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Technical and economical evaluation of hydropower grid connection in Burundi

Master of Science thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ISSN 1652-8557
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Cover:
Photograph showing the 70kV power line between Ruzizi I and Bujumbura alongside RN5. Photograph copyright by Elias Hartvigsson.

Chalmers Reproservice
Gothenburg, Sweden 2012

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Abstract

The Swedish company, African Power and Water are in the phase of starting to construct a hydropower plant in the Kaganuzi valley, 40 km north of Bujumbura, Burundi's capital. The purpose of the thesis is to analyze the grid in order to find the best point of connection for African Power and Waters hydropower plant. The grid is simulated in order to identify bottlenecks for power transfer and overload in the system using Power World Simulator. The thesis also takes into account the construction of two similar hydropower plants and their planned connection to the grid.

It is found that the best connection for the KAGU006 hydropower plant is to use a T-off connection on the passing 110kV power line. The connection shows the lowest total costs, losses and environmental impact. The results also shows that the grid needs to be expanded or upgraded in order to handle the increased power generation, regardless of connection point for KAGU006. It is also found that a vast majority (97%) of the people are currently using wood and charcoal to meet their energy needs. A transition from a wood based energy system to an electric based energy system will have great impact on electricity consumption and the grid in the future. In order to support this transition Burundi is in need of a more detailed master plan regarding their future electricity generation and distribution.

Keywords: Hydropower, Africa, energy, power grid, Burundi

Acknowledgements

This project would not have been possible without the help and support of many people. First and foremost I would like to thank my supervisors: Jimmy Ehnberg and German Maldonado at Chalmers University of Technology and Torkel Hammerby at African Power and Water. Their help and guidance was crucial for me. I would also give my deepest wishes to the time and effort Mr. Victor Girukwishaka, Mr. Deo Hurege and Mr. Makuwa Moise, their assistance and support vas invaluable in order for me to carry out my work in Burundi. I also want to send my gratitudes to the people in REGIDESO that spent time answering my questions.

Last I would also like to thank Hamed Raee, Elena Malz, Jonna Rosen and Mojgan Nikouei for making a great atmosphere in the office even during hard times.

Contents

Abbreviations

APW	African Power and Water
PWS	Power World Simulator
KAGU006	Hydropower plant project by African Power and Water
KABU16	Hydropower plan project north of KAGU006
MPAN032	Hydropower plan project close to Bubazna substation
EBR	ElByggnadsRationalisering
REGIDESO	Water and Electric Authority in Burundi
UNDP	United Nations Development Program
ABER	Directorate for electrification of rural areas
AHR	Directorate for water of rural areas
DRC	Democratic Republic of the Congo
MWEM	Ministry of Water, Energy and Mines
SHER	Belgium Hydropower company
HPP	HydroPower Plant
LDC	Least Developed Country
IGTC	ICCC Global Trade Centre

1 Introduction

This project is done as a Master of Science thesis at Chalmers University of Technology together with African Power and Water (APW), Sweden. APW is a small Swedish company located in Huskvarna, working in the energy and water industry, specializing in Africa. They are currently planning the construction of a hydropower plant (HPP) in the Kaganuzi valley in Burundi. Burundi is a small landlocked country in eastern Africa and lies between Rwanda, Democratic Republic of the Congo (DRC) and Tanzania. As its neighbor Rwanda, Burundi suffered from ethnical conflicts during the 1990s and 2000s but have seen an increase in security during the last years.

The power plant to be constructed, KAGU006, will increase the maximum capacity of the electrical power system with 8.7MW to roughly 59 MW. This thesis aim is to analyze the current electrical grid and identify possible connection cases for the hydropower plant to the grid. The connections cases will then be analyzed from a technological and economical perspective in order to find the case that best suits the project. Two other hydropower plants that are planned to be taken online at the same time as KAGU006 and in the vicinity of the site, are also taken into account. Many more plans for new power plants exist, but they are not taken into account since they are planned further into the future and/or are located far away from the site of KAGU006.

The technical analysis is done by creating a model of Burundi's transmission grid together with calculations of losses, to evaluate the capacity of the grid for each connection case and development scenario. The model is developed in Power World Simulator (PWS) and based on data supplied by REGIDESO. Economical estimations are done of investment costs (taken from EBRs catalogue) in each case and are connected to the results from the simulations and calculations of losses. Because of the measures taken by the Burundian government against deforestation and by the environmental impact of the power lines, each case is also evaluated from an environmental perspective before the final recommendation of a connection point.

1.1 Purpose

The purpose of the project is to find the best point of connection of the KAGU006 hydropower plant to the Burundian electrical power grid and to evaluate KAGU006 contribution to the energy system. The best point of connection is determined according to a technical and economical criteria. The evaluation of cases is done with the aid of simulations and economical analysis. The final proposal is a recommended connection point to the grid for the KAGU006 hydropower plant.

1.2 Limitations

In the scenarios of future HPP, only two other plants are taken into account. Only the two closest substations and a T-off connection on a passing 110 kV line are investigated. The model in PWS is an aggregated transmission line model built from the one-line data supplied by REGIDESO. The developed model have aggregated the loads and generation in those areas where both generation and loads are very small in relation to the size of grid.

The prices for equipment are based on the Swedish average prices found in the EBR catalogue. This includes shipping, installation and insurance in Sweden and it is likely that these costs will differ for the Burundian market. Maintenance costs are not considered for the power lines since it is not sure who will be the maintainer.

The grid simulation in PWS is done in a steady state without short circuit analysis. Since Burundi is a small country and all power lines are shorter than 80 km (except for the power line connecting Ruzizi I and SNEL which is 112 km) power line are approximated as short lines. Therefore the shunt capacitance can be neglected in calculations.

The losses calculated in the grid are only the active power losses. Losses such as reactive power losses or losses occurring because of effects such as voltage shift is not taken into account. The losses are also calculated based on the assumption that the systems are symmetrical. The total economical losses are based on a 20 years operation of the plant. The total costs including inflation during this time is calculated with the inflation of Burundian franc which is assumed to be the currency APW is paid in.

The capacity calculations are done for bare overhead power lines and steady state thermal rating according to the IEEE [15]. The calculations makes assumptions of a number of parameters values. See appendix B for parameters and parameter values.

Since the design plans for KAGU006 are yet to be finished. The generation that have been assumed are based on 8.7 MW power output and 49.83 GWh of annual generation which the closest estimation that can be done currently.

It should be noted that this project have not investigated any possible juridical or political problems in Burundi associated with the types of connection discussed.

Finally it should be noted that the calculations done in this work are rough and are only estimates and do not show the full behavior or respond of Burundi's power grid nor the exact costs of the connection cases.

2 Background

This section will give a brief background of Burundi. The chapter is divided into general information about Burundi, its history, cconomy, energy system, electrical situation and power grid. A small background to APW and the KAGU006 project is also given.

2.1 Burundi

Burundi is a small landlocked country situated in the north of lake Tanganyika between Rwanda, Tanzania and Democratic Republic of the Congo (DRC), see map (3.1.1). Burundi's surface size is roughly 28 000 km^2 and the total population is roughly 8 million of which about 800 000 lives in the capital Bujumbura. Burundi have a equatorial climate with considerable altitude variation (772 m - 2670 m) and an average altitude of 1700 m. The high altitude gives only a moderate average temperature of 15-23 degrees. Days are however warm, with temperatures exceeding 30 degrees not being unusual [8].

