terminal and line cost plus losses). For distances longer than the break even distance, HVDC systems cost less than AC line. For undersea connection, HVDC cables are used.

AC cables would require reactive compensation at regular intervals, which is very impractical at sea [Larruskain et al, 2011].

Furthermore, market tendency in recent years has shown that converter stations costs are falling, whilst AC substation costs have been rising, therefore the difference between initial costs has been dropping. As a result above a certain transmission distance, the HVDC will always give the lowest cost. The break-even distance is marked with a cross in the Figure 3-3. The distance depends on several factors, such as transmission medium and different local aspects (permits, cost of labor, etc). Therefore, an analysis must be made for each individual case. The break even distance in overhead lines ranges from 400-800km, whereas in submarine cables it is much smaller and ranges from 40-80km [Larruskain et al, 2011].

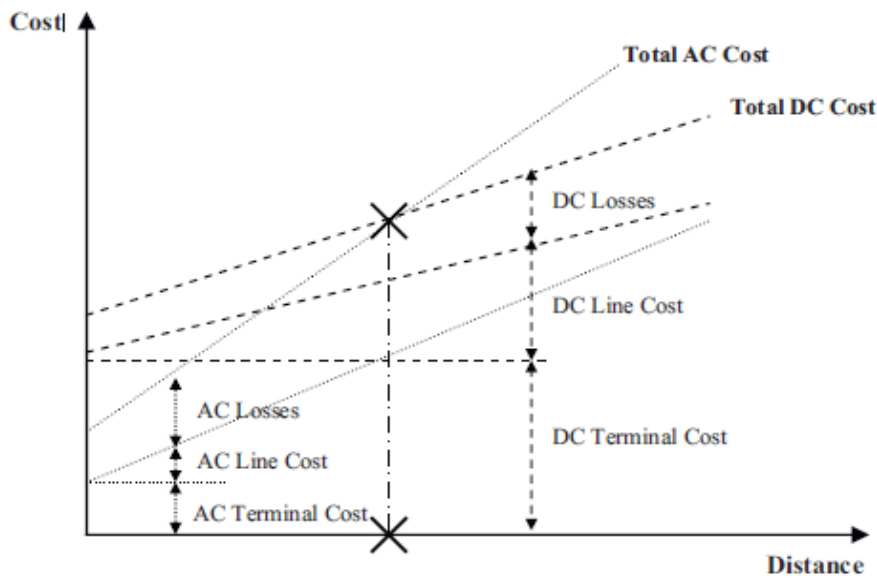


Figure 3-3: HVAC vs. HVDC cost [Larruskain et al, 2011]

Line commutated converter (LCC) HVDC systems use thyristor valves. They thus inherit the advantages in terms of power flow control of thyristor based FACTS. A new development in the HVDC systems is the voltage source converter (VSC) HVDC. This new technology has some important advantages over LCC HVDC. While the latter can only control active power, the former can control both active and reactive, which is advantageous for grid operation. The ability to control reactive power means that no external reactive power sources have to be

connected to the converter. With LCC HVDC, bulk reactive filters are needed. Therefore, VSC HVDC has a much smaller footprint. Its drawbacks compared to the LCC HVDC are the higher losses and lower power and voltage ratings. In Table 3-6 the ratings for HVDC systems are given.

Table 3-6: Limits of HVDC systems [Buijs et al, 2001]

	LCC HVDC	VSC HVDC
	State-of-the-art: installed	
Transmission capacity (MW)	6300	350
Voltage (U_{dc}) (kV)	± 600	± 150
	State-of-the-art: possible	
Transmission capacity (MW)	6400	1100
Voltage (U_{dc}) (kV)	± 800	± 300

The number of network elements with VSCs in transmission grid is currently limited. However, they offer the most possibilities and are likely to become attractive when several grid issues disallow conventional AC and would require a combination of FACTS. For example, LCC HVDC in weak networks, are prone to commutation failure and voltage instability and have to be supported by additional FACTS such as SVCs. A VSC converter can operate in a weak network without need for additional FACTS.

In conclusion, the motivations to use HVDC are; long distance bulk power transmission, long cable transmission, asynchronous interconnection, stabilisation of power systems, long distance water crossing and less environmental impact. Some of the major limitations are; very expensive converter stations, difficult on multi-terminal connection and DC switching difficulty. Larruskain et al [2011] and Setreus and Bertling [2008] have more detailed discussions on this. HVDC can find application in Uganda in projects with longer lines, for example, Karuma-Juba interconnection project.

Table 3-7: Examples of projects with VSC-HVDC technology [Agelidis et al, 2006 and Juiping et al, 2008]

Project	Rating	Distance	Technology	Application / reason	Year
Gotland, Sweden	50 MW	70km	VSC (Submarine Cable)	Small Scale Gen, Wind Power, Voltage Support	1999
Eagle Pass, USA	36 MW	(Back to Back) B-t-B	VSC	Interconnection, Voltage Control	2000
DirectLink, Australia	180 MW	65km	VSC (underground cables)	Controlled Asynchronous Connection, easy to get permission for underground cables	2000
Caprivi Link	300 MW	970 km	VSC (OHL)	Connection of weak AC networks	2009
Valhall, Norway	78 MW	292 km	VSC (Submarine Cables)	off shore electrification, minimizing emission of green house gasses, improve operation efficiency	2010

3.8 IN SUMMARY

This chapter has reviewed 5 transmission technologies. It has also discussed how these technologies can overcome the transmission constraints faced in Uganda and finally it identifies limitations the technologies have. Table 3-8 summaries the discussion by giving a qualitative snapshot of the comparative technology evaluation in regards to overcoming these constraints.

Table 3-8: Comparative evaluation of the technologies

	Environment	Cost	Technical	
			Stability and control issues	Increasing Capacity
New AC OHL	Weak	Good	Good	Strong
AC Underground Cables	Strong	Weak	Good	Good
Uprating	Good	Strong	Good	Strong
HVDC	Good	Weak(<400km) Strong(>400km)	Strong	Strong
FACTS	Strong	Weak	Strong	Weak

Advanced technologies (e.g. FACTS and HVDC) offer the hope of better control of transmission flow and voltages. Such improved control would permit the system to be operated closer to its thermal limits, thereby expanding transmission capabilities without increasing its foot prints. Less environmental and technical constraints will be faced, thus reducing the conflicts about transmission siting. Unfortunately, these advanced technologies are still too expensive for wide spread application in Uganda, although they may be economical in niche applications. They are promising for future applications like RES integration (wind and solar) and long distance interconnection (e.g. Karuma- Juba interconnection).

From the discussions, the most promising transmission technologies that can find wide application in Uganda are AC OHL and uprating. Also as an application of AC OHL, overbuilding can also find application since it reduces environmental impact and is cheaper in the long run. Therefore, these technologies will be applied as planning solution in the analysis ahead.

4 THEORY DEVELOPMENT

4.1 INTRODUCTION

As discussed in chapter 2, transmission planning is a very complex process and recent trends make it even more complicated. These introduce more constraints with conflicting objectives and increased uncertainty, thus bringing about a paradigm shift to the planning environment and making traditional planning methods inadequate. Chapter 3 discusses how different transmission technologies can be used to overcome and (or) minimize these constraints. Based on the findings, the planning method adopted to achieve our goal (i.e. use of technology and quality decision making to minimize transmission constraints) is illustrated in Figure 4-1 .

As shown in Figure 4-1, the proposed process begins with a clear identification of the purpose of the transmission plan, followed by a comprehensive assessment of the current situation. This situation analyses provides a firm basis for assessing future conditions, problems, constraints and potential solutions (including other transmission technologies). The MCDM assesses the various transmission alternatives that might solve the identified problems and constraints. The planning methodology goes further to acknowledge the hard uncertainties that the planning process faces. A final decision is made guided by the results from the MCDM model.

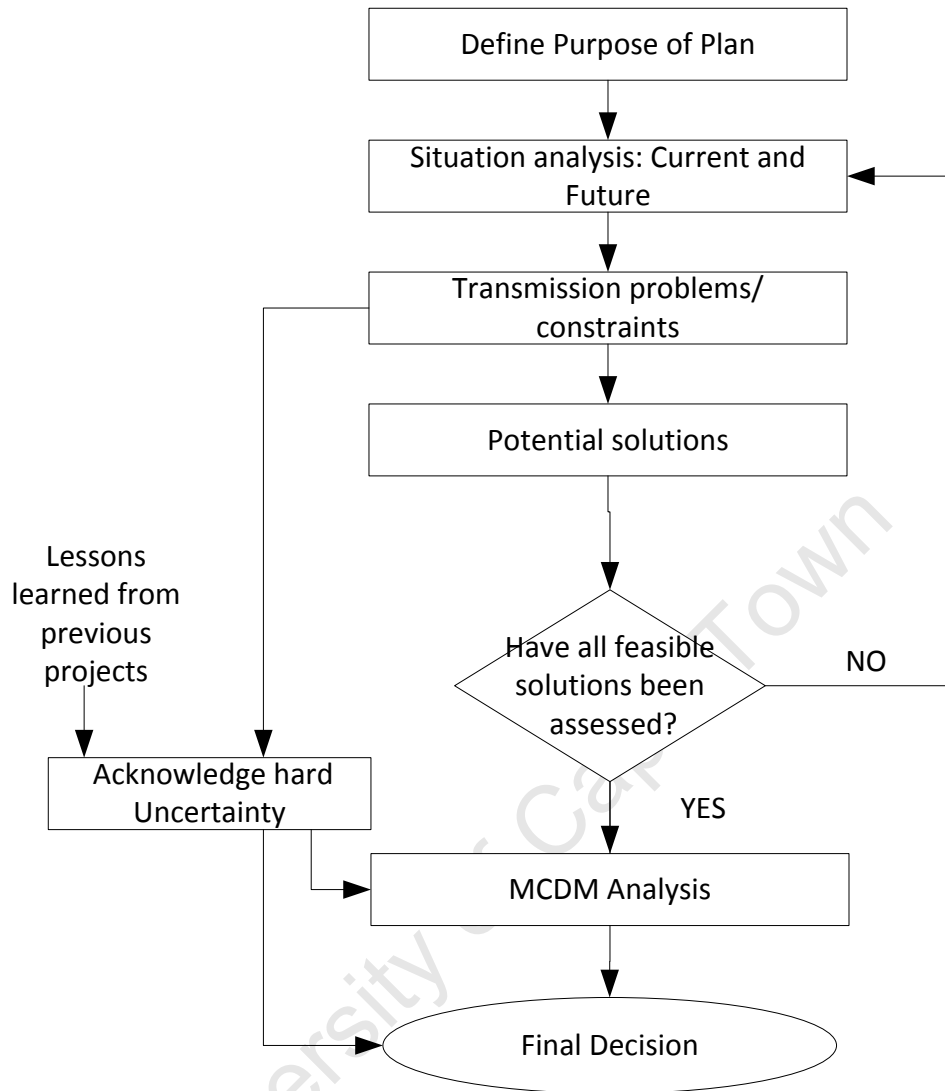


Figure 4-1: Proposed planning methodology for this dissertation

4.2 MCDM ANALYSIS

The MCDM process adopted in this research project is the simple multi-attribute rating technique (SMART) value function approach [Belton and Stewart, 2002; Espie, 2003]. Based on the linear function (Equation 2.1), this will involve assigning user preference weights to the constraints, calculating the value function for each criterion, and finally aggregating the weights and the values. The total decision score for each alternative solution is then determined using a linear additive-value function to sum the individual scores for each criterion. The alternative

that produces the lowest weighted score is considered as the most desirable solution and thus the alternative will face less project constraints.

The next sections (4.2.1 -4.2.6) describe in detail how the MCDM will be carried out in the analysis (i.e. it breaks down the MCDM process into systematic steps and is guided by the SMART). The Figure 4-2 below gives an overview and summary of the steps of the SMART MCDM.