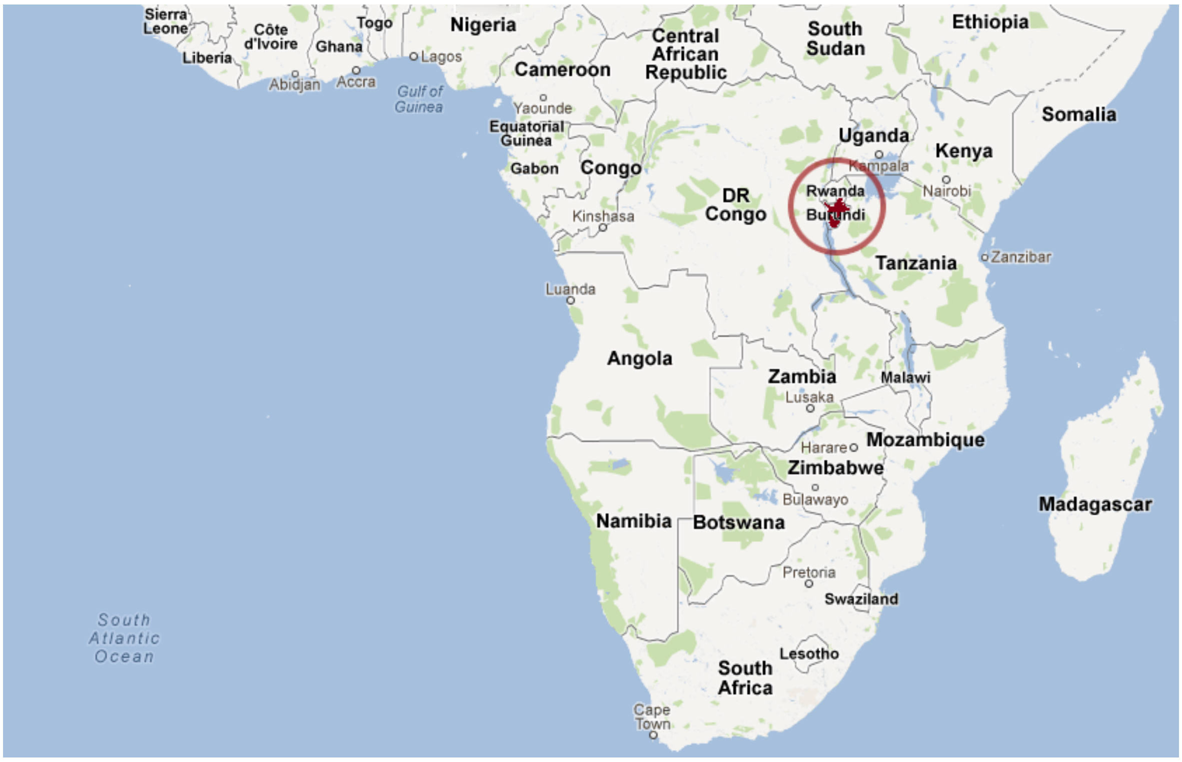

Figure 2.1.1: *Burundi's location.*

2.1.1 History

Burundi have had some troublesome years since it's declaration of independence from the Belgium colony Ruanda-Urundi in 1962. For over 30 years various temporary governments succeeded each other after coup or coup attempts until the first free election was held in 1993. The conflicts have been similar with those in its northern neighbor Rwanda, focusing on the two different ethnic groups, hutus and tutsis. After 1993 the conflict escalated into a civil war after the assassination of the elected president, Melchior Ndadaye. The fighting sides where usually represented by rebel groups and the army. It wasn't until 2002 that the last rebel group officially laid down weapons and converted to a political party. But the unrest continued and UN sent a peace force (ONUB) to Burundi in 2004 to enforce security. The UN forces managed to increase the peace and security in Burundi and the number of violent incidents declined. Sporadic attacks still occur and in 2011 36 people where killed in a bar in the outskirts of Bujumbura [4]. This have left most state departments in Europe and America to still discourage from trips to Burundi [17], [24], [2].

The conflicts have left the country shattered and the main victims of the conflicts have been the population. Since the UNDP presented their Human Development Index in 1990, Burundi have been ranked as one of the poorest countries in the world [25]. The conflicts also had a great impact on the country's infrastructure which have booth been shattered but also lacked appropriate maintenance and development.

2.1.2 Economy

In 2010 Burundi's GDP was 5.04 billion USD and GDP per capita was 600 USD (ranked 223 in the world). The inflation adjusted GDP growth rate was 4.2% in 2010 (ranked 91 in the world [8]).

The unemployment rate is very high, especially for young people looking for their first job which have an unemployment rate of 60%. The main source of employment is the agriculture sector which employs 70% of the population [6]. The agricultural market is mostly focus on coffee and tea [16].

Burundi's governmental budget is mostly based on foreign aid, and in 2011 53% of the government budget originated from aid[6]. Amongst the internal tax revenues most (54%) comes from domestic goods and services [16]. Since Burundi is a landlocked country it is dependent on roads for its export. Most road are in bad or partly bad condition which makes exporting goods problematic. Most exports goes through lake Tanganyika to Tanzania and then continues to harbors in Dar es Salaam. The main export is coffee (48%) followed by tea (23%). The coffee is primary exported to Europe (Switzerland, Belgium, UK and Germany are main importers) and tea is primary exported to countries in the East African Community (EAC) [16].

2.1.3 Energy system

Burundi's energy system is focused around four main energy carriers: wood, charcoal, oil and electricity. Compared to other sub-Saharan countries Burundi have a unusually high percentage use of wood and charcoal. Wood and charcoal together represents 97.5% of Burundi's total energy consumption, the other 2.5% is shared between oil and electricity. Most of this energy usage is from households as seen in table (2.1.1). A very small amount of peat is also used exclusively by some parts of the public sector. The total energy usage for each sector in 2003 is shown in table (2.1.1). In 2003 the total energy consumption was 1.314 million tonnes of oil equivalent [7].

	Percentage	Wood	Charcoal	Oil	Electricity
Transport and Industry	2.8	x	x	x	x
Households	94	89	10	0.4	0.3
Trade	0.14	x	x	x	x

Table 2.1.1: Energy use per sector in Burundi. "x" marks unknown quantity. All values are showed as percentage values.

The "x" in table (2.1.1), marks lack of data. However for the transport and industry sector is known that the main energy carrier is oil. The petroleum is imported and distributed within the country by road and there currently exists two storage depots. One with the size of 14 000 m^3 in Bujumbura and one with a size of 20 500 m^3 in Gitega [7].

When it comes to the electricity usage there were 39 204 connections to the power grid in 2008. This includes connections for households, governments and business. Out of these 39 204 connections, 34 700 were household connections. There are approximately a total of 1.6 million households in Burundi, which means that approximately 2% of the households have access to electricity. The connected households are mostly situated in Bujumbura (80%). The growth in connections to the power grid have mainly been from households while governments and business have remained constant or with a more modest growth. Between 2000 and 2008 the average growth in new grid connections was 4.2% [7].

The agriculture together with the high usage of wood and charcoal for energy have had serious impacts on the country's forest cover of about 180 000 hectares. This have lead to that Burundi lost 40.5% of its forests between 1990 and 2010 and have therefore taken a number of emergency measures to address the situation [10].

The electricity production is almost exclusively generated from HPP in Burundi and it's neighboring countries [21]. There currently only exist one small thermal power plant in Bujumbura which is used during periods of unusual high demand (because of high running costs). The average generation during June in 2012 can be seen in figure (2.1.2). The same data is also used to calculate the duration charts seen in figure (2.1.3), [13].

The lack of new investments and appropriate maintenance during the last decades have made the electrification rate low, even in comparison to other sub-Saharan countries [12]. The lack of access to electricity have lead to problems for enterprises and according to a recent survey made by the World Bank 41% of the companies respondents answered that the access to electricity was the main constraint on production (followed by finance, 16%, and political instability, 14.5%) [26].

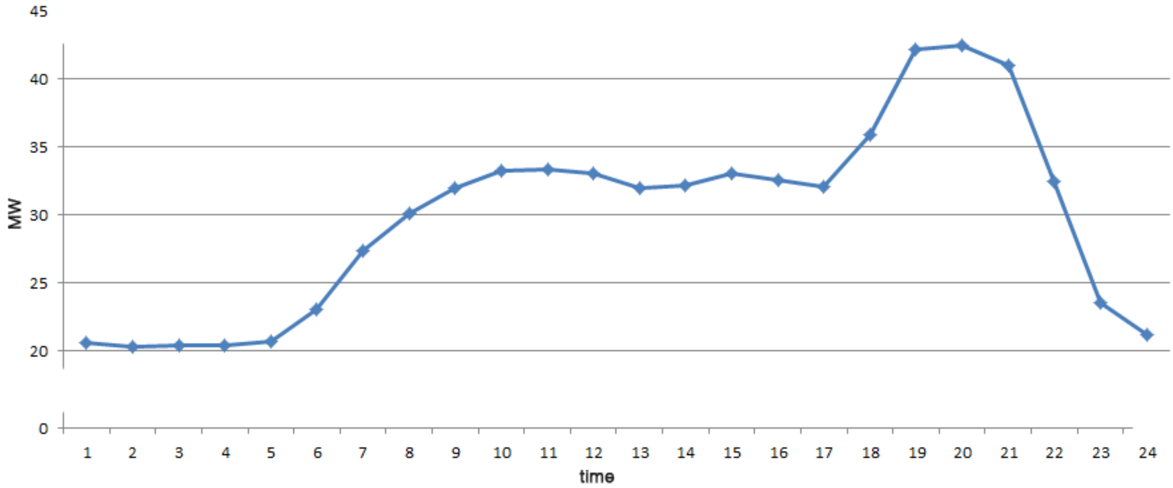

Figure 2.1.2: *The data is the average from generation over the period of 1-27 of June 2012. [13]*

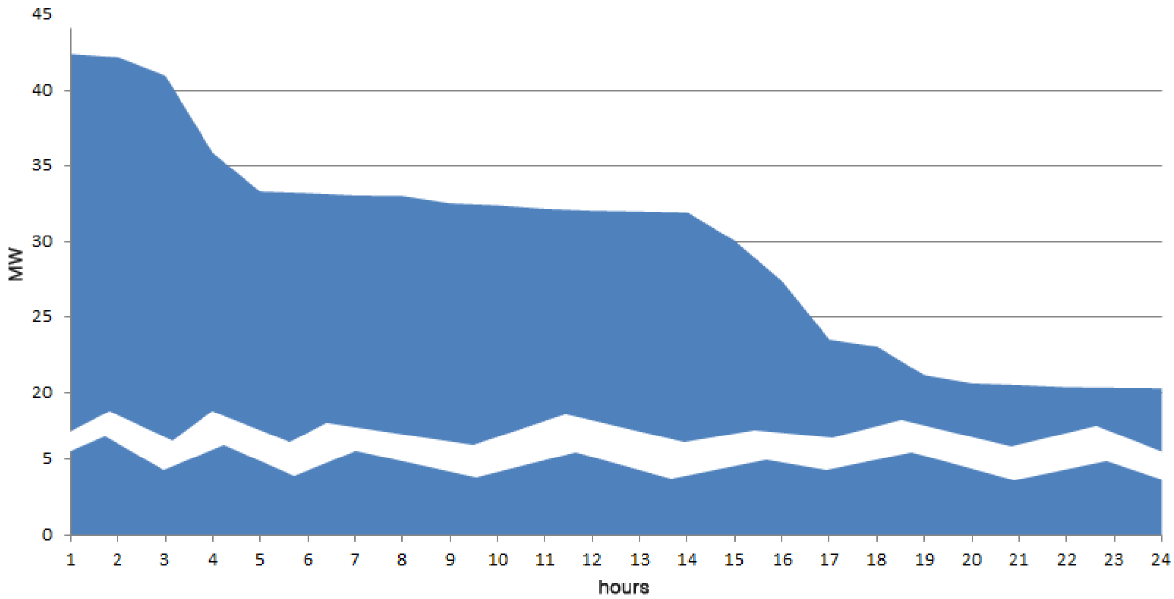

Figure 2.1.3: *The data is the average from generation over the period 1-27 of June 2012. [13]*

At the current electricity price, the demand is higher than the generation which gives a relatively big deficit of 20 MW [23]. In order to handle the difference in consumption and production REGIDESO applies load control. By disconnecting parts of the grid during periods they can reduce the total consumption and prevent blackouts because the grid is overloaded. The disconnected load varies between 5-10 MW depending if its day/night and/or rain/dry season [14].

Even if the current numbers shows that there is a large deficit and also a problem of accessibility, Burundi holds a lot of hydropower potential. It is estimated that Burundi's hydropower capabilities is around 1300 MW, of which roughly 300 MW is economically exploitable [9]. For the future, this and more will be needed since the consumption is estimated to grow to 395 GWh in 2015 from about 220 GWh in 2010 [7], [1].

Organizational Structure

In Burundi the water and electric authority, REGIDESO (Regi de Distribution d'Eau et d'Electricite) is responsible for the country's transmission, generation and distribution. REGIDESO operates under the supervision of the Minsitry of Water, Energy and Mines (MWEM). REGIDESO is also supported by two directorates: ABER and AHR. ABER are responsible for electrification of rural areas while AHR is responsible for water access in rural areas. ABER is a very small actor in the electric market in Burundi since almost all electricity is consumed within cities. Only Bujumbura consume more than 70% of the electricity in Burundi [14].

2.1.4 Electrical Power System

Burundi's current electrical installed capacity is 50 MW with an annual generation of 241 GWh in 2010 (an increase from 204 GWh in 2009), [21], [13]. Except from a thermal power plant in Bujumbura that is operating only during exceptional high demand (since the price of thermal power is about four times that of hydropower generated power) all this power is generated from hydropower plants in Burundi and neighboring Rwanda.

The Burundian transmission grid is built around 30 kV and 110 kV voltage levels. There exist one 70 kV connection from the Ruzizi I power plant in Rwanda but there are no further plans for expansion of the 70 kV system. Future plans does involve the expansion to 220 kV power line systems in multiple locations. Neither of these power lines will according to current plans replace any current 110 kV lines but will need new or expansion of current substations.

The power grid is currently focused in the north-western part of Burundi. This is the effect since currently all large HPP in Burundi are situated in the north or on the border between Rwanda and DRC. The fact that Bujumbura is located in the north with its 70% of the country's consumption is also likely a big reason.

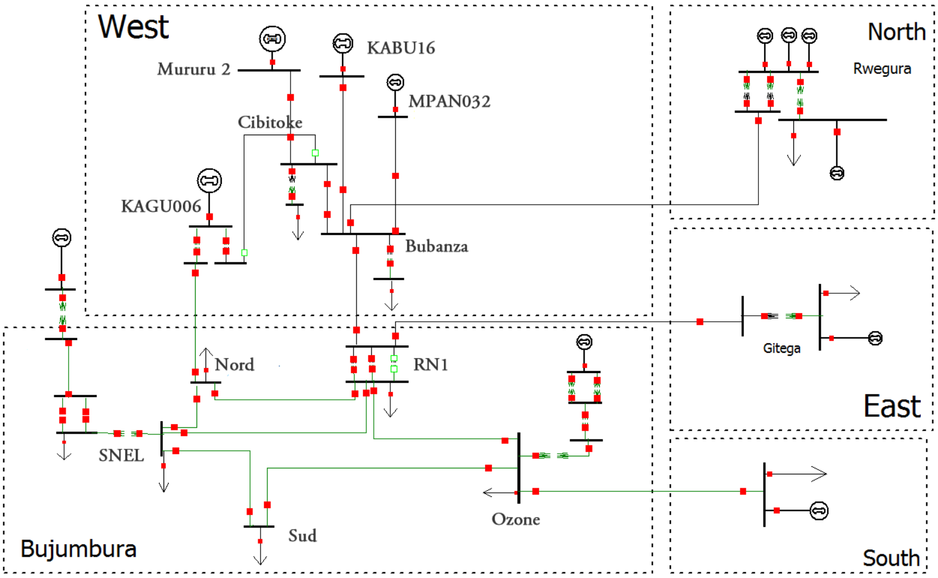

Figure 2.1.4: *Single-line diagram of Burundi's existing transmission grid.*

Future plans for the electrical power system

Burundi's plans for expansion of the grid are not clear. REGIDESO knows that the grid needs to be expanded in order to handle future generation and load. However there do not seem to be any overall plan for this expansion. There exist some general idea for the expansion but this mostly involves a few very high voltage lines for the largest power plants that are planned for the future [19]. There is a lack of connection between future projects and the expansion/upgrade of the grid which will be required for the future.

Burundi have a relative large database of feasibility studies for hydropower sites. Almost all of these plans are either in the stage of renewing the feasibility study or waiting for finance [20]. Their timeframe is thus relatively unclear.

2.2 Environmental impact of overhead power lines

This project does not aim to do a full environmental impact analysis of the overhead power lines needed for the construction of KAGU006 but still aims to give a short summary of possible environmental impacts. The environmental impact of an overhead power lines partly depends on the topography, land usage, existing eco systems and so on. Apart from the direct impact on the environment overhead power lines also have a visual impact. An impact that also depends on the topography. This thesis focus on visual impact and impact that is associated with the crossing over fragile or in other way eco valuable land. [27]

2.3 African Power and Water

African Power and Water (APW) is a Swedish Limited liability company based in Huskvarna, Sweden. APW focus is on providing energy and water solutions for Africa. APW turned to the Burundian government in 2008 to investigate the possibilities to construct a hydropower plant. After the first feasibility study, a site in Kaganuzi valley was chosen and the project was named KAGU006. African Power and Water consists of three shareholders, Resurshuset, PLS System and IGTC. The background of PLS System and Resurshuset contributes to make APW also interested in investigating further solutions for energy such as refining Jathropa oil, as well as water solutions.

2.3.1 The KAGU006 Project

APW's main project is the planning of a hydropower power plant in the Kaganuzi valley 40 km north of Bujumbura, see map (3.1.1). The site for the powerhouse lies a few km from RN5, the current biggest road connecting Rwanda and Burundi. The planned dam will be constructed at a location a few km away from the powerhouse which will require the construction of a 2 km pipe from the dam to the powerhouse. Next to the road and a few km from the site lies the village of Ndava. For the benefit of the community, it's planned that the dam will also be used for water supply to the residents in Ndava.

There are currently different alternatives of generators, power generation and considerations of what type of hydropower plant that will be used, see table (2.3.1), [18]. There are multiple alternatives, but the alternatives showed in table (2.3.1) are what is currently being considered to be most likely by AWP. Measurements of the flow indicates that it will be in the vicinity of 8-9 m^3/s.

Characteristics	0A	1A	0B	1B
Number of units	2	3	2	3
Unit Power (kW)	3920	2620	4420	2960
Total Power (kW)	7680	7680	8680	8680
Yearly output (GWh/year)	40.88	44.15	46.14	49.83
Average Power	4666	5040	5266	5688
Head (m)	79	79	81-89	81-89

Table 2.3.1: Current hydropower Alternatives and data from the feasibility study [18].

Alternative 0A and 1A represents run-of-the-river power plant, while Alternative 0B and 1B represents a run-of-the-river peak power plant. However, the measurements made to support the numbers in table (2.3.1) was made on an daily basis and does not take into account hourly variations in the discharge resulting from the running of the Rwegura HPP. According to the latest feasibility study made by SHER they suggest that regardless of which alternative used, Francis type turbines to be used. Considering the discharge and the head from the dam, both Pelton and Francis turbines are possible

Figure 2.3.1: *Map of KAGU006s position.*

options. Kaplan turbines are disregarded because of the relative high head which makes them suboptimal. According to the economical estimations done by SHER, Francis turbines are the best option [18].

The current most likely option and what is being considered by APW for KAGU006, is alternative 1B. The alternative have the highest output and also uses three instead of two turbines. By using three rather than two turbines it is possible to achieve higher output during maintenance.

3 Methodology

The thesis is based on data and information that is used for simulation and analysis of the Burundian electricity grid. For the simulation of grid, the software Power World Simulator (PWS) have been used. PWS is an interactive visual power system simulation software for high voltage power systems. PWS has been used in such way that it takes the system distributed load as input and returns the load of each component in the grid. The version of PWS used in the simulations is currently the latest version, Simulator 16.

3.1 Data collection

In order to create the single-line model in PWS, data about the transmission grid, its capacity and generations/loads needed to be collected. Therefore a list, see below(4.2.7), with the need data was created.

- Data and for transformers, power lines and generators.
- Data for current deficit and how the load disconnection is currently handled.
- Single-line diagram over the transmission grid, now and possible expansion.
- Future plans on new power plants and how/where these will be connected.
- Current load distribution.
- Current situation of substations in Bujumbura, Bubanza and Gitega. Reserve connection points, status and so on.

Because of Burundi's current situation the most reliable way of obtaining information about the grid was to visit REGIDESO's office in Bujumbura. Data was obtained through meetings with officials from REGIDESO and numerous visits were done to substations that was either of interest because of possible connection possibilities with KAGU006, or because they would be an integral part of the grid distributing the power to and in Bujumbura. The substations condition, capacity, potential of expansion was investigated.