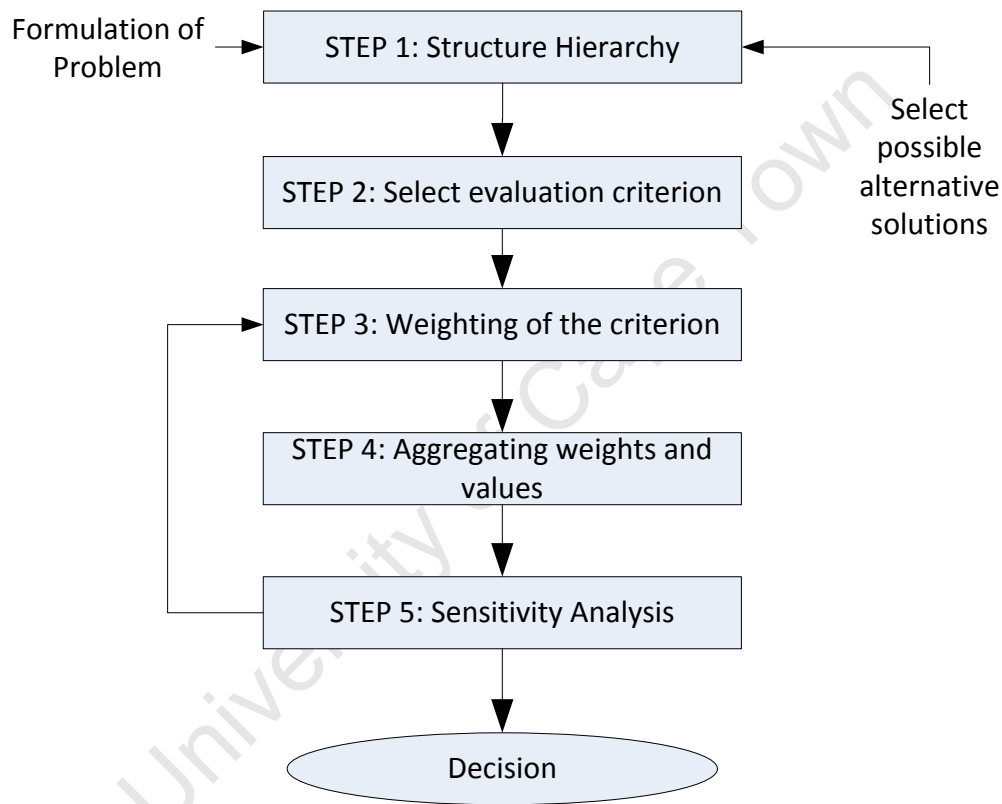


Figure 4-2: Summary of the MCDM

4.2.1 Step 1: Structure the hierarchy

The first step of the MCDM is to structure the problem (or modeling the problem) as a decision hierarchy as described in Saaty [1994]. This is perhaps the most creative part of decision making that has a significant effect on the outcome.

A useful way to proceed in structuring a decision is to come down from the goal as far as one can by decomposing it into the most general and most easily controlled factors. One can then go up from the alternatives beginning with the simplest sub criteria that they must satisfy and aggregating the sub criteria into generic higher-level criteria until the levels of the two processes are linked in such a way as to make comparison possible.

The decision hierarchy for this dissertation will have 3 levels. Level 1 is the overall goal, level 2 are the selected criteria that must be satisfied to fulfil the overall goal and level 3 are the alternative planning solutions that can be used to optimize the criteria described in level 2.

For example, assume the overall goal is “G”; the criteria that need to be satisfied to achieve the goal are C1, C2, C3 and C4; and finally the different solutions that can be used are S1,S2,S3,S4,S5 and S6. Figure 4-3 shows an illustration of the decision hierarchy of this example.

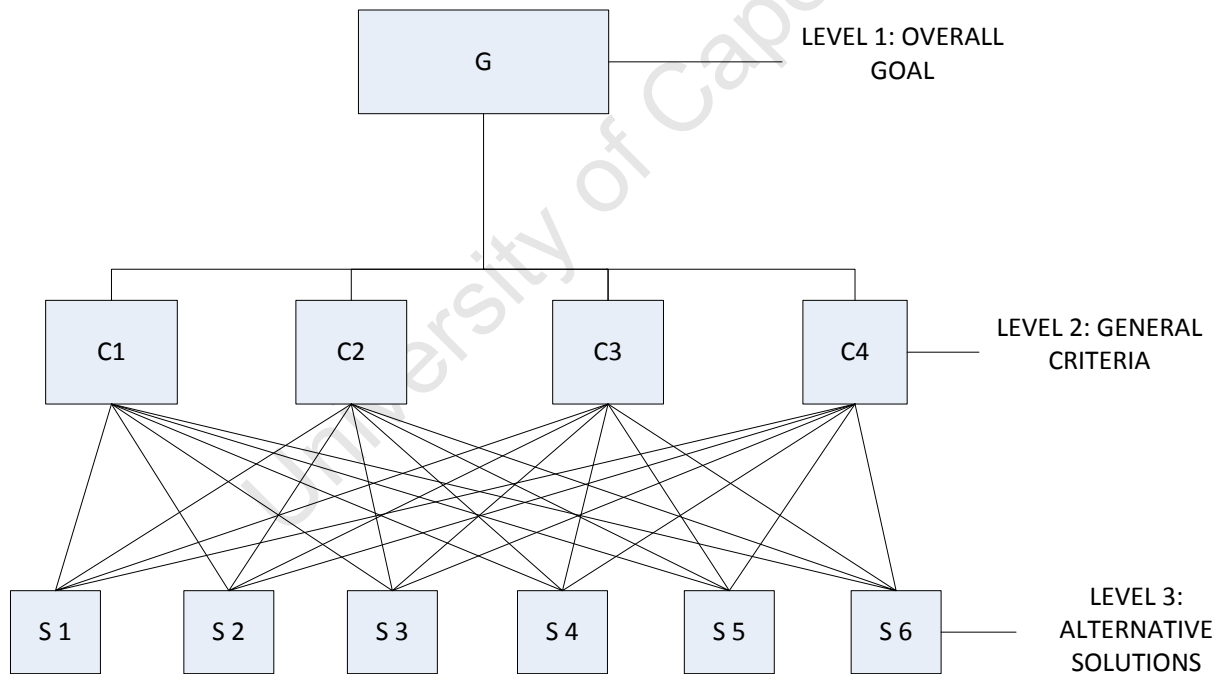


Figure 4-3: Decision hierarchy

4.2.2 Step 2: Select evaluation criterion

To allow each technology option to be assessed, evaluation criteria need to be identified. From the finding in the literature review, the constraints common to Uganda are:

- Financial constraints[UETCL,2008]
- Technical constraints[UETCL,2012]
- Environment constraints[NEMA, 2011; UETCL, 2008; Kakura et al, 2001; and Akampurira et al., 2009]
- Political constraints [Akampurira et al, 2009; UETCL,2008 ;and Bekker and Gaunt, 2006]

The next sub-sections contain evaluation criteria for the constraints to be used in the MCDM analysis. The political constraints are characterised by hard uncertainty so modelling using probability is meaningless [Young, 2001; and Bekker and Gaunt, 2006]

4.2.2.1 Environmental Impact (EI) criterion

The goal is to minimize the environmental effect (social environment and natural environment) by use of different transmission technologies. That is to say, minimize the impact on settlement (settlement areas, cultural assets, and real assets), recreational use (fields and grassland), landscape (view places) and areas of unspoiled nature (forestry).

The method that will be adopted for this criterion is to consider the total surface area occupied by the tower footing (ROW inclusive) and the span of the new or modified transmission technology to represent the likely environmental impact for each circuit route [Saulo et al., 2010; Espie et al., 2003; L'Abbate et al., 2010]. Typical values of ROW are shown in the Table 4-1 below.

Table 4-1: Typical ROW for 110kV to 380kV double circuit lines [Kiessling, 2003]

Rated voltage, kV	110	220	380
Right of way (ROW), m	40 to 50	55 to 60	60 to 70

The author acknowledges that EIA involves more than just surface area occupied by the lines (as already discussed) and requires specialists to carry out this assessment. The surface area is used to give a scale of the impact the technology will have on the environment in comparison to other technologies. The EIA also depends on the type of land use (social sensitive sites, ecologically sensitive sites and archeologically sensitive sites), so the impact will vary depending on the proximity to these key features of environment. This can be captured by assigning environment a higher weight in the MCDM analysis depending on the type of land use.

For each proposed transmission technology, the environmental impact criterion (EI_c) will be represented by the surface area (tower footing, ROW and span), which will be calculated using Equation 4.1.

$$EI_c \equiv A = (\text{tower footing} + \text{ROW}) \times \text{span} \quad 4-1$$

This surface area will then be summed over all new or modified circuits to determine a weighted value for each technology.

4.2.2.2 Cost Criterion

The goal of this criterion is to identify from the selected transmission technologies that satisfy the basic electric criteria, the option with a minimum economic and financial impact. The method that is going to be adopted here is to calculate the capital cost.

Capital cost is an important factor when assessing alternative planning solutions. This is a summation of the costs involved in implementing each of the options selected plus any ongoing costs related to implementation or other operational aspects associated with the network. The cost of each option will either be expressed as a current cost or as a future worth equivalent at the end of the planning period, converted using the present-worth calculation.

To get the dimension of the monetary streams comparable, everything must be referred to a specified time, i.e. accumulated or discounted. Normally in the investigation process, this is the investment time. The on today's time discounted value of a future size is the actual cash value or present value. The cash value contains installation overall costs for the transmission lines,

transformers, bus bars, if necessary compensation equipment, and relevant building as well as replacement-overall-costs for equipment at the end of the life time.

The capital expenditure of transmission lines is highly dependent on; line voltage, number of circuits and conductor cross section area. However, other factors contribute significantly to decrease or increase the required investment such as tower heights, characteristics of the line route, and resulting relationships between the suspension towers to strain towers and the external loads, for instance wind and or ice loads. The degree of reliability and security can also play a significant role in the total investment. Also, indemnities to be paid to land owners have been increasing in recent years. The separation of investment is given in Table 4-2.

Table 4-2: Separation of investment in % [Kiessling, 2003]

Voltage, kV	110	220	380
Circuits	35 to 45	40 to 50	45 to 55
Towers	35 to 45	35 to 45	35 to 45
Foundation	15 to 25	10 to 20	7 to 15
Engineering	5	4	3

Generic unit cost estimates from Lavalin and Brinckerhoff [2011] based on projects in the year 2010 are shown in the Table 4-3 below. These cost estimates depend on the technology, voltage level, the configuration and the capacity of the line. For each line, a fixed cost is added to take into account the AC substations additions at each line end.

Table 4-3: Unit cost of transmission lines [Lavalin and Brinckerhoff, 2011]

Technology	Voltage level, kV	Configuration	Line cost, k\$/km	Fixed cost, M\$
AC	132	double cct	180	8
AC	220	double cct	240	10
AC	345	double cct	350	12
AC	400	double cct	400	13

The present values (PV) will be calculated and is carried out to capture the erosion of future income by inflation and the existence of risk. This will be calculated by multiplying by a unit cost given by $(1+i)^t$, where t , is the number of years and i , is the inflation rate [Saulo et al, 2011].

4.2.2.3 Reliability Criterion, R_c

The reliability criterion adopted in this dissertation is the expected energy not supplied (EENS), and this will be calculated as described below [Billinton and Allan, 1996];

$$EENS = \sum U_f \cdot P_f \quad 4-2$$

Where; U_f is the probability of being in a failure state f i.e. unavailability in hr/yr and

P_f is the power not supplied during the failure state f in MW

For a series network, $U_s = \lambda_s \cdot r_s$; where λ_s is the failure rate of a single component that is the equivalent of the components in series and r_s is the total repair time of the single component.

For a two parallel network, $U_p = \lambda_p \cdot r_p = \lambda_1 \lambda_2 \cdot r_1 r_2$; where λ_p , is the failure rate of a single component that is equivalent of the components in parallel and r_p , is the total repair time of the single component

The EENS value will provide a quantitative prediction of the system performance, and also provide a way of constantly evaluating the respective and relative reliability levels of alternatives proposed.

The goal of this criterion is to identify the alternative with minimum EENS value. So this implies that the alternative with the least EENS performs most adequately for the period of time intended under the operating conditions.

The values from each criterion are compared with one another against the criterion goal by normalising to a convenient scale (i.e. 0-1). This develops single dimension utilities by converting measures into value functions (utilities) that can be used in Equation 2.1.

4.2.3 Step 3: Weighting the criteria

The next step is to determining the relative importance and weight of the each criterion with respect to the function objective of the transmission project. This can be referred to as user preference weights.

Not all criteria will be equally important. User preference weights allow the designer to stress some criteria over others. For example, some utilities may be forced to stress cost very heavily over others because of very limited resources while other utilities may prefer more reliable designs. It can be noted that relative score representing performance may assume slightly different values depending on the experts involved in their choice but this disparity is not substantial. On the other hand, the user preference weights may differ widely from one user to another depending on the prevailing conditions under which the network is being designed [Atanackovic et al, 1998].

The user preference weights represent the users concerns under different circumstances, thus is subjective. It is also perhaps the most contentious issue associated with the MCDM techniques as the chosen weight values will have direct impact on the resulting solution desirability score.

Elicitation of weights can be difficult, several methods have been proposed for reducing the burden of the process. Many of these methods involve asking the decision maker simple questions about the relative importance of the attributes and using the responses to identify weights that are intended to approximate the decision makers true weight. One of the proposals has been the based on the rank order centroid (ROC) weights [Barron and Barrett, 1996; Edward and Barron, 1994]. Barron and Barret [1996] found that ROC captures a substantial portion of the information content of totally precise weights and compared to other approximation methods, ROC is clearly and overwhelmingly the most efficacious. In this light, the dissertation will adopt the ROC weighting method to estimate the weights.

In the ROC method, weights are assessed based on the rank order of the criteria importance. The rank order will be determined by the decision maker based on the objective/ goal of the

process. The ROC assigns weights as follows, w_1 is the most important objective, w_2 is the weight of the second most important objective and so on. For k objectives,

$$w_1 = \frac{1 + 1/2 + 1/3 + \dots + 1/k}{k}$$

$$w_2 = \frac{0 + 1/2 + 1/3 + \dots + 1/k}{k}$$

$$w_k = \frac{0 + 0 + 0 + \dots + 1/k}{k}$$

More generally, the weight of the k^{th} attribute is:

$$w_k = (1/k) \sum_{i=1}^k (1/i) \quad \mathbf{4-3}$$

Table 4-4 contains weights calculated from Equation 4.3 for values of k from 2 to 6.

Table 4-4: ROC weights for indicated number of attributes

Rank	Number of attributes				
	6	5	4	3	2
1	0.4083	0.4567	0.5208	0.6111	0.7500
2	0.2417	0.2567	0.2708	0.2778	0.2500
3	0.1583	0.1567	0.1458	0.1111	
4	0.1028	0.0900	0.0625		
5	0.0611	0.0400			
6	0.0278				

4.2.4 Step 4: Aggregating weights and the value functions

The model used is an additive model (Equation 2.1 of this dissertation), the total score for each alternative being the sum of the weighted value scores for all the criteria for the alternative. In other words, the total decision score for each alternative is then determined using linear additive –value function to sum the individual scores of each criterion [Espie et al 2003, Atanackovic et al, 1997].

The weighted evaluation for each technology alternative will be obtained by multiplying the matrix of evaluation rating (value function or score) by the vector of attribute weights (W) and summing over all attributes. Mathematically represented as;

$$\textit{Weighted score for alternative} = \sum \textit{attribute weight} \times \textit{value function}$$

$$\mathbf{WS}_k = \mathbf{W}_C \times \mathbf{Score}_{C_k} + \mathbf{W}_E \times \mathbf{Score}_{E_k} + \mathbf{W}_R \times \mathbf{Score}_{R_k} \quad \mathbf{4-4}$$

Where \mathbf{WS}_k is the weighted score for the alternative, \mathbf{W}_C , \mathbf{W}_E and \mathbf{W}_R are the user preference weights from table 3.3 of cost, environment and reliability respectively, and $\mathbf{Score}_{C(E,R)_k}$ is the score of cost (environmental impact, reliability) of alternative k . Therefore, the alternative with the lowest weighted score is considered as the most desirable among the assessed alternatives since it faces least constraints (i.e. 0-least constraint and 1- more constraint).

4.2.5 Step 5: Sensitivity analysis

To ensure that the decision process is indeed robust, a sensitivity analysis will be performed on the criteria ranks [Valiris et al., 2005]. It is going to take the form of changing the rank position of different criterion and see what effect it has on the overall weighted score.

4.3 ACKNOWLEDGEMENT OF HARD UNCERTAINTY

Bekker B (2010) defines hard uncertainty as, a type of uncertainty in which the set of all outcomes of an action is unknown and can only be hypothesized, or if all the outcomes are known, the probability distributions of all these outcomes are unknown or not fully definable. Humans and other stimuli create the future and modelling using probability is meaningless.

Bekker and Gaunt [2007] used an uncertainty checklist as a means of making uncertainties explicit in electrification projects, thus increasing the quality of decision making, and ultimately the success of the project. This makes potentially hidden project uncertainties explicit without restoring to subjective numerical methods.

That said, the dissertation goes further to try to improve the quality of the planning process and ultimately the success of the project by acknowledging uncertainties and to do this, proposes

the use of an *uncertainty checklist*; created from literature and lessons learned from failures and problems on previous transmission expansion projects.

This checklist will ensure the following:

- that all the uncertainties have been considered and that measures are put in place to overcome them
- that uncertainties are explicit to the decision maker
- that potentially hidden project uncertainties and outcomes are considered
- that the DM is informed about the major uncertainties that lead to project failure and
- it will bring the attention of the decision maker on where measures are required to reduce the impact of hard uncertainty.

The final step is to make the decision or recommendations based on the results of the MCDM analysis. This will be a quality decision.

4.4 IN SUMMARY

This chapter has proposed a planning methodology that will be tested on the case study identified in the next chapter. The key benefit of this method is that it uses MCDM that can handle a multiple and conflicting objective problem. It also further acknowledges hard uncertainties that are usually ignored. Therefore, the approach leads to a more comprehensive decision making process and makes it possible to select a planning solution that optimizes (minimize) constraints.

The next chapter is the case study on which the analysis will be applied.

5 CASE STUDY: THE PROBLEM AND ALTERNATIVES

5.1 INTRODUCTION

This chapter describes the case study. It is one of the transmission projects proposed for transmission grid expansion in the GIP 2008-2023. The chapter also proposes alternative transmission solutions that can be considered based on discussions in chapter 3. It finally gives a brief discussion of St. Clair curve that is used to estimate the loading limits of the transmission lines.

Uganda has had an increasing demand for power and this is evident from Figure 1-1. The average load growth in the past 20 years has been approximately 5.9% per annum. Assuming factors remain constant (5.9% load growth) for the next 30 years, a future load forecast is presented in Figure 5-1 below. The constant load forecast method used in this analysis is the most practical approach; considering so many other uncertainties.

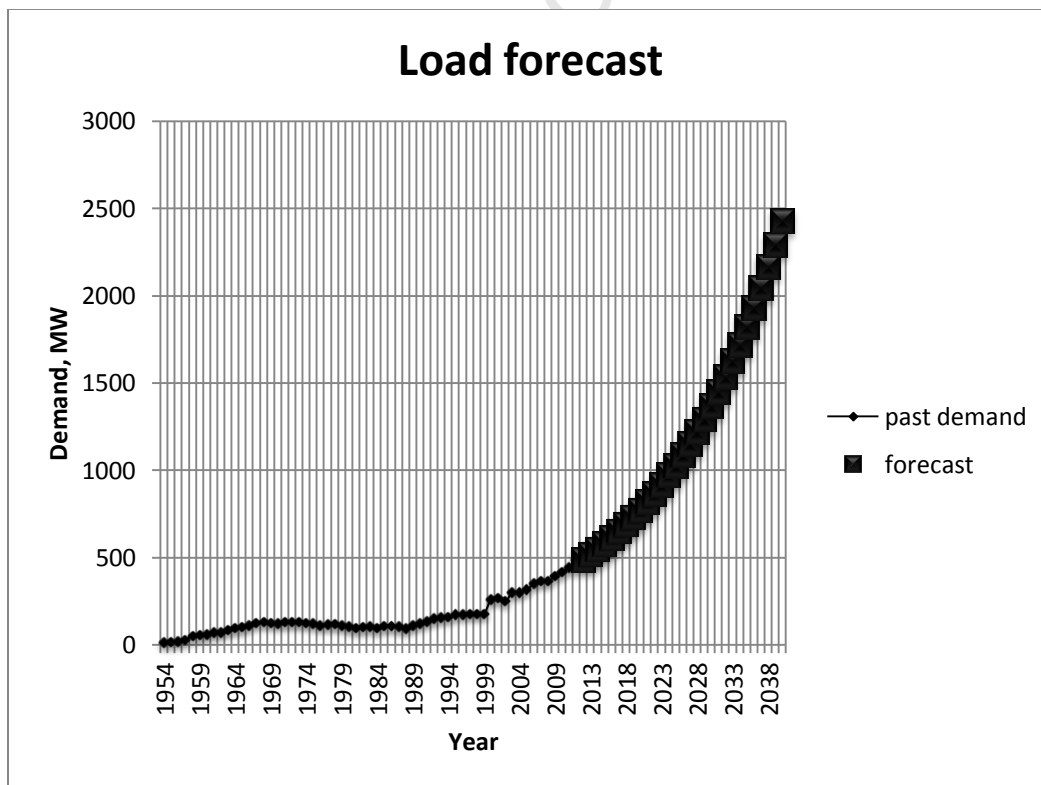


Figure 5-1: Electricity demand forecast

From the graph above it is evident that in the periods of political instability, the demand dropped (i.e. 1978-1986) and in periods of political stability (i.e. 1990 to 2012) the demand has been increasing. Therefore, the forecast in Figure 5.1 assumes political stability and so does the dissertation.

The GIP 2008-2023 was released to meet the proposed programmes for system expansion. The components of the projects include the construction of power transmission line, construction of substations, resettlement and compensation, and consultancy services [UETCL, 2008]. The GIP 2008-2023 projects were categorized as follows:

- Power evacuation projects (e.g. Karuma interconnection project 400kV, Mputa interconnection project 132kV and Isimba interconnection project 132kV)
- System extension projects (e.g. Kawanda-Masaka 220kV, Mutundwe-Entebbe 132kV, Opuyo-Moroto 132kV and Mirama-Kabale 132kV)
- Regional interconnection projects e.g. Bujagali -Tororo-Lessos 220kV (Uganda to Kenya), Mbarara-Mirama-Birembo 220kV (Uganda to Rwanda), Masaka-Mutukula-Mwanza 220kV (Uganda to Tanzania), Nkenda-Mpondwe-DR Congo 220kV
- Reinvestment projects (e.g. Tororo-Opuyo-Lira 132kV and Nalubale-Lugazi 132kV)

The objective of these projects is to build a robust network, enhance transfer capacity, improve reliability and quality of power supply, and provide capacity for regional power trade. The project to be analysed is the regional interconnection project between Uganda and Kenya, and its objective is to boost regional trade between the two countries. Figure 5-2 shows the existing and proposed future transmission lines in East Africa.