In PWS the transmission grid have been sectioned into five sections: Bujumbura, North, South, East and West, see figure 3.1.1. The added generation is distributed as load amongst each region and substation according to each sectors current fraction of the load. As an example: since Bujumbura is responsible for 70% of the load today therefore 70% of the new power will be distributed in Bujumbura as a load. The load is further distributed amongst the five substations in Bujumbura. This distribution is done according to the fractions of each substation transforming capacity. In order to keep simulations and calculations conservative according to capacity of components and uneven generation during dry and rain season, the load is increased with 5%. The load is taken as the maximum generation in June (which is in the beginning of the dry season).

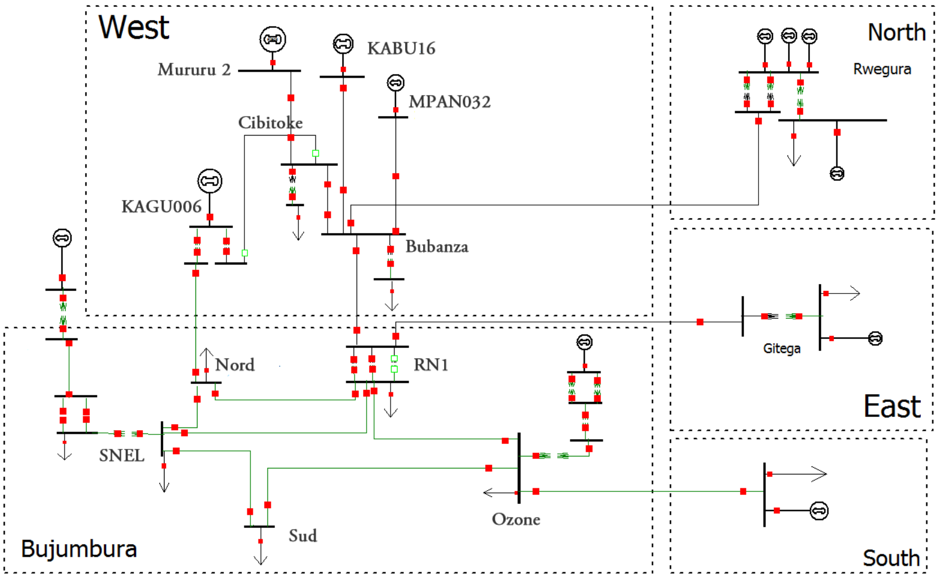

Figure 3.1.1: *Single-line diagram of Burundi's existing transmission grid.*

3.2 Connection cases

In order to find the evaluate the connection possibilities to the grid, economy and the environment a series of connection cases are defined. The cases will represent the different possible connection points and how the KAGU006 plant can be connected to these points. Apart from the scenario proposed by REGIDESO were the connection point is the substation "Poste Nord" in Bujumbura two other connection points are investigated. These are a new power line to Bubanza (which is the connection point currently in the contract) or a direct connection to the passing 110kV power line.

As can be seen in figure 3.2.1 there there are two relatively close substations to the site, in Bubanza and Cibitoke. Both are located approximately 15 km away from the KAGU006 site. Connecting at either of these sites would require 15 km of power line to be constructed. The third closest substation is in Bujumbura 40 km away and is the connection point suggested by REGIDESO. The substation is called "Poste Nord" and is only a 30 kV substation as opposite to the other two which work at both 110 kV and 30 kV. This connection would require the construction of 40 km of power lines. Apart from the substations there is the possibility of an T-off connection to the 110 kV power line between Cibitoke and Bubanza. This line passes the investigated site for the generators by less than 1 km and therefore would require the least amount on newly constructed power line.

These different connection possibilities are listed below and defined in detail as cases. Depending on how the connection to the substation/power line is done sub cases are created. Each case is represented by a number and each sub case is represented by a letter.

- case 1a: Site - Bubanza, 30 kV. The KAGU006 plant is connected to the substation in Bubanza 15km to the east using a 30 kV power line. The 30 kV power line will be connected using a 30/110 kV transformer and then be connected to the 110 kV bar. The power is transmitted from Bubanza using the current 110 kV to RN1 in Bujumbura.
- case 1b: Site - Bubanza 110 kV. Same case as above but the connection to Bubanza is made using a 110 kV power line instead of the 30 kV power line, therefore no transformer is needed.
- case 2a: Site - Bujumbura, 30 kV. The KAGU006 plant is connected to the substation "Poste Nord" in Bujumbura using a 30kV power line. The connection can either be done using the current switch rated for 630 A or a new 1250 A switch.
- case 2b: Site - Bujumbura, 110 kV. Same case as above but the transmission is done with a 110 kV line instead of the 30 kV line. Therefore a 110/30 kV transformer is needed in "Poste Nord".
- case 3a: Site - 110 kV line. The case represents the connection is made to the existing 110 kV power line between Cibitoke and Bubanza using a 6.6 kV power line from the generator to the passing 110 kV power line. A new substation for the connection needs to be constructed and a 6.6 kV power line is used from the generator to the substation.
- case 3b: Site - 110 kV line. The case represents the connection is made to the existing 110 kV power line between Cibitoke and Bubanza using a 110 kV power line from the generator to the passing 110 kV power line. A new substation for the connection needs to be constructed and a 30 kV power line is used from the generator to the substation.
- case 3c: Site - 110 kV line. The case represents the connection is made to the existing 110 kV power line between Cibitoke and Bubanza using a 30 kV power line from the generator to the passing 110 kV power line. A new substation for the connection needs to be constructed and a 110 kV power line is used from the generator to the substation.

A schematic view over Burundi with the three connection cases marked out can be seen in figure 3.2.1. Red shows case 1, blue case 2 and black existing power lines, utilized by case 2 and 3.

3.2.1 Dismissed cases

All cases requiring a 30 kV connection in Bubanza or Cibitoke have been dismissed since the installed 30/110 kV transformer is rated for 5 MVA at each of the substations. A 30

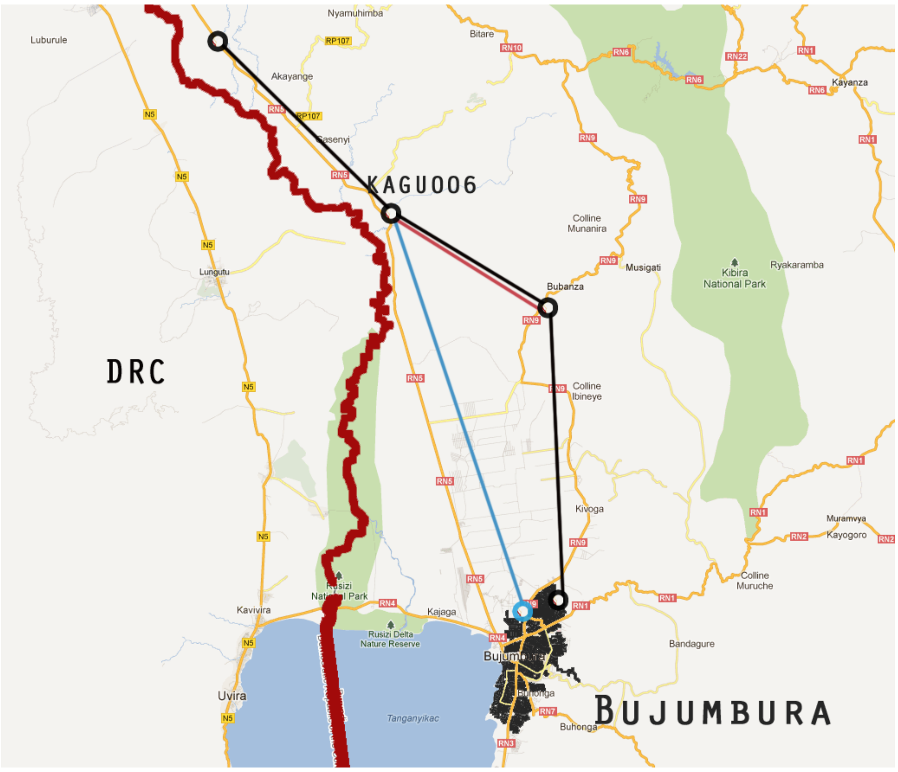

Figure 3.2.1: *Figure showing the three connection cases position in Burundi. Red shows case 1, blue case 2 and black existing power lines, utilized by case 2 and 3.*

kV connection could be made theoretically but since both Bubanza and Cibitoke uses only about 3 MW of power AWP would be able to generate at their maximum capacity [23]. Connection to the 110 kV busbar in Cibitoke is not considered. The substation is 15 km north of the KAGU006 site and would therefore require construction of new power lines away from Bujumbura. Since the 110 kV power line from Cibitoke is connected in Bubanza before going to Bujumbura, this would mean an extra 30 km of power line and therefore increase losses without having any obvious economical or environmental benefits compared to case 1. Connection with other voltage levels than 30 kV or 110 kV have been dismissed apart from case 3a when 6.6 kV is used because of the very short distance and the power output from the generators are 6.6 kV. Introducing other voltage levels would require extra transformation and therefore also costs. With the introduction of a third voltage it would likely be harder to find personal working with this technology in Burundi compared to the already existing voltage levels. Connection to other substations within Bujumbura have been dismissed since they are to far away from the site, and other substations outside Bujumbura have been dismissed because of their long distance to the site.