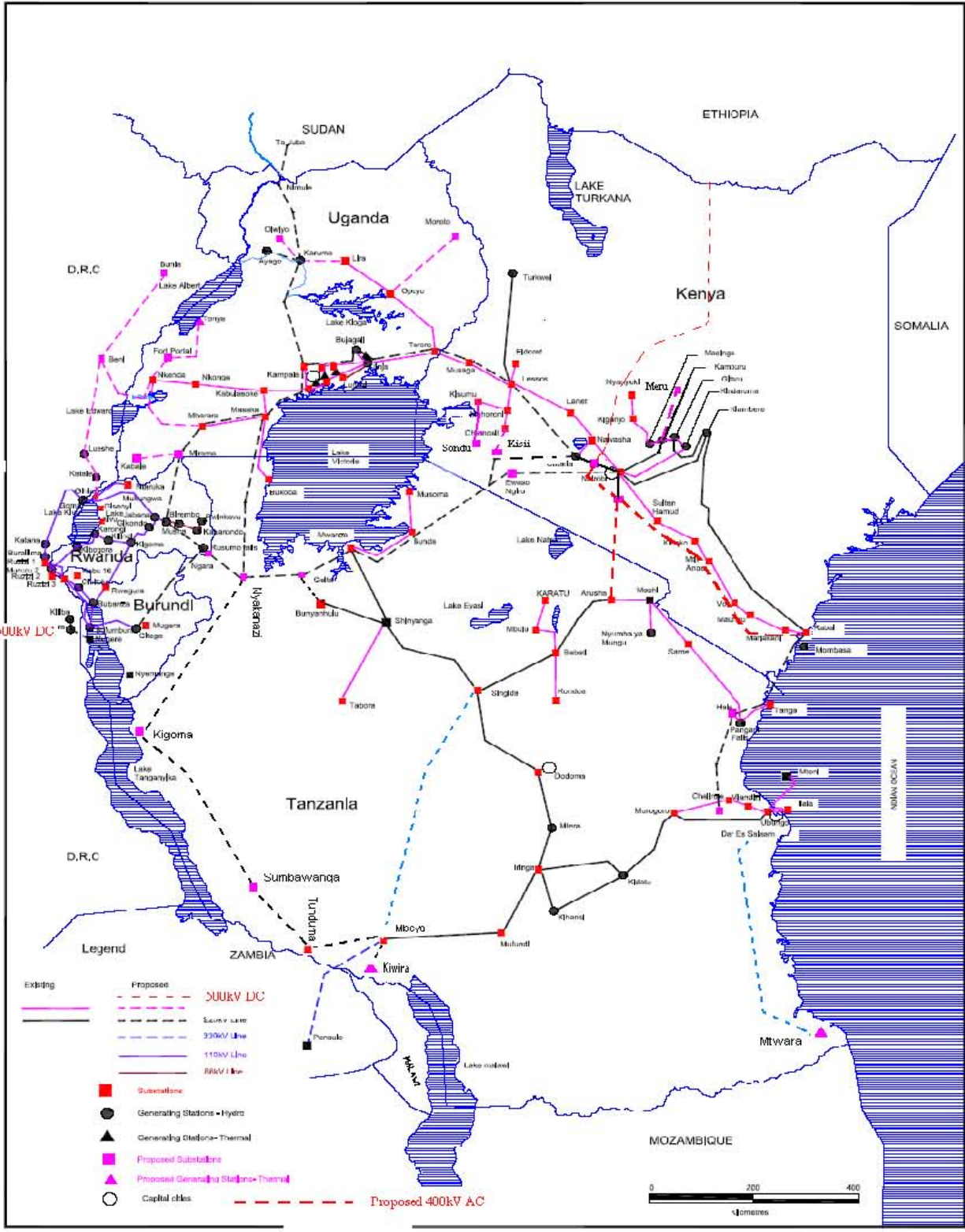


Figure 5-2: Existing and future transmission lines the East African Community [EAPP, 2011]

5.2 UGANDA-KENYA INTERCONNECTION

Currently, Uganda and Kenya are interconnected via a double-circuit 132 kV line from Tororo (Uganda) to Lessos (Kenya). Uganda exports power to Kenya since 1958 following the construction and commissioning of Owen falls power station in Uganda and the 132 kV line from Tororo to Nairobi [Lavalin and Brinckerhoff, 2011]. The transfer capacity of the line is 118 MW.

A recent power transfer forecast based on the “National Generation Plan and Regional Interconnection Plans” (NGP_RIP) and the “Regional Generation Plans and Regional Interconnection Plans” (RGP_RIP); gives the maximum possible transfer between any two countries in the EAPP along with the transmission requirements over the period 2013-2038 and the transfer capacity between Uganda and Kenya. The estimated transfer capacity is 794 MW between the two countries for this period [Lavalin and Brinckerhoff, 2011].

The GIP 2008-2023 proposed another interconnection between Uganda and Kenya. Currently, funds have been secured for a 220 kV line to be constructed in parallel with the existing 132 kV interconnection between Tororo and Lessos and will be extended to Bujagali in Uganda. The line will have a transfer capacity of 300 MW and the earliest year of commissioning is 2014.

Lavalin and Brinckerhoff [2011], also propose construction of yet another 220kV line from Bujagali to Lessos to meet the increased capacity. Its transfer capacity is expected to be 440 MW and the earliest year of commission is 2023. This is illustrated in the Table 5-1 and Figure 5-3.

Table 5-1: Existing, under construction, and proposed interconnection between Uganda and Kenya [Lavalin and Brinckerhoff, 2011]

Project	Voltage, kV	Distance, km	Capacity, MW	Configuration	Status
Uganda-Kenya	132	254	118	double-circuit	Existing
Uganda-Kenya	220	254	300	double-circuit	Funds secured
Uganda-Kenya	220	254	440	double-circuit	Proposed

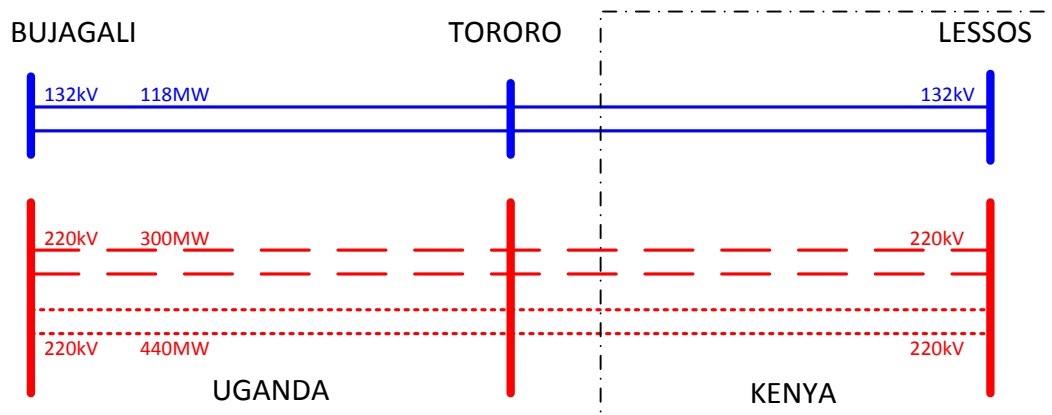


Figure 5-3: Kenya- Uganda interconnection [Lavalin and Brinckerhoff, 2011]

5.3 TRANSMISSION LINE DESIGN AND CAPACITIES (ST. CLAIR CURVE AND SIL)

Depending on the power transfer capacity and the distance between the power systems, the technology of the transmission line and the voltage level can be defined. For HVAC technology, the characteristics of the proposed transmission lines for each voltage level are given in Table 5-2. It should be noted that this conductor selection for the HVAC transmission is based on similar previous projects. However, in the design phase, a detailed conductor selection study should be performed for optimum conductor performance.

Table 5-2: SIL of typical AC OHLs

Voltage, kV	Surge impedance Z_c, Ω	Surge Impedance Load, MW	Conductor size per phase (ASCR), mm ²
132	320	54	1x795
220	280	176	2x468.6
345	285	418	2x954

The transmission line loadability curve, also known as the St. Clair curve has been a valuable tool for quickly estimating the power transfer capabilities of transmission lines. Due to its universal characteristics, i.e. applicable to all voltage levels, the St. Clair curve is generally accepted in the industry as a convenient reference for estimating the maximum loading limits on transmission lines.

The St. Clair curve, presented in Figure 5-4, shows the loadability of transmission lines in terms of their surge impedance loading (SIL). It is well known that the per unit line data normalised using SIL and surge impedance is constant i.e. independent of the line construction and voltage rating. Therefore can be used universally [Hao and Xu, 2008].

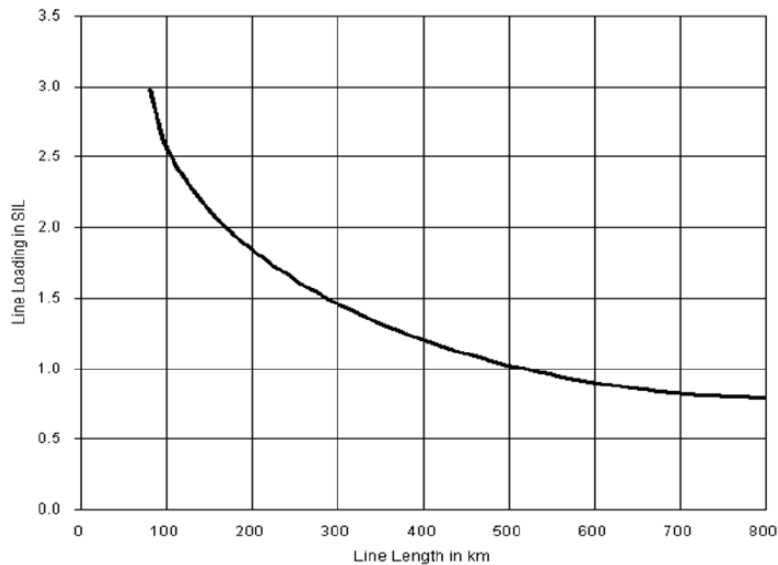


Figure 5-4: Transmission line loadability curve (St. Clair curve)

This curve shows the limiting power (in terms of the Surge Impedance Loading, SIL) that can be transmitted over a single circuit transmission line as a function of the line length. Short lines (<80 km) are limited by the thermal limit, medium lines (<300 km) are limited by the voltage drop limit (maximum 5%) and long lines (>300 km) are limited by the steady state stability limit. This curve assumes 50 kA fault duty at the two line ends which represents two well developed systems.

Based on the SIL given in Table 5-2 and the loadability curve shown in Figure 5-4, the capacity of the dissertations proposed new AC technology and voltage have been calculated, with the following assumptions:

- The capacity was reduced by 20% as the short circuit levels may not be 50 kA as assumed in the loadability curve.
- The capacity of a double-circuit line is twice as much as that for a single-circuit line.
- A 1.5 SIL for 254 km

A summary of line capacities is given in Table 5-3 and the detailed calculations are presented in Appendix F.

Table 5-3: Summary of possible maximum capacities of different voltages

Voltage, kV	Distance, km	Capacity, MW	Configuration
132	254	130	double-circuit
220	254	422	double-circuit
345	254	1000	double-circuit

5.4 PROPOSED ALTERNATIVES

SC-Lavalin and PB [2011], proposed construction of two double circuit 220 kV AC OHLs to meet the estimated power transfer between Uganda and Kenya. This is shown and illustrated in Figure 5-3 and Table 5-1 above. For the analysis going to be done, this will be considered as alternative one, **A1**. This dissertation proposes other alternatives that could have been considered for this interconnection.

5.4.1 Alternative two (overbuilding)

The dissertation proposes construction of one double 345 kV circuit instead of two 220 kV AC OHLs. This will be alternative two, **A2**. The aim is to achieve less environmental impact, cheaper costs in the long run and of course boost regional power trade.

5.4.2 Alternative three (uprating)

This alternative uses uprating. In this a case it will be done only after the construction of the 220 kV in 2014. Therefore assuming a successful voltage uprating feasibility study, the dissertation proposes refurbishment of the old already existing 132 kV line by replacing the conductor and voltage uprating and construction of a 132 kV line. This will be alternative three, **A3**. The aim here is to achieve cheaper costs by uprating than construction of the 220 kV line.

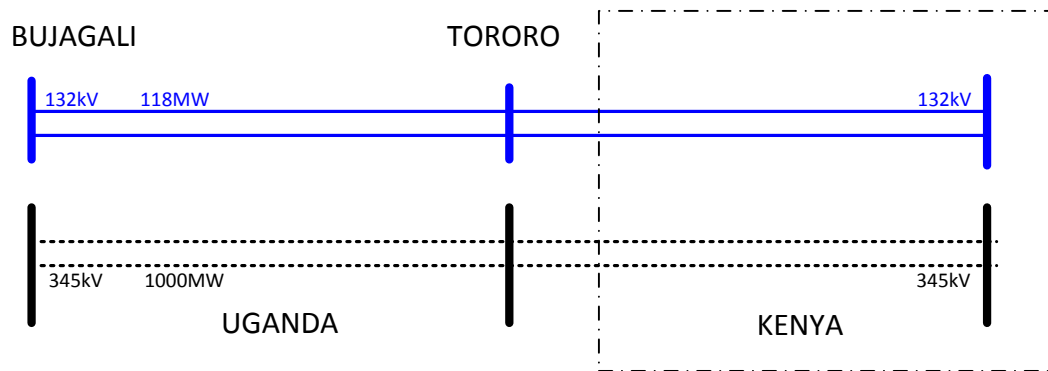


Figure 5-5: Alternative 2

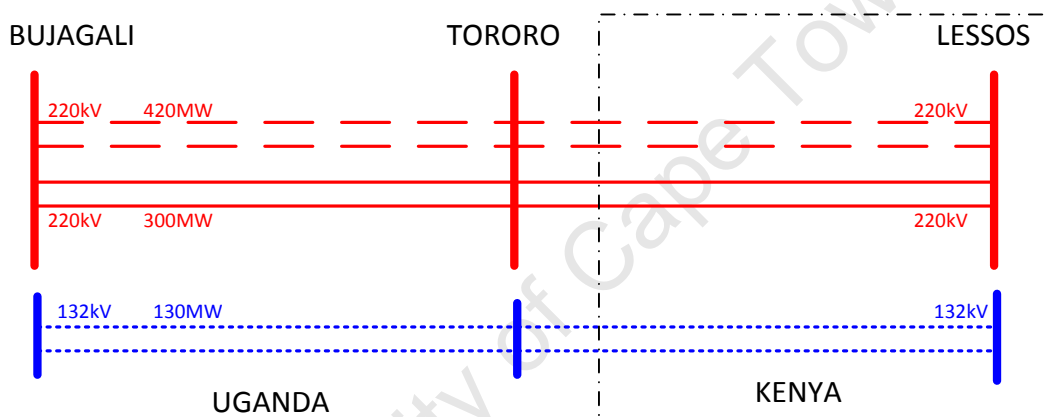


Figure 5-6: Alternative 3

5.5 IN SUMMARY

This chapter has described the case study and has also proposed two different planning solutions (i.e. A2 and A3) that can achieve the same objective of boosting regional trade as the originally proposed solution (A1). The different planning solutions use different transmission technologies as discussed in chapter 3.

In the next chapter, actual test will be carried out on the different cases described above. The results are also presented.

6 CASE STUDY: EVALUATION AND RESULTS

6.1 INTRODUCTION

This chapter presents the application of the theory developed in chapter 4 and uses it on our case study identified in chapter 5. This leads to a set of results which will be presented. The chapter continues to acknowledge the likely hard uncertainties to be faced in the process. Finally the results will be analysed and discussed.

6.2 MCDM ANALYSIS

Step 1: Structure the decision hierarchy

The first level called “the goal” of our decision hierarchy is “optimum grid expansion taking into account cost, reliability and environment constraints”. The next level down is the subsequent elements that achieve the goal (i.e. the general criteria). In this case, the dissertation has identified three criteria and these are cost, environmental, and reliability criteria. The final level are the “alternative transmission planning solutions (that apply different transmission technologies)” that can satisfy the criteria in the above level (level 2). In this case, these are the proposed alternative technologies identified in the section 5.4 (i.e. A1, A2 and A3). The Figure 6-1 below illustrates the decision hierarchy to be analyzed.

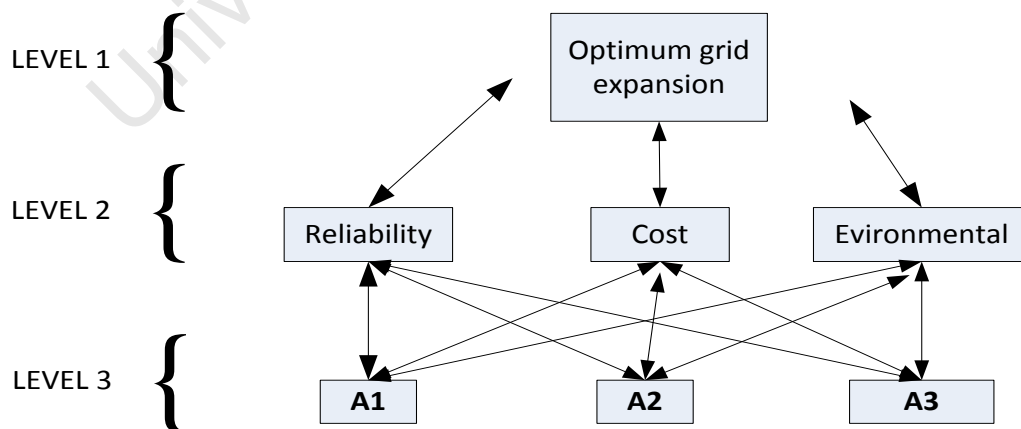


Figure 6-1: Transmission alternatives decision hierarchy

Step 2: Evaluation criterion

Environmental impact evaluation, EI_c :

The criterion used is from section 4.2.2.1. From Equation 4.1 and Table 4-1, the additional environmental impact can be calculated as shown below:

- Span= 254 km
- ROW for; 132 kV double circuit line – 45 m, 220 kV double circuit line – 55 m, 345 kV double circuit line – 60 m [Kiessling, 2003]

$$EI_c (A1) = (55 + 55)254 = 27,940 m^2$$

Using the same procedure the environmental impacts of A2 and A3 are calculated.

$$EI_c (A2) = (60)254 = 15,240 m^2$$

$$EI_c (A3) = (55 + 55)254 = 27,940 m^2$$

Cost criterion, C_c

- Cost estimate from Table 4-3, the line estimates cost per km and fixed substation cost respectively used are; 132 kV double circuit – 180 k\$/km and 8 M\$; 220 kV double circuit – 240 k\$/km and 10 M\$; 345 kV double circuit – 350 k\$/km and 12 M\$ [Lavalin and Brinckerhoff, 2011].
- These estimates are used to find the present value (PV) by multiplying by a unit cost given by $(1+i)^t$ where: t , is the number of years from base year and i , is the inflation rate.
- Price reference year- 2014
- Currency- USD
- i = usually a premium of **10%** for electrical power industry [Khatib, 1996 and Espie, 2000]
- For the case of uprating, the dissertation assumes; Successful feasibility study that allows voltage uprating without tower changes (refer to chapter 3 for explanations as to

why this is a viable option for the case of Uganda); cost of upgrading will be cost of feasibility study (engineering), plus cost of demolition, plus cost of the lines, and finally plus cost of upgrading substations. Albizu et al. [2005], say that savings of up to approximately 50% can be achieved with respect to the investment of new lines for cases of voltage upgrading.

From Table 4-2 (separation of transmission investment), the dissertation approximates that; that is 35% for lines, 4% for engineering and feasibility studies, 1% for demolition (i.e. 40% of the transmission line cost); cost of upgrading substation is approximately 80% the cost of a new 220 kV substation.

$C_c(A1) = \text{present value of 220 kV in 2014} + \text{present value of 220 kV in 2023}$

$$220 \text{ kV}(2014) \rightarrow (240k \times 254) + 10M = 71 \text{ M\$}$$

Using the present worth calculation i.e. multiplying by $(1+i)^t$

$$220 \text{ kV}(2023) \rightarrow 71M \times (1 + 10\%)^9 = 167.4 \text{ M\$}$$

$$\therefore C_c(A1) = 71 + 167.4 = 238.4 \text{ M\$}$$

$C_c(A2) = \text{present value of a 345kV double circuit line in 2016}$

$$345 \text{ kV in 2016} \rightarrow ((350k \times 254) + 12M) \times (1.1)^2 = 122.1 \text{ M\$}$$

$$\therefore C_c(A2) = 122.1 \text{ M\$}$$

$C_c(A3) = \text{present value of 220 kV in 2014} + \text{present value of 132 kV in 2016}$
 $+ \text{present value of upgrading 132 in 2023}$

$$132 \text{ kV in 2016} \rightarrow (180k \times 254) + 8M \times (1.1)^2 = 65 \text{ M\$}$$

Using the upgrading assumptions above,

upgrading 132 to 220 kV in 2023

→ 40% of 220 kV line cost + 80% of the substation cost

$$\therefore \text{uprating cost} \rightarrow ((240k \times 254) \times 40\%) + (10 \times 80\%) \times 1.1^9 = 76.4 \text{ M\$}$$

$$\therefore C_c(A3) = 71 + 76.4 + 65 = 212.4 \text{ M\$}$$

Reliability criterion (EENS), R_c

From Equation 4.2, $EENS = \sum_{i=1}^m P_f \cdot U_f$:

Figure 6-2: Failure and outage duration rates of double line circuits

Voltage, kV	Failure rate λ , f/km-yr	Average outage duration r , hrs
132	0.0064	1
220	0.0044	4
345	0.0031	6

Table 6-1: EENS of alternative 1 (A1)

Down states	Unavailability U_f , hr/yr	Power not supplied P_f , MW	EENS $U_f \cdot P_f$, MWh/yr
220kV double line down	4.47	242	1081.74
220kV double line down	4.47	242	1081.74
132kV double line down	1.57	0	0
Both 132 and 220kV lines down	8×10^{-4}	372	0.2976
Both 132 and 220kV lines down	8×10^{-4}	372	0.2976
Both 220kV and 220kV lines down	2.28×10^{-3}	664	1.5139
132kV, 220kV and 220kV lines all down	4×10^{-7}	794	0.00032
		TOTAL	2165.58942

Table 6-2: EENS of alternative 2 (A2)

Down states	Unavailability U_f , hr/yr	Power not supplied P_f , MW	$U_f \cdot P_f$, MWh/yr
345kV double line down	4.72	664	3134.08
132kV double line down	1.57	0	0
Both 132 and 345kV down	8.4×10^{-4}	794	0.81
		TOTAL	3134.89

$$R_c(A1) = 2165.6 \text{ MWh/yr}$$

$$R_c(A2) = 3134.9 \text{ MWh/yr}$$

$$R_c(A3) = 2165.6 \text{ MWh/yr}$$

The table below show a summary of the normalized scores for the different alternatives. Appendix G presents the detailed calculations.