3.3 Development Scenarios

Other than investigating different connection cases, the simulation will also take into account some of the future HPP plans. Because of Burundi's large electricity deficit they will need, and plan to, construct many more power plants. Currently there are 21 hydropower projects in pipeline either waiting for finance or finalization of the feasibility study [20]. Other projects including peat power plants also exists [13]. Burundi's current plan is to install 200 MW until 2020 [3]. Since KAGU006 won't be online until 2014, the electricity and grid situation in 2014 will be different compared to today. REGIDESO have two other HPP projects in the vicinity of KAGU006 that will according to current plans be connected to the Bubanza substation and can affect KAGU006.

- KABU16: KABU16 is a hydropower plant about 10 km north of KAGU006. It is located along the Kaburantwa river and projected to have a power output of 20 MW. KABU16 is planned to be connected to the Bubanza substation and to be taken online around 2014/2015.
- MPAN032: MPAN032 is a HPP located near Mpanda village just south of the city of Bubanza. MPAN032 is planned to have a power output of 10.4 MW and is planned to be connected to the Bubanza substation with a 30 kV power line and to be online around 2014/2015.

3.3.1 Dismissed Scenarios

The other 16 planned HPP are dismissed from the simulations and analysis. Some of them are planned to be located far away from the site of KAGU006 others have a big uncertainty if and when they will be constructed. Lastly the data available about the way they would be connected to the grid when this analysis was done wasn't available. There are two more planned HPP projects together with Rwanda and DRC, Ruzizi III and Ruzizi IV. There is also a project in pipeline for a HPP together with Tanzania at the Rusumo falls. These three will all be of considerable size (between 60 MW-287 MW each), but since financing for the projects are not yet determined, their timeframe is uncertain, they are therefore not considered.

4 Theory

In this chapter the theory needed for understanding of the subject of power grids, their distribution and operation within the context of this project. The theory section also gives a small introduction to the theory of hydropower. The theory chapter is divided into two sections: hydropower and electrical power grids. Each section is further divided into subsections to improve the overview of the subjects.

4.1 Hydropower

Hydropower is one of the oldest and simplest form of harvesting energy from nature and have been used for almost 2000 years. In modern society hydropower is almost exclusively used to generate electricity through the use of turbines and generators. Small (less than 30 MW) hydropower systems have seen an increase in popularity since they require less planning oct have a smaller impact on the environment compared to large scale hydropower systems [11]. Since LDCs estimate to be home of 48% of the worlds hydropower potential, small, mini and micro hydropower systems have been seen as a viable solution to the electricity deficit in many LDCs [11].

The theoretical extractable energy from a hydropower plant is determined by two parameters: flow and height different between inlet (or water level depending the design) and outlet. The height difference from inlet/water level and outlet is decided during the construction and is determined by the landscape that the HPP is built in and the HPP type. The height difference is commonly named hydraulic head. From the reservoir the water is either first transported by a pipe to the location of the generator house or straight to the penstock. The penstock is basically a large pipe transporting the water to the turbines. A schematic view of a HPP can be seen in figure 4.1.1.

The theoretical amount of energy that can be extracted is based on simple principles of potential and kinetic energy, the expression can be seen in (4.1.1).

$$P = \rho \cdot Q \cdot g \cdot h \tag{4.1.1}$$

Taking the efficiency of the turbines and generators into account the expression changes to (4.1.2).

$$P = \eta \cdot \rho \cdot Q \cdot g \cdot h \tag{4.1.2}$$

Where η is the combined efficiency of the turbines and generator.

As seen from figure (4.1.1) and equation (4.1.2) for a HPP with a reservoir the height, h, will decrease when during times of low or no runoff to the reservoir. Therefore a HPP should not be able sustain a power production during times when the content of the reservoir is used since the power output is linearly proportional to the hydraulic head. This can be true during long times when the refilling is slow or nonexistent. However

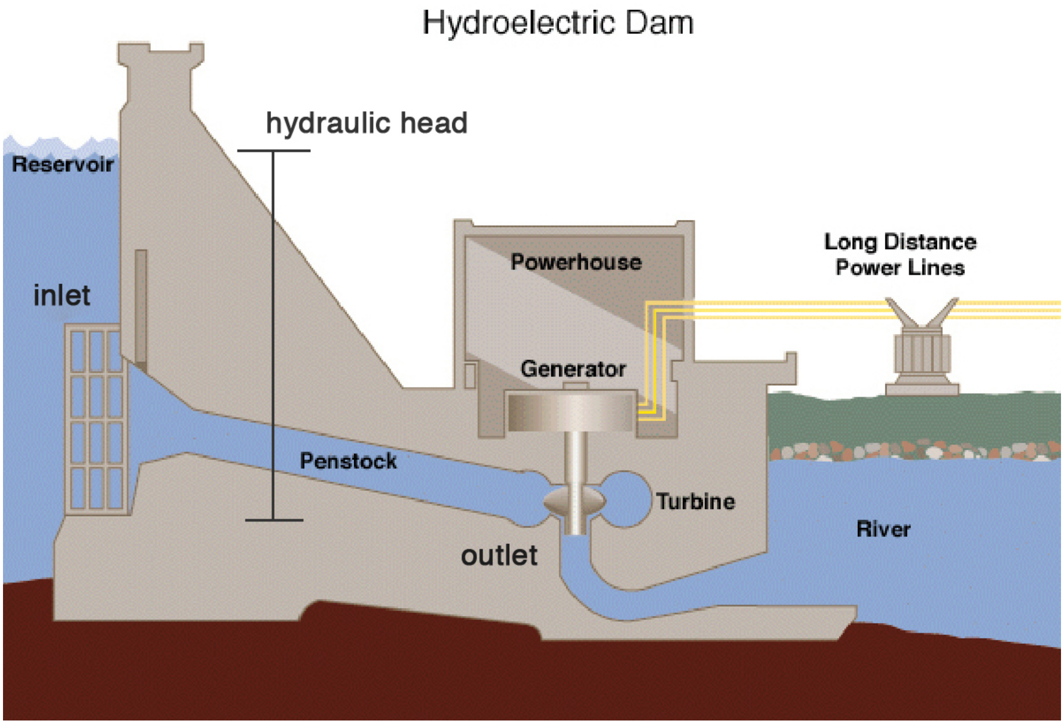

Figure 4.1.1: *A schematic view of a HPP with a reservoir. Figure from Wikimedia Commons.*

most HPP can also control the flow into the turbines by opening or closing the inlet to sustain an even power production.

Depending on how the water is used in a HPP, they can be divided into two categories: run-of-the-river and reservoir plants. Both categories uses the hydraulic head for the generation but have different ways of utilizing the flow. Run-of-the-river HPP don't use any reservoir to store water but utilizes the natural flow in the river to produce power. There exist cases of run-of-the-river HPP that uses small reservoirs to handle small discharge variations in the river. Reservoir plants on the other hand uses very large reservoirs to store water. The stored water can then be used when the river flow is very small or even zero. Therefore the HPP can produce power in a more controlled way and during periods when flow is low but demand is high. Reservoirs can be very large, and sizes exist up to 30 km^3 [5].

The height and and flow decides what type of turbine that is most suited for a power plant but also the operating conditions since their efficiency curves are different. There are generally three types of turbines that are used in HPP: Kaplan, Francis and Pelton. No details regarding efficiency curves and over details are laid out here but it should be noted that Francis turbines can be used for higher heads than Kaplan turbines [11].

4.2 Electrical power grids

Electrical power grids (or simply grids) are the core in the electrical systems and are responsible for that the generated power can be transmitted and distributed to all users. Electrical grids are generally distinguished into transmission grids and distribution grids and consist of the following components.

- Substations: Substations are nodes in the grid. They are responsible for the distribution of incoming and outgoing power, often between different voltage levels. Various types of substations exist depending of their application such as distributing, transmitting or collecting of power or conversion of voltage. Substations are found in both transmission and distribution grids.
- Transformers: Transformers are located in substations and are responsible for transforming the voltage levels between two different voltage levels in order to facilitate a connections with other parts of the grid. They are one of the key components that define the capacity a substation can handle.

Since this project focuses on the transmission grid in Burundi it is necessary to make the differentiation between transmission grid and distribution grids. The below table summarizes the similarities and differences for the two different grids.

- Transmission grid: Transmission grids are responsible of the transmission from the generating plants to selected substations (nodes) in the grid. This means that transmission lines cover great distances and therefore operate in higher voltages.
- Distribution grid: Distribution grids are responsible for all short (in the context) distance power transmission. Because of the shorter distances distributions grid are operated on a lower voltage.

In modern electrical AC grids, the power is transmitted using three phases. Three phases means that there are three conductors sending current and that each conductor is phase shifted against the other two with an angle β. The implications being that more power can be transmitted but also that the power remains time independent, which is not the case for single phase AC systems.

4.2.1 AC

AC is the most common way of transporting power in todays electrical grids, it is easy to transform between voltage levels and the fact that high-powered generators works on AC are a few of the reasons. During steady state all currents and voltages varies as a sinusoidal function, see figure (4.2.1a). A sinusoidal function in steady state can also be described with a indicator (the indicator being the RMS value of the sinusoidal function) and a phase angle, see figure (4.2.1b). The indicator and phase angle can also be viewed as describing a point in the complex plane. By identifying the value in the complex plane and using complex notation the calculations are greatly simplified since they can be done with complex numbers instead of sinusoidal functions.