Table 6-3: Summary of normalized scores

Criteria	Normalized Scores		
	A1	A2	A3
Cost	0.4161	0.2131	0.3708
Environment	0.3929	0.2142	0.3929
Reliability	0.2901	0.4198	0.2901

Step 3: Weighting the criteria

As discussed in section 4.2.4, selection of the criterion weights is the most contentious issue of MCDM techniques because the selected values are subjective and directly impact the final solution. To reduce the subjectivity and simplify the weighting process, the dissertation uses the ROC weighting method to estimate the criterion weights. In order to estimate, the ROC method requires the rank order of the criteria importance. This is going to be determined based on the project objective. The rank order for this case is as follows:

- Rank 1 is the cost criterion. This is because Uganda is a developing country with limited resources, so minimizing cost of any project is a key issue that is considered greatly. As discussed in 2.2.1, UETCL doesn't have cost reflective tariffs and is forced to depend on subsidies to fill the gap between a very high average purchase and a fixed bulk tariff. Therefore, UETCL has to rely on funding from donors, who are more willing to fund cheaper projects, so, minimizing cost is a prerequisite.
- Rank 2 is the reliability criterion. This is because in the GIP 2008-2023, the objective of the proposed projects is to build a robust network, enhance transfer capacity, improve reliability and quality of power supply, and provide capacity for regional power trade. Also transmitting reliable bulk power is one of the missions of UETCL. Therefore, reliability will be ranked second because it is one of the major objectives of the transmission grid expansion.
- Environmental impact criterion is ranked 3rd. This is because the route of the line has proximity to mainly low socially, ecologically and archeologically sensitive areas.

Using the ROC weights in Table 4-4 and the above rank positions, Table 6-4 below summarizes the weights of our criteria.

Table 6-4: Criteria preference weights

Rank	Criteria	ROC weights
1	Cost	0.6111
2	Reliability	0.2778
3	Environment	0.1111

To ensure that the final score is robust, a sensitivity analysis is carried out in step 5.

Step 4: Aggregating the weights and the value functions

Using Equation 4.4, the ROC weights in Table 6-4 and the normalised score summarised in Table 6-3, the weighted scores of each alternative solution are calculated. The weighted scores (WS) of each alternative are summarised in the Table 6-5 below.

Table 6-5: Summary of the weighted scores

Criterion	Weights	Normalized Scores		
		A1	A2	A3
Cost	0.6111	0.4161	0.2131	0.3708
Environment	0.1111	0.3929	0.2142	0.3929
Reliability	0.2778	0.2901	0.4198	0.2901
Total	1			
Total, <i>WS</i>		0.3785	0.2706	0.3508

Based on the initial ranks assigned weights and the calculated weights, alternative **A2** has the lowest score of 0.2706. Therefore, **A2** is the most optimum option that will face least constraint to the transmission grid expansion project. To ensure the decision analysis is indeed robust a sensitivity analysis is carried out in the next step.

Step 5: Sensitivity analysis

The sensitivity analysis is going to take the form of changing the rank positions of different criterion. This will directly imply a change in the calculated ROC weights. Therefore, all possible rank position combinations are assigned to the criteria and the ROC method used to estimate the new preference weights. The Table 6-6 below gives a summary of the criteria rank positions and a position rank summary of the weighted scores of each alternative.

Table 6-6: Sensitivity analysis summary

CRITERIA RANK POSITION			WEIGHTED SCORE RANK POSITION OF THE ALTERNATIVE		
1	2	3	1	2	3
Cost	Reliability	Environment	A2	A3	A1
Cost	Environment	Reliability	A2	A3	A1
Reliability	Cost	Environment	A3	A1	A2
Reliability	Environment	Cost	A3	A1	A2
Environment	Cost	Reliability	A2	A3	A1
Environment	Reliability	Cost	A2	A3	A1

From the Table 6-6 above, planning solution A2 will be the most optimum solution as long as cost and environment are ranked highest. Planning solution A3 is most optimum when reliability is ranked highest.

The dissertation assumes political stability. As an extension of the sensitivity analysis that is in case of political instability, the demand will not increase as in Figure 5.1 but may in fact drop as was the case in 1978 to 1986 (Figure 1.1). Therefore, alternative A2 will no longer be an option since the demand is not expected to grow. This leaves alternative A3 as the most optimum option.

6.3 ACKNOWLEDGING UNCERTAINTY

The planning process is characterised by uncertainties, some of which have so far not been considered. This section acknowledges the hard uncertainties, and discusses what impact they would have on the process and result. From the literature, political and social constraints are identified as some of the constraints facing transmission grid expansion in Uganda and they have hard uncertainty.

Uganda being a developing country, where services like electricity are usually treated as commodities to be used as rewards for politically friendly communities and denied those that are politically hostile. Political support is therefore a hurdle that must be overcome before any transmission project. That said political support is a prerequisite that must always be considered before major transmission projects. This also extends to donor support as well since they control the funding of projects.

Institutional barriers are also identified as being common to Uganda. The ones common to Uganda are; corruption, non transparent process, low level of skills, badly designed procedure and bureaucratic processes. These can result into a slow planning processes and finally bad decisions. For example, corrupt transmission planners may opt for a more expensive option so that there is more to embezzle from the projects and thus, making a bad choice. For the case study above (an interconnection project), planning processes is likely to take longer because of lack of a harmonized procedure. In this light, it is important to carefully consider institutional

constraints and put in place measure to overcome or reduce their impact on the process and the outcome.

Finally, from the literature, the social constraint identified in Uganda was vandalism of transmission equipment as a means of opposing transmission line construction. This is mainly because HV transmission lines transmit bulk power to distant areas and there are cases where the lines pass through areas that are not receiving grid power. Transmission planners need to put in place measures to avoid this before it happens, for example, they planners can propose cheaper power options (e.g. Solar home systems) for the locals not going to receive grid connection. This can reduce their opposition to the construction of these lines. Also in case the locals have a history of vandalism and high levels of opposition, the planner should rank the environmental criterion highest so that, the selected planning solution is environmentally friendly.

The figure below proposes an uncertainty checklist that is created from literature and lessons learned from failures and problems from previous similar projects. This checklist will be beneficial in the planning process and will better its quality. This checklist will ensure that all the uncertainties are explicit and that measures are put in place to overcome or reduce their impact.

<u>POLITICAL</u>	<u>HUMAN BEHAVIOUR</u>
<input checked="" type="checkbox"/> <i>Political support</i>	<input checked="" type="checkbox"/> <i>Vandalism and Theft</i>
<u>INSTITUTIONAL</u>	
<input checked="" type="checkbox"/> <i>Lengthy processes</i>	<input checked="" type="checkbox"/> <i>Harmonized procedure</i>
<input checked="" type="checkbox"/> <i>Corruption</i>	<input checked="" type="checkbox"/> <i>Public process</i>
<input checked="" type="checkbox"/> <i>Low Skills</i>	

Figure 6-3: An uncertainty checklist for transmission projects in Uganda from literature and previous similar projects, showing that each item has been considered.

6.3.1 Impact of hard uncertainty on the rank position

In this section, the dissertation discusses how the hard uncertainties will probably affect the proposed planning process. This is done by reflecting the impact of the hard uncertainty on the rank position of the planning process. Some of the extreme scenarios are discussed below.

High levels of vandalism of transmission infrastructure: In this case the environmental criterion will be ranked highest. From Table 6.6, alternative A2 is the most desirable in this case. A3 is the next desirable and finally A2. This is because A3 and A2 scored highly in the environmental criterion.

High levels of corruption: In this particular scenario, the dissertation assumes that the transmission planners are extremely corrupt. The corrupt planners could directly opt for A1 which scored worst in the cost criterion or they could rank the cost criterion lowest so that a more expensive option is selected in the planning processes. From Table 6.6, when cost is ranked lowest and reliability highest, A3 is the most optimum followed by A1 then finally A2. Another scenario is when cost is ranked lowest and environment highest, A2 is the most optimum followed by A3 then finally A1. A1 is not optimum in both cases because it performs poorly in the environmental criteria.

As already discussed above, the other institutional constraints will mainly slow down the planning process.

In this light, it is evident that hard uncertainties affect the planning process because they can affect the planning solution chosen. Therefore, it is very important to acknowledge hard uncertainties.

6.5 IN SUMMARY

This chapter has applied the theory developed on the case study and produced a set of results. The next chapter gives an evaluation of the planning process and discusses the results.

7 EVALUATION OF THE PROPOSED PLANNING PROCESS

7.1 EVALUATION USING LITERATURE

The planning process is of high quality as shown in the analysis contained in the table below. In this analysis the identified characteristics of a high quality decision making (section 2.4 of this dissertation) serves as the benchmark against which to evaluate the planning process.

Table 7-1: Evaluation of the planning process

High quality decision making characteristics	Criteria of tools and approaches that aid high quality decision making	Contribution of the tool/approach (Negative, None, Limited, Strong, Not Applicable)
Well considered	Decision problem structured (i.e. objectives, criteria and alternatives clearly defined)?	Strong: The process adopts an MCDM model that provides structure. The model is structured as a decision hierarchy with 3 levels. Level 1 is the overall goal, level 2 are the selected criteria that must be satisfied to fulfil the overall goal and level 3 are the alternative planning solutions that can be used to optimize the criteria described in level 2.
	Multi-dimensionality acknowledged?	Strong: The process acknowledges multi-dimensionality by having different decision criteria that must be satisfied (i.e. Level 2 of the MCDM model)
	Soft uncertainty acknowledged?	Strong: The MCDM model acknowledges these as well. That is, level 2 of the model addresses the technical, environmental and financial analysis.
	Hard uncertainty acknowledged?	Strong: Potential hard uncertainties are identified from lessons learned and literature. The process ensures that they are acknowledged by use of an uncertainty checklist(e.g. political influence, social opposition and effectiveness of the institutional structure)
Informed	Incorporate past lessons learned/ experiences?	Strong: Process encourages acknowledging of both soft and hard uncertainties. It also encourages uses of other technologies being used elsewhere that may have added advantage (e.g. uprating). The process also learns from past experiences. There is also strong emphasis on stakeholder inclusiveness and transparency improving the likelihood of accurate, adequate, and unbiased data.
	Accurate, adequate and unbiased data?	
Inclusive	Stakeholder inclusive?	Strong: The process encourages stakeholders inclusion

Transparent	Transparent data sources/ methodologies?	Strong: The MCDM model provides structure that allows easier interpretation of the process. For example it would enable analysts to assess whether or not an appropriate range of criteria are assessed. It can also readily be apparent if the weighting of lower level criteria skews the decision making process in favor of a higher order criterion. Therefore, MCDM creates an audit trail that can easily be followed.
	Audit trail?	
Flexible and adaptive	Process can adapt to context through iterative feedback loops?	Strong: The process has a feedback loop that ensures all feasible planning solutions have been considered for different alternative future scenarios.
Implementation plans	Detailed implementation plans as outcomes?	Strong: The process acknowledges environmental, social and institutional constraints that are likely to be faced. Therefore, it is able to make recommendations for a smoother implementation process and putting in place measures to reduce or overcome the negative impact of these constraints.

7.2 PRACTICAL TEST WITH THE UTILITY PLANNERS

Test questions were prepared and used as a forum for discussion with utility engineers in Uganda. The discussion was held with two planning engineers in UETCL, both having about 20 years of working experience in the utility. Below are the test questions and the outcome of the discussions.

7.2.1 Test questions

The Figure 7.1 below has the test questions used during the discussion.

DISCUSSION QUESTIONS FOR UETCL ENGINEERS
1. How is transmission planning carried out in UETCL?
2. What key constraints are considered in the planning process?
3. What challenges (difficulties, problems, issues, etc) are faced in the process of project implementation that either lead to project delays or failure? (rank them)
4. What is UETCL doing to overcome or mitigate these challenges?
5. How do you think these issues can be solved?
6. Do you think use of different transmission technology can solve some of these challenges faced?
7. Do you think a more comprehensive and rigorous planning process would reduce or mitigate these challenges faced in the grid expansion process?
8. Description of the dissertation's proposed planning process (chapter 4)
9. Seeing this process, are there any other challenges you want to add to question #3?