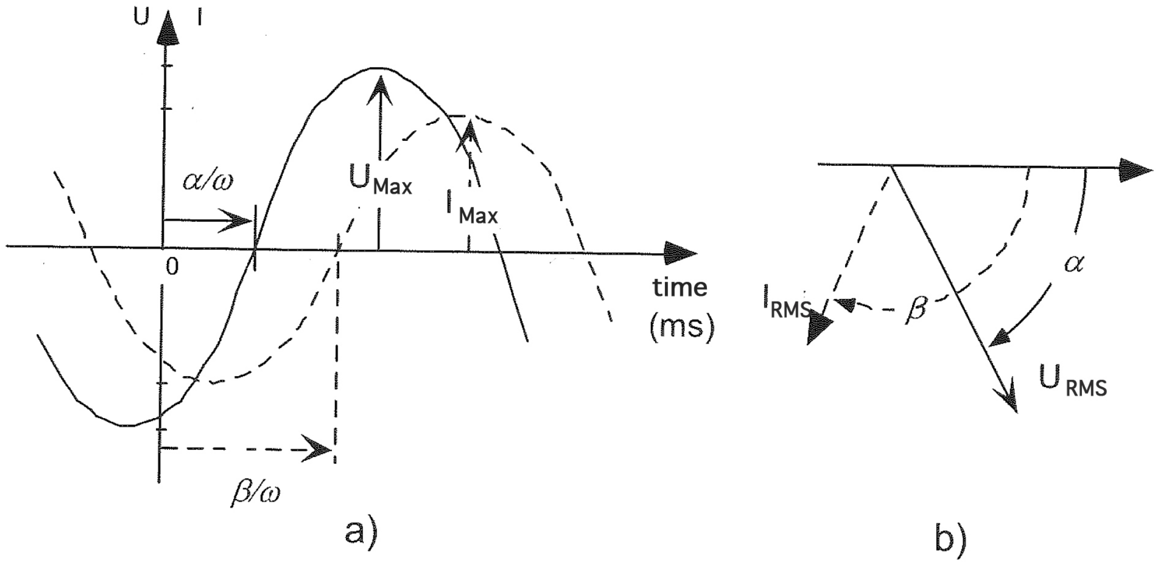

Figure 4.2.1: *Figure a) showing time varying sinus functions of voltage and current and figure b) shows indicators and respective angles. Figure supplied by the electrical engineering department at Chalmers University of Technology.*

The sinusoidal functions in figure a (4.2.1) can be described as a time variating function as seen in equation (4.2.1).

$$\begin{aligned} i(t) &= I_{max}\cos(\omega t + \beta) \\ u(t) &= U_{max}\cos(\omega t + \alpha) \end{aligned} \tag{4.2.1}$$

Where I_{max} and U_{max} are the top values as seen in figure (4.2.1), ω is the frequency and β and α are the phase angles of the voltage and current. ω is 2π times the frequency.

The effective (RMS) value for a sinusoidal function is its top value divided by $\sqrt{2}$. We then get the following effective values for the sinusoidal function in (4.2.1) and respective effective values in the complex plane.

$$\begin{aligned} U = U_{max}/\sqrt{2} \qquad \underline{U} = U\angle{-\beta} \\ I = I_{max}/\sqrt{2} \qquad \underline{I} = I\angle{-\alpha} \end{aligned} \tag{4.2.2}$$

For the sake of simplifications with the calculations, the angle of the voltage is usually taken as a reference and set to zero.

4.2.2 Power

For a given moment of time, the power that flows through a certain point is equal to the current times voltage. Using equations (4.2.1) the power as a function of time becomes, after some simplifications, equation (4.2.3).

$$p(t) = i(t) \cdot u(t) = \frac{U_{max} I_{max}}{2} \cos(\phi) - \frac{U_{max} I_{max}}{2} \cos(2\omega t + \phi) \tag{4.2.3}$$

where

$$\phi = \beta - \alpha \tag{4.2.4}$$

is the angle of difference between the voltage and current. However when doing calculations on power lines, the power that flows through a line is more of interest than the power at every moment of time. Calculating the time average for a full number of periods for equation (4.2.2) results in equation (4.2.5).

$$P = UI \cos(\phi) \tag{4.2.5}$$

Equation (4.2.5) is also called Active power and is one of the central parts in AC systems.

If the part of the current in phase with the voltage is removed and the RMS value is taken of the remaining component we get the remaining part of the power, see equation (4.2.6).

$$Q = UI \sin(\phi) \tag{4.2.6}$$

Where Q is called reactive power. Since cosine and sinus are orthogonal functions P and Q are orthogonal (and independent) and can be changed separately. Even though the active power represents the actual energy flowing through a given piece of equipment, reactive power is very important for understanding power engineering, an example is as a measure of the size capacitors need to be to correct for phase shifting.

Active and reactive power can be combined into what is called apparent power (S), see figure (4.2.2).

Apparent power is important because it is used for rating transformers and power lines in a grid. The reason apparent power is used and not active power is because a transformer or a power line can handle a certain voltage and current irresponsible of their phase shift.

From figure (4.2.2) and equations (4.2.5) and (4.2.6) its seen that $S = UI$. From basic trigonometric and Pythagoras theorem we get the following expressions.

$$\begin{aligned} S^2 &= P^2 + Q^2 \\ P &= S \cos(\phi) \\ Q &= S \sin(\phi) \end{aligned} \tag{4.2.7}$$

It is very importance to understand apparent power (S), active power (P) and reactive power (Q) and how they interact as they are a central element in power engineering. The apparent power S, can also be defined using complex notation as a vector in the

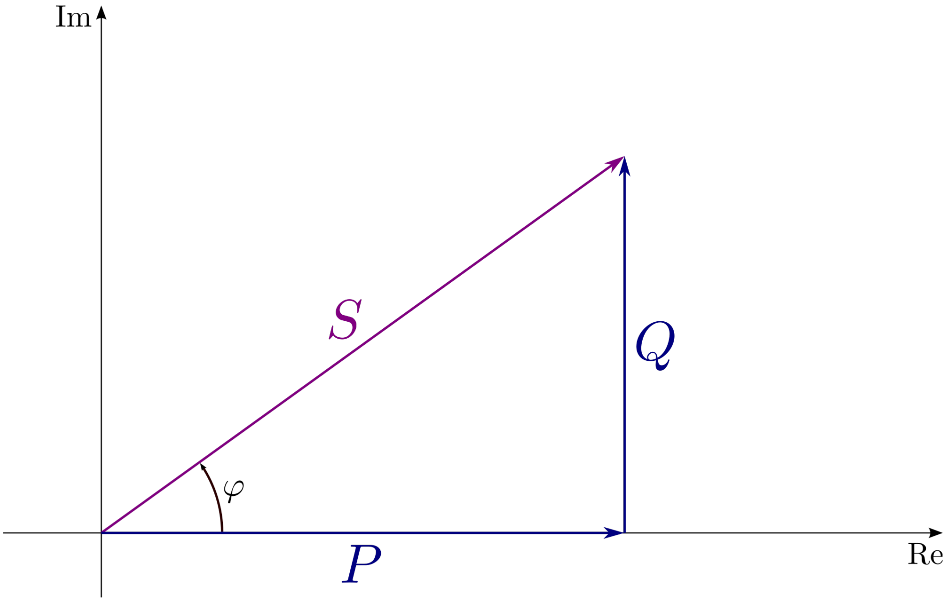

Figure 4.2.2: *Figure showing a graphic representation of complex power in the complex plane. Figure from Wikimedia Commons.*

complex plane and using effective values for the complex vector from (4.2.2). It is then defined according to equation (4.2.8) with the complex conjugate of the current.

$$\underline{S} = \underline{U} \cdot \underline{I}^* \tag{4.2.8}$$

Or through the alternative way of

$$\underline{S} = P + jQ \tag{4.2.9}$$

Apparent, active and reactive power are measured with different physical quantities since they represent different aspects of AC-power. Apparent power has the units Volt-Ampere (VA), active power Watts (W) and reactive power Volt-Ampere Reactive (VAR).

4.2.3 Three Phase

Three phase systems was introduced in AC systems to increase power transmission and to guarantee a steady power flow to appliances connected to the system. Three phase systems can be constructed in two ways, either as three single one phase system or as one integrated three phase system, see figure (4.2.3). The figure shows that there are considerable design advantages of a single integrated three phase system rather than three separate one phase systems since no returning power lines are needed (this only apply to symmetrical systems, but it is from here on assumed).

Another important aspect of three phase system is that in contrast to single phase system it is possible to extract two different voltage levels deepening on much power an appliance is using. Either the appliance is connected between ground and a phase

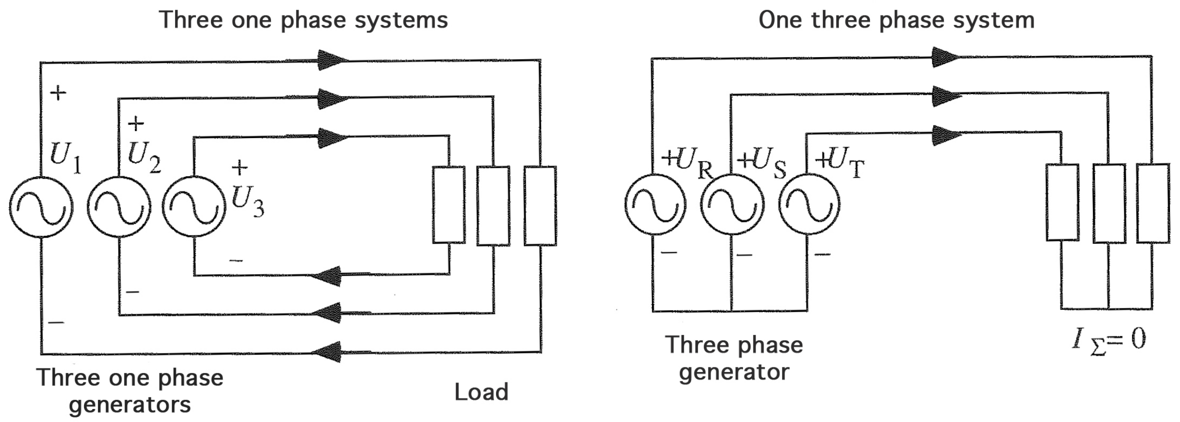

Figure 4.2.3: *Schematic figure showing the difference between three one phase systems and a single symmetrical three phase system. Figure supplied by the electrical engineering department at Chalmers University of Technology.*

(Line-Neutral, LN) or between two different phases (Line-Line, LL). For a 120° phase shift of the LN voltages, the factor between LL and LN voltages is a factor of $\sqrt{3}$.