Figure 7-1: Test questions

7.2.2 Problems faced

Some of the major challenges identified are:

- Financing: UETCL cannot afford to finance most of its transmission projects, therefore, relies on funds from development partners. Fund sourcing is usually done for both the feasibility study and implementation process. This is a hectic and very time consuming process.
- Acquisition of Way- Leaves and ROW: This is an issue due to the type of land ownership and also speculation after the valuation exercise. In Uganda individuals own land, therefore UETCL has to compensate each land owner. This process is cumbersome, costly and time consuming. In addition, there are also cases where the HV lines pass through areas that are not going to benefit directly from this transmission. This makes the process of acquisition of ROW more complex.
- Continuous vandalism of the steel towers: This occurs during both operation and construction of the transmission infrastructure. Locals use the steel to make local charcoal stoves and also some sell this steel to steel rolling factories that buy scrap steel.
- Corruption: This results into suspension of funding by the development partners, which in turn results into termination of projects.
- Limited skilled labor in the market: The Ugandan market lacks enough adequate skilled labor to effectively manage, supervise and operate the power industry.
- Lack of a centralized technical archive: Useful technical data for planning and forecasting is hard to compile. This makes the planning process more difficult.
- Other challenges faced are rapid technology change, way leave encroachment, and implementation of Government Policies and strategies which are at times very ambitious.

These result into delays in project implementation and at times project cancellation.

7.2.3 Any benefits of the proposed process

From the discussion, the interviewed planning engineers agreed that new technologies can play a role in mitigating some of the issues. For example UETCL is exploring the use of monopole transmission structures and compact line design to solve the vandalism and reduce ROW acquisition problems respectively. The proposed process encourages use of new transmission technologies to solve some of the constraints faced in the planning process, therefore electricity power utilities will benefit from this.

Also from the discussion, it was discovered that UETCL acknowledges soft uncertainty. According to UETCL planning process, the planning solution must be technically, economically, financially and environmentally viable. The most optimum solution is selected.

Finally, some of the identified hard uncertainties are acquisition of ROW, vandalism of transmission infrastructure, corruption, and political interference. By acknowledging these hard uncertainties in the planning process, UETCL will be more prepared to avoid or minimize any negative impact they may have to the project. By doing this, a more timely project implementation is expected.

7.3 DISCUSSION OF RESULTS

In the case study, three different planning solutions that apply different transmission technologies are proposed as solutions that can optimize the planning considering the different identified constraints. SMART MCDM process is used to determine the most optimum solution. The results are discussed below.

From Table 6-3, A1 and A3 performed best in terms of the reliability criterion. A2 performed best in both environment and cost criteria. Aggregating these scores and the preference criterion weights (Table 6.4), the weighted scores summarised in Table 6.5 were obtained. A2 is the most optimum solution followed by A3 and in last place A1.

A2 also brings out the need to do proper load forecasting and thus being able to identify an appropriate voltage to use for transmission projects. This will avoid construction of two transmission lines where only one line could have done the job. Economies of scale in

transmission investment argue for overbuilding, rather than under building, transmission. It is substantially cheaper per GW-km to construct a higher voltage line than lower voltage line (it is cheaper in the long run too). A higher voltage line also requires less land per GW-mile, which should reduce opposition from local landowners and environmentalist bodies. Also, building a larger line now eliminates the need to build another line in several years. This situation can eliminate the need for another potentially bruising and expensive fight over the need for and location of another line. In addition, the availability of suitable land on which to build can only decrease and get more expensive to acquire in the future, as populations grow and economies expand. On the other hand, overbuilding reduces the reliability of the network and increases financial risk to transmission owners.

A3 performed second best. A3 uses line uprating which can be cheaper depending on the feasibility studies compared to building new AC OHL lines. Although, uprating has a limitation that it requires already existing infrastructure in order to be applicable. It can lead to substantial saving of transmission investment. This will be highly beneficial to a developing country especially one with old transmission infrastructure and low voltage lines like Uganda.

A1, uses only AC OHL, it should be noted that this still has wide application especially in rural electrification and is the cheaper option in such a case.

A sensitivity analysis was carried out by varying the criteria rank positions that directly affects the weights of the criteria. Table 6-6 summarises the results. It is observed that A2 remains the most optimum solution as long as either cost or environment criterion is ranked highest, followed by A3 and lastly A1. This is mainly because A2 is cheaper in the long run and at the same time has the lowest environmental impact. It can also be observed that when reliability is ranked highest, A3 is the most optimum solution followed by A1 and lastly A2. In this light, depending on the project objective, different solutions will be optimum.

The process also acknowledges hard uncertainties by use of an uncertainty checklist. Therefore, the dissertation assumes measures are put in place to overcome the impact of these hard uncertainties. For example for the issue of corruption, the decision makers are to come up with an audit trail that would reduce loop holes that corrupt officials take advantage of.

7.4 IN SUMMARY

Transmission network planning is a very complicated decision making problem with both multiple decision makers and multiple decision criteria. Recent trends and challenges make it even more complicated and perverse, much more uncertain than it was several years ago. The process therefore needs to be made more rigorous.

For the case of Uganda, in the past, before the electricity market liberalization, in a centrally managed power system, the system operator could in general control the whole power system. The transmission network was then expanded with the aim to minimize both generation and transmission costs, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

Nowadays, there are increasing concerns over issues like environmental impact, social welfare and political influence. In addition to this, many electricity power industries, including Uganda, are now restructured and liberalized. These combined are stimulating a paradigm shift in planning for the industry by creating more multiple and conflicting decision criteria and more uncertainties as well.

Conventional techniques (e.g. least cost planning) fail to integrate all these multiple criteria making them inadequate. This results into poor quality decisions and in turn delays in transmission project implementation or even in extreme cases, can lead to project failure.

The proposed planning process is more comprehensive and rigorous giving an all-round consideration for transmission expansion planning. It uses an MCDM model which makes explicit a coherent family of criteria, integrates all the multi criteria, provides structure, encourages multidimensional perspective (instead of focusing mainly on the financial dimension), and also provides a common terminology for discussion throughout the decision making process.

In Albar et al [2007] and Espie et al [2003], MCDM models have been used and tested in electricity utility planning. They have proved to have the ability to structure a complex, multi-person, multi-attribute and multi-period problem hierarchically. It was discovered that

evaluating all planning problems simultaneously can provide substantial benefits to utilities, not only in terms of improving the desirability of possible solutions but also by potentially deferring network investment. It was also discovered that the models have the ability to make strategic planning decisions relating to both the whole network and also particular planning problems.

The process also encourages use of different mature transmission technologies that are already being used elsewhere in the world other than AC OHLs. This is because of the additional benefits they have and fewer constraints they face. Therefore, depending on the type of project different technologies have added advantages and can tackle some of the constraints encountered by AC OHLs. For example, from the case study, overbuilding finds application rather than under building transmission lines because it is substantially cheaper per GW-km to construct a higher voltage line than lower voltage line. A higher voltage line also requires less land per GW-mile, which should reduce opposition from local landowners and environmentalist bodies. Uprating can also find added application considering that most transmission lines in Uganda are old and nearing the end of their life time. This is illustrated clearly in chapters 3, 4, 5, and 6. Uprating will not only be a cheaper option but also more environmentally friendly option than building new AC OHLs.

From the results it is evident that the planning solutions that use other technologies (i.e. uprating and overbuilding AC OHL) performed better than the alternative that had only AC OHL. Therefore, Uganda should look into taking advantage of these technologies. The process also uses an MCDM model that considers all the criteria with conflicting objectives to find the most optimum solution. The proposed planning process also develops an uncertainty checklist to be used to ensure that most hard uncertainties are considered during the decision making process.

Therefore, these approaches properly considered are capable of assisting TSO decision makers to make a quality decision. In turn this will better the success of transmission projects because the negative impact of the formerly unconsidered criteria is prevented or reduced.

8 CONCLUSION

8.1 REVIEW OF RESEARCH QUESTIONS

The hypothesis and research questions formulated in 1.6 are summarised below:

The hypothesis is:

Different transmission technology options as demonstrated elsewhere and quality decision making can be used to overcome or minimize constraints faced by transmission grid expansion in Uganda.

Research Questions:

- 1. What loads are expected in Uganda?***
- 2. What technology options are being considered or used for grid expansion in Uganda?***
- 3. What constraints are faced in the process of grid expansion in Uganda?***
- 4. What other existing technology options can be used for grid expansion and how would they overcome these constraints?***
- 5. How are the best choices identified?***

The research questions, listed above, led to preliminary answers that tested the validity of the hypothesis. A summary of the answers is reviewed below.

A review of load growth and forecasts of future growth in Uganda revealed that the demand showed no growth between 1968 and 1990 but has increased steadily since then, putting the transmission system under pressure. More power is needed in the areas already being supplied and regions without electricity need to be connected to the central system. Approaches being considered by the planners include expanding the present network and adding a network of higher operating voltage. However, these improvements are frequently delayed by problems including financial constraints, acquisition of way leave and ROW, continuous vandalism of steel towers, limited skilled labour in the market, corruption, and an inadequate planning process.

To minimize these problems, other appropriate transmission technologies can be used because of the additional benefits they have and fewer constraints they face. These include HVDC, uprating, FACTS and underground cables. To ensure quality decision making, both hard and soft uncertainties need to be acknowledged. The soft uncertainties are acknowledged in the MCDM model and the hard uncertainties are by use of an uncertainty checklist. The checklist is used to make more apparent a wide range of possible uncertainties and focuses attention of the decision making process on where measures are required to reduce the impact of hard uncertainty. The use of the MCDM model and uncertainty acknowledgement improves the quality of the decision making process.

8.2 LIMITATIONS

The dissertation focuses on transmission technology options, technology assessment, grid expansion constraints and quality decision making, but the author acknowledges that transmission planning is a much more complex process than the dissertation has shown. For that matter, additional, more detailed and technical studies would be required to reach the final plan.

Decision aiding can't be forced upon the decision maker. The TSO in Uganda is government owned, and electricity service delivery represents political capital and favour. Decision makers positioned within this landscape might have little motivation to implement a decision aiding process that will lead to a more transparent decision with an audit trail.

The SMART MCDM analysis is refined, through subdivision into lower criteria, and will require a wide range of professionals who can provide specific expertise. However, the resources for these activities are in short supply in Uganda and many similar countries.

Last but not least, the dissertation brings out the need to consider other technologies and only five mature transmission technologies were analysed. The dissertation author acknowledges technologies such as dynamic line rating, wide area monitoring, etc. These technologies can contribute greatly to the increase in transfer capacity. They can however be catalogued as

technologies that enhance ‘a more efficient use of existing assets’, whereas the scope of this work is focused on hardware investments.

8.3 VALIDITY OF HYPOTHESIS

Notwithstanding the limitations, the planning and decision making approach developed in the dissertation was tested with a practical example, by comparison with the literature and in discussions with Ugandan transmission planners. The results consistently indicated that the approach developed would have advantages and improve transmission planning. Therefore, it can be stated that the testing of the hypothesis ‘different transmission technology options as demonstrated elsewhere and quality decision making can be used to overcome or minimize constraints faced by transmission grid expansion in Uganda’ has been shown to be valid.

8.4 RECOMMENDATION

The understanding gained during the testing of the hypothesis led to a number of proposals on how quality decision making and transmission technology can be used to improve transmission project success. These proposals are briefly discussed below:

- 1) Identify and use a structured, formal decision aiding process that supports high quality decisions to a large extent, from the inception of the programme/project through to post-implementation monitoring and evaluation. It should be able to structure a complex, multi-person, multi-attribute and multi-period problem.
- 2) Identify as wide a list as possible of uncertainties from past experiences and literature that might hinder achievement of the project objectives. From this list, identify the main hard and soft uncertainties. Ensure that mechanisms are in place within the planning process to acknowledge and quantify the impact of the identified soft uncertainties. Also ensure that mechanisms are in place within the decision aiding process to acknowledge and monitor the impact of the identified hard uncertainties.
- 3) Although AC OHLs still have a wide application in Uganda, UETCL should also consider using other transmission technology options for transmission grid expansion. For example, uprating showed to be an attractive option for a system like Uganda characterised by growing demand for electricity and thus need to boost transmission

capacity and transmission lines that are nearing the end of their life time (thus requiring refurbishment). UETCL will benefit from the original transmission line designs used that were overly conservative design methods, and more stringent code requirements than currently were used. Also consideration of the available types of insulator assemblies and special conductors, computer software is also available, some compact line design techniques may be applied, as well as configuration of the uprating circuits can minimize the impact of the uprating on the existing structures. Other technologies like FACTS and HVDC will also find application in Uganda in the near future.

In conclusion, transmission expansion planning is a key issue. In this changing environment, a good transmission plan should not only be least cost but be more comprehensive, considering all additional objectives and uncertainties. This dissertation proposes a method to tackle this issue by using technology and quality decision making.

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APPENDICES

Appendix A: Summary of the annual maximum demand from 1954-2012 [ERA, 2012]

Year	MW	Year	MW	Year	MW
1954	15.1	1974	125.9	1994	161.4
1955	15.6	1975	122.3	1995	173.6
1956	21.6	1976	112.4	1996	174
1957	29.8	1977	114.4	1997	178.6
1958	51.8	1978	119.4	1998	179.8
1959	57.8	1979	113.8	1999	180
1960	62.8	1980	106.2	2000	260
1961	73.6	1981	99	2001	270
1962	73.4	1982	99.8	2002	250
1963	85.3	1983	106.2	2003	300
1964	99.1	1984	97.6	2004	300
1965	103	1985	109.8	2005	317
1966	113.9	1986	107.4	2006	350
1967	126.7	1987	103.6	2007	367
1968	131.9	1988	94.6	2008	365
1969	128.8	1989	110.8	2009	394
1970	124.6	1990	122.8	2010	418
1971	129.9	1991	136.2	2011	443
1972	132	1992	151	2012	487
1973	130	1993	157.2		

Appendix B: PB Base, High and Low Demand Forecast for Uganda [Lavalin and Brinckerhoff, 2011]

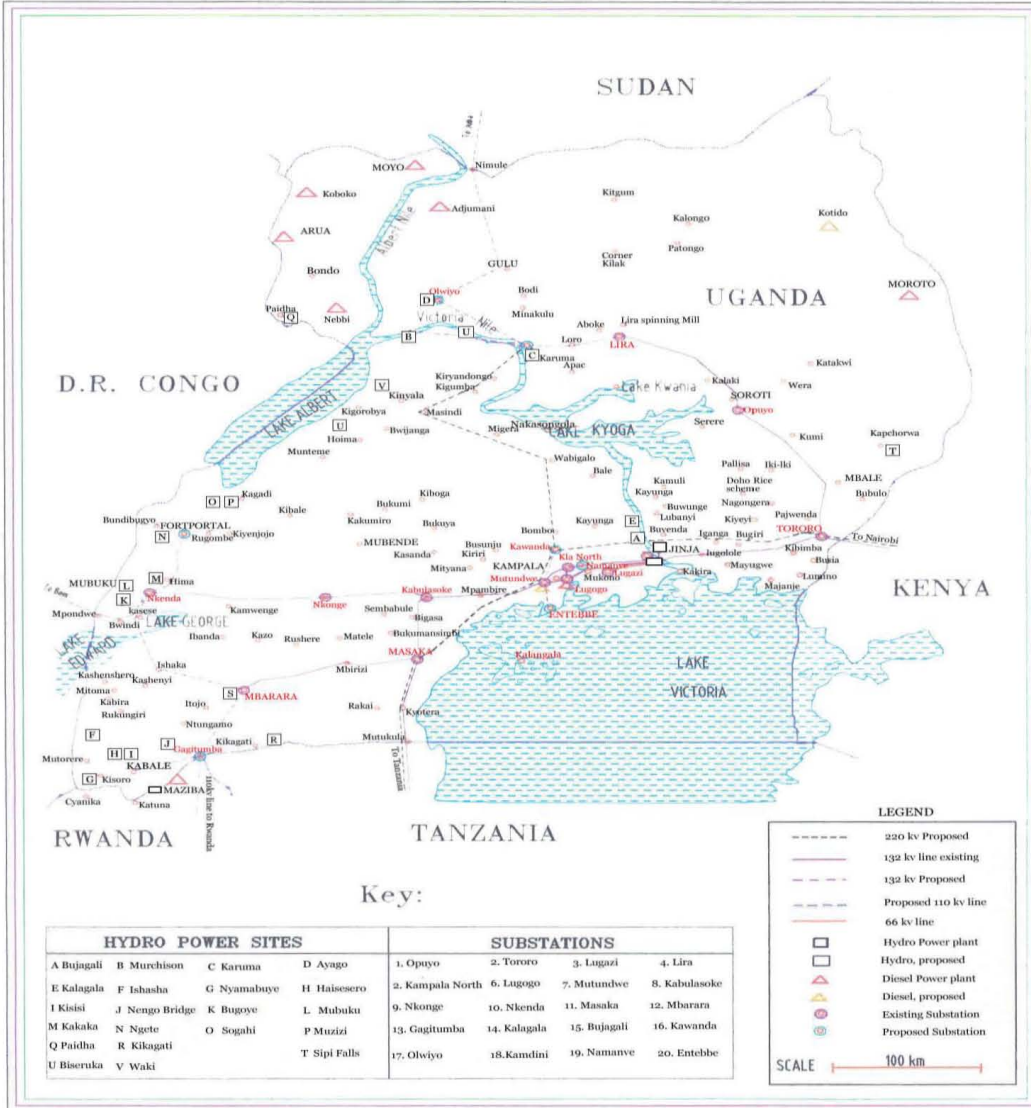
Year	PB Low Case			PB Base Case			PB High Case		
	Generation (GWh)	Peak Demand (MW)	Load Factor (%)	Generation (GWh)	Peak Demand (MW)	Load Factor (%)	Generation (GWh)	Peak Demand (MW)	Load Factor (%)
2009	2784	541	58.7%	2877	561	58.5%	3397	597	65.0%
2010	2901	570	58.1%	3026	596	58.0%	3982	702	64.8%
2011	3012	597	57.6%	3188	633	57.5%	4564	805	64.7%
2012	3121	623	57.2%	3371	673	57.2%	5146	908	64.7%
2013	3203	643	56.9%	3560	715	56.8%	5663	998	64.8%
2014	3279	662	56.5%	3788	764	56.6%	6165	1084	64.9%
2015	3351	679	56.3%	4030	816	56.4%	6651	1167	65.1%
2016	3419	695	56.2%	4288	871	56.2%	7122	1247	65.2%
2017	3481	710	56.0%	4561	929	56.0%	7577	1324	65.3%
2018	3540	724	55.8%	4851	990	55.9%	8018	1398	65.5%
2019	3622	741	55.8%	5123	1045	56.0%	8518	1480	65.7%
2020	3676	750	56.0%	5362	1091	56.1%	8977	1551	66.1%
2021	3778	772	55.9%	5685	1158	56.0%	9537	1647	66.1%
2022	3913	800	55.8%	6056	1233	56.1%	10178	1759	66.1%
2023	4048	828	55.8%	6434	1310	56.1%	10831	1873	66.0%
2024	4184	857	55.7%	6821	1389	56.1%	11497	1990	66.0%
2025	4321	886	55.7%	7216	1470	56.0%	12175	2109	65.9%
2026	4459	915	55.6%	7620	1552	56.0%	12867	2231	65.8%
2027	4598	944	55.6%	8031	1636	56.0%	13570	2355	65.8%
2028	4738	973	55.6%	8450	1722	56.0%	14287	2482	65.7%
2029	4880	1003	55.5%	8878	1809	56.0%	15016	2612	65.6%
2030	5022	1033	55.5%	9313	1898	56.0%	15757	2744	65.6%
2031	5065	1032	56.0%	9754	1978	56.3%	16548	2883	65.5%
2032	5246	1069	56.0%	10203	2069	56.3%	17348	3025	65.5%
2033	5428	1107	56.0%	10659	2162	56.3%	18156	3168	65.4%
2034	5611	1145	55.9%	11123	2257	56.3%	18972	3312	65.4%
2035	5796	1184	55.9%	11594	2353	56.2%	19797	3459	65.3%
2036	5982	1223	55.8%	12072	2450	56.2%	20629	3607	65.3%
2037	6170	1262	55.8%	12559	2549	56.2%	21470	3757	65.2%
2038	6358	1301	55.8%	13052	2650	56.2%	22319	3908	65.2%

Appendix C: Uganda Generation [Lavalin and Brinckerhoff, 2011]

Plant Name	Nom. Cap. MW	Energy in GWh		Plant Factor	Earliest year on power
		Avg. GWh	Firm GWh		
Hydro Existing					
Misc plants	15			0.00	
Nalubaale	180	769	766	0.49	
Kiira 11-15	200	747	747	0.43	
Bugagali 1-5	250	1970	1966	0.90	2011
Small Hydro	50			0.00	2011
S/T	695	3485	3480		
Thermal Existing					
Kakira	17	112	112	0.75	
Namanve	50	329	329	0.75	
Invespro HFO IPP	50	329	329	0.75	
Electromax IPP	10	66	66	0.75	
S/T	127	834	834		
Total Existing Supply	822	4319	4314		
Hydro Future					
Karuma high	700	5512	5512	0.90	2018
Murchison fall high	750	5904	5904	0.90	2019
Isimba	100	788	788	0.90	2016
Ayayago	550	4336	4336	0.90	2019
Small Hydro candidates	37				2016
S/T	2137	16540	16540		
Thermal Future					
Kampala steam	56	392	392	0.80	2016
Tallow steam	53	371	371	0.80	2016
Tallow GT	57	399	399	0.80	2016
Tallow CCGT	185	1296	1296	0.80	2016
Tallow diesel	10	70	70	0.80	2016
Geothermal	33	231	231	0.80	2016
S/T	394	2761	2761		
Total Future Option	2531	19301	19301		
Total Future Supply	3353	23620	23615		

Appendix E: [UETCL, 2010]

UGANDA ELECTRICITY TRANSMISSION COMPANY LIMITED
PRESENT AND FUTURE ELECTRICITY TRANSMISSION NETWORK



Appendix F: Capacity calculations

Using the SIL given in Table 5-2 and the loadability curve shown in Figure 5-4, with the following assumptions:

- The capacity was reduced by 20% as the short circuit levels may not be 50 kA as assumed in the loadability curve.
- The capacity of a double-circuit line is twice as much as that for a single-circuit line.
- A 1.5 SIL for 254 km

132kV double-circuit line:

$$54 \times 2 = 108$$

$$108 \times 1.5 = 162$$

$$162 - (20\% \times 162) = 129.6 \approx \mathbf{130MW}$$

220kV double-circuit line:

$$176 \times 2 = 352$$

$$352 \times 1.5 = 528$$

$$528 - (20\% \times 528) = 422.4 \approx \mathbf{422MW}$$

315kV double-circuit line:

$$418 \times 2 = 836$$

$$836 \times 1.5 = 1254$$

$$1254 - (20\% \times 1254) = 1003.2 \approx \mathbf{1000MW}$$

Appendix G: Normalized scores

Environmental impact criterion (E_c)

	E_c	Normalized score
A1	27940	0.3929
A2	15240	0.2142
A3	27940	0.3929
Total	71120	1

Cost criterion (C_c)

	C_c	Normalized score
A1	238.4	0.4161
A2	122.1	0.2131
A3	212.4	0.3708
Total	572.9	1

Reliability criterion (R_c)

	R_c	Normalized score
A1	2165.6	0.2901
A2	3134.9	0.4198
A3	2165.6	0.2901
Total	7466.1	1