The complex power $\underline{S}$ for a complete three phase system then becomes.

$$\underline{S} = 3\underline{U}_{LN}\underline{I}_L^* \tag{4.2.10}$$

I_L is an abbreviation for phase current and is the standard quantity used together with Line-Line voltage. From equation (4.2.10) we can calculate the active and reactive power for the total three phase system as

$$\begin{aligned} P &= 3 \cdot U_{LN} I_L \cos(\phi) \\ Q &= 3 \cdot U_{LN} I_L \sin(\phi) \end{aligned} \tag{4.2.11}$$

Equation (4.2.12) can also be written using Line-Line voltage levels and then becomes

$$\begin{aligned} P &= \sqrt{3} \cdot U_{LL} I_L \cos(\phi) \\ Q &= \sqrt{3} \cdot U_{LL} I_L \sin(\phi) \end{aligned} \tag{4.2.12}$$

Since all voltages are measured as Line-Line, equations (4.2.12) are commonly used for calculation of three phase AC power.

4.2.4 Losses

Power losses in AC systems can be of either active (MW) or reactive (MVAR) type. A single phase power line can be modeled as a system consisting of a perfect conductor connected with a resistance. The power consumed by 1 three phase power line is then described as for any circuit, see equation (4.2.13).

$$P_{losses} = 3R \cdot I_L^2 \tag{4.2.13}$$

Where I_L is the line current and R the total resistance of the power line. The line current will be set by the total load, P, in the end of the power line, according to equation (4.2.14).

$$P_{demand} = \sqrt{3}U_{LL} \cdot I_L \quad \rightarrow \quad I_L = \frac{P_{demand}}{\sqrt{3}U_{LL}} \tag{4.2.14}$$

Inserting equation (4.2.14) in (4.2.13) results in equation (4.2.15).

$$P_{losses} = 3 \cdot R \cdot I_L^2 = \frac{R \cdot P_{demand}^2}{U_{LL}^2} \tag{4.2.15}$$

As seen the losses are proportional to the square of the current (or load/voltage). So a larger load will increase the fraction of power lost in transmission.

4.2.5 Line Capacity

Capacity (steady state thermal rating) of power lines is determined by the amount of current they can carry. The maximum current is determined by a number over variables and to calculate the exact value would require a very detailed and complex theory. A simplified approach is therefore done here in accordance to the methods proposed by the IEEE [15].

When a power line carries current the temperature of the line increases as a result of the resistance. The conductivity of a material is for all common materials proportional to the temperature. Higher temperature gives higher resistance. Therefore as the current increase so will the resistance. and with the resistance the heat losses. If the power line is overloaded the heat makes the power line expand and can make it come in contact with other objects, risking a short circuit. In a worst case scenario, the power line could even break at the connection point due to angle created by the overhang.

The theory in [15] takes into account three different effects of current capacity: convection heat loss, conduction (radiated) heat loss and solar heat gain.

With these effects taken into account, the steady-state thermal rating (ampacity) of a bare overhead power line can be estimated.

Convection heat loss (q_c)

Therefore the rate at which the convention of heat is carried out is direct related to the current of the power line.

Assuming non zero wind speed the rate of heat losses is shown in (4.2.16) or (4.2.17).

$$q_{c1} = \left[1.01 + 0.0372\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.52}\right] k_f K_{angle}(T_c - T_a) \tag{4.2.16}$$

$$q_{c2} = \left[0.019\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.6}\right] k_f K_{angle}(T_c - T_a) \tag{4.2.17}$$

Where ρ_f is air density, D is conductor diameter, μ_f the viscosity of air, k_f is the thermal conductivity of air, K_{angle} is the wind direction factor, V_W is the air speed at the conductor, T_c is maximum allowable temperature and T_a is actual carrying temperature.

Which of the expressions (4.2.16) or (4.2.17) that is used depends on the wind speed. Equation (4.2.16) is used for low wind speeds and (4.2.17) is used for high wind speeds. The definition of high and low wind speed in not clearly defined, therefore the larger of the two calculated values is always chosen.

Conduction heat loss (q_r)

Heat does not only escape a power line through the means of convection but also through conduction. This is stated as radiated heat loss in [15]. Heat conduction is a process of heat flow from a waker to a cooler body in order for the system to reach thermal equilibrium. The expression describing heat conduction is described equation (4.2.18).

$$q_f = 0.0178D\epsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \tag{4.2.18}$$

Where ϵ is the emissivity of the material (usually aluminum or copper).

Solar heat gain (q_s)

Solar heat gain is the heating effect resulting from solar radiation on the power line. The result is a function of material properties, solar altitude, azimuth and the atmosphere.

$$q_s = \alpha Q_{se} \sin(\theta) A' \tag{4.2.19}$$

where

$$\theta = \arccos\left[\cos(H_c)\cos(Z_c - Z_l)\right] \tag{4.2.20}$$

The parameter values are taken from a table in [15] to match the conditions in Burundi.

Steady-state thermal rating

Using the results from above, the steady-state thermal rating can now be calculated using equation for steady-state heat balance, (4.2.21)

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \tag{4.2.21}$$

Where $R(T_c)$ is the resistance at the maximum allowable temperature. Using equation(4.2.12) the rated capacity is then

$$P = V_{LL} \sqrt{\frac{3(q_c + q_r - q_s)}{R(T_c)}} \tag{4.2.22}$$

4.2.6 Power Grid Security

Since the electricity is of uttermost importance in modern societies it is of great importance that the electrical system do not fail even in extraordinary cases. To make sure that even in the case of component failure the grid can supply power without a complete blackout a number of criteria have been created called n-0, n-1, n-2 and so on. When a grid is said to be n-0 secure is corresponds to that the grid can operate during normal conditions (no component failure). A n-1 contingency is then when one component in the power system have failed. And the n-1 criteria is when the grid still can operate during those conditions. And an n-2 contingency is then the case when two components break down, n-3 when three components brake down and so on. In Sweden the standard when constructing or expanding the power grid is that it shall at all times be able to handle a n-1 contingency.

5 Electrical grid calculations

In the electrical grid calculations chapter will the results from the PWS simulations be presented together with cost estimations and line losses. The PWS simulations are presented per sector as have been defined previously. The chapter starts with the PWS simulations results before before showing the n-1 contingency results and last are the cost estimations. The full cost estimations can be seen in the appendix A.

5.1 Capacity simulations

The results in the following section shows the capacity of central equipment in the transmission grid for the different cases and with different HPP connected. The baseline (called Base and defined in the first row in table (5.1.3) and (5.1.2)) is the maximum generation during June plus 5% [22]. This corresponds to a load of 48.64 MW. The power plants KAGU006 (8.7 MW), KABU16 (20 MW) and MPAN032 (10.4 MW) are then sequentially added to increase generation. The results of the distribution to each sector and scenario can be seen in tables (5.1.3) and (5.1.2).

	Total Load	Bujumbura	North	South	East	West
Max (10th of June, 2012, 19:00)	46.32	32.58	3.9	3.28	3.32	3.24
Max + 5% (=Base)	48.64	34.2	4.09	3.45	3.48	3.4
Base, KAGU006	57.64	40.53	4.85	4.09	4.13	4.02
Base, KAGU006, MPAN032	68.04	47.86	5.72	4.82	4.87	4.76
Base, KAGU006 MPAN032, KABU16	88.05	61.92	7.4	6.24	6.3	6.16
Base, MPAN032, KABU16	79.04	55.59	6.65	5.6	5.66	5.52

Table 5.1.1: Electrical load distribution for the different scenarios. Numbers are given in MW.

A more detailed view of the load distribution in Bujumbura is seen in table (5.1.2). The corresponding generation can be seen in table (5.1.3).

The results are presented per sector according to the five sectors (North, South, East, West and Bujumbura) that was supplied by REGIDESO. The sectors of most interest for KAGU006 is West and Bujumbura since the site and the transmission lines to Bujumbura is located in sector West.

A schematic view of the model divided into sectors is seen in figure (5.1.1).

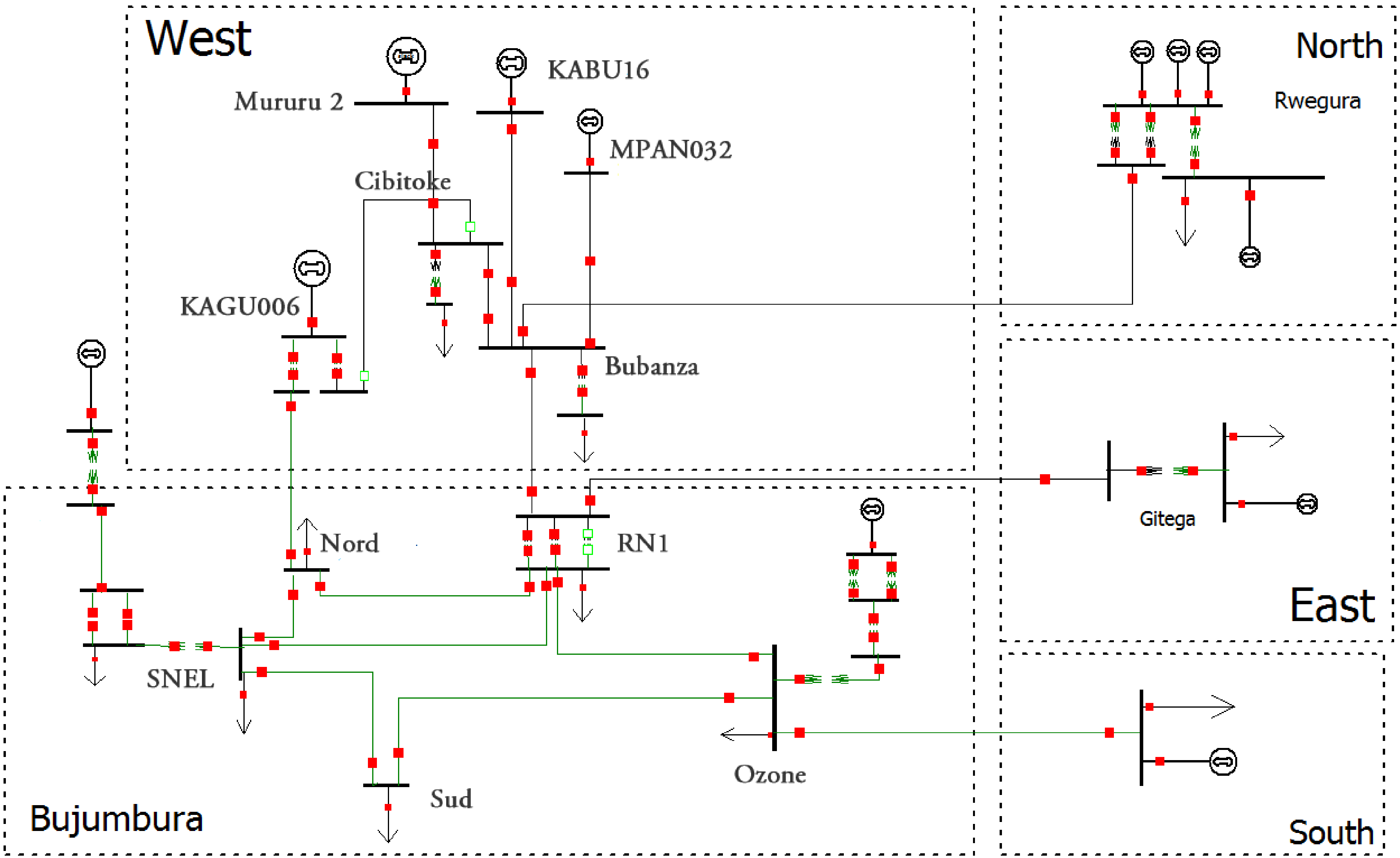

Figure 5.1.1: *Single-line diagram showing the model and it's divided sectors.*

	Bujumbura	Nord	Sud	Ozone	SNEL (x2)	RN1
Max (10th of June, 2012, 19:00)	32.58	4.79	4.79	4.79	4.32	9.57
Max + 5% (=Base)	34.2	5.03	5.03	5.03	4.53	10.05
Base, KAGU006	40.53	5.96	5.96	5.96	5.37	11.91
Base, KAGU006, MPAN032	47.86	7.04	7.04	7.04	6.34	14.06
Base, KAGU006 MPAN032, KABU16	61.92	9.1	9.1	9.1	8.21	18.2
Base, MPAN032, KABU16	55.59	8.17	8.17	8.17	7.37	16.34

Table 5.1.2: Load distribution in Bujumbura for different scenarios. Numbers are given in MW.

	Ruzizi I	Ruzizi II	Rwegura	Mugere	North	South	East
Base	4.2	17.1	17.3	7	0.75	1.25	2.3
Base, KAGU006	4.2	16.2	17.3	8	0.75	1.25	2.3
Base, KAGU006, MPAN032	4.2	16.7	17.3	8	0.75	1.25	2.3
Base, KAGU006 MPAN032, KABU16	4.2	17.7	17.3	8	0.75	1.25	2.3

Table 5.1.3: Power generation for the different scenarios.

5.1.1 North

In table (5.1.4) the capacity of transformers at the Rwegura HPP and total load in the North sector is shown. The load is aggregated from sector North to one load and then placed on the 30 kV busbar in Rwegura. The used capacity does not change for any equipment for connection cases but only for the development scenarios, therefore only one table is shown below. Values shown in bold marks overloading.

	6.6/30kV Transformer	6.6/110kV Transformer
Base	83%	58%
Base, KAGU006	**118%**	50.8%
Base, KAGU006, MPAN032	**139%**	46.9%
Base, KAGU006, MPAN032, KABU16	**181%**	43%

Table 5.1.4: Used capacity and load for sector "North". Data does not change between Case 1,2 or 3.

5.1.2 South

As in sector North, the load in sector South is also aggregated to one load and connected to a busbar which in turn is connected to the substation Ozone, see figure 5.1.1. To the busbar is also Nyemanga HPP connected with a static generation of 1.25 MW. As in sector North, no changes in load, generation or used capacity is changed for any of the connection cases. Values shown in bold marks overloading.

5.1.3 East

The sector East is aggregated in the same way as sector North and South with one load. The total generation in East, mainly from Ruvyironza and Gikonge HPP, have been aggregated to one static generation of 2.3 MW. And as for the previous sectors there is no change in load, generation or used capacity for the connection cases. The load on the transformer in Gitega can be seen in (5.1.5). Values shown in bold marks overloading.

	30/110kV Transformer
Base	15%
Base, KAGU006	18%
Base, KAGU006, MPAN032	24%
Base, KAGU006, MPAN032, KABU16	37%

Table 5.1.5: Used capacity and load for sector East. The data does not change between Case 1,2 or 3.

5.1.4 West

The results from sector West are shown in tables (5.1.6) and (5.1.7). Table (5.1.6) only shows the results from case 3. The results from case 1 is identical with case 3 except that the used capacity of the power line between Cibitoke and Bubanza is lower. The capacity of the power line between Cibitoke and Bubanza is for Case 1 constant at 24% for all scenarios. Values shown in bold marks overloading.

	Ruzizi I (generation, MW)	Ruzizi II (generation, MW)	Mururu 2 - Cibitoke	Cibitoke - Bubanza	Bubanza - RN1	Ruzizi I - SNEL
Base	4.2	17.1	28%	26%	45%	11%
Base, KAGU006	4.2	16.2	27%	38%	56%	12%
Base, KAGU006, MPAN032	4.2	16.7	28%	39%	72%	12%
Base, KAGU006, MPAN032, KABU16	4.2	17.9	30%	39%	**101%**	12%

Table 5.1.6: Case 1 and 3: used capacity and load for sector West. Right side shows power lines load.

	Ruzizi I (generation MW)	Ruzizi II (generation MW)	Mururu 2 - Cibitoke	Cibitoke - Bubanza	Bubanza - RN1	Ruzizi I - SNEL
Base	4.2	17.1	28%	26%	45%	11%
Base, KAGU006	4.2	16.2	27%	24%	42%	11%
Base, KAGU006, MPAN032	4.2	16.6	28%	24%	57%	12%
Base, KAGU006, MPAN032, KABU16	4.2	17.7	29%	24%	86%	12%

Table 5.1.7: Case 2: used capacity and load for sector West. Right side shows power lines load.

5.1.5 Bujumbura

The results from Bujumbura are divided into two sections. The first will show the data from normal operation within Bujumbura while the second part will show the results from the contingency analysis for n-1 criteria in Bujumbura's transmission grid. Values shown in bold marks overloading.

	30/110kV (RN1)	6.6/70kV (SNEL)	6.6/30kV (SNEL)	6.6/35kV (Mugere)
Base	65%	39%	3%	68&
Base, KAGU006	81%	39%	8%	76%
Base, KAGU006, MPAN032	**101%**	40%	13%	76%
Base, KAGU006, MPAN032, KABU16	**141%**	40%	23%	76%
Base, MPAN032, KABU16	**123%**	40%	19%	76%

Table 5.1.8: Case 1 and 3: Load of transformers in Bujumbura.

	30/110kV (RN1)	6.6/70kV (SNEL)	6.6/30kV (SNEL)	6.6/35kV (Mugere)
Base	65%	39%	3%	68&
Base, KAGU006	59%	39%	7%	74%
Base, KAGU006, MPAN032	79%	40%	13%	74%
Base, KAGU006, MPAN032, KABU16	**119%**	40%	23%	74%
Base, MPAN032, KABU16	**123%**	40%	19%	76%

Table 5.1.9: Case 2: Load of transformers in Bujumbura.

Contingency results

Table (5.1.10) and (5.1.11) shows the capacity of the lines in Bujumbura's transmission grid for each Case and scenario. Table (5.1.10) shows capacity for Case 1 and 3 and (5.1.11) shows capacity for Case 2. Each table also shows capacity with or without the extra connection of KABU16 and MPAN032. The x-axis in each table represents a power line connection. An "x" marks a broken connection for that line and power lines that are overloaded are marked in bold.

Load	Sud-Ozone	SNEL-Sud	Nord-SNEL	RN1-Ozone	RN1-SNEL	RN1-Nord
Base, KAGU006	21%	17%	12%	30%	47%	49%
	x	38%	20%	12%	60%	58%
	37%	x	5%	48%	37%	42%
	23%	15%	x	32%	57%	37%
	13%	48%	24%	x	66%	62%
	32%	7%	47%	42%	x	86%
	30%	9%	37%	39%	89%	x
Base, KAGU006, MPAN032	22%	23%	17%	43%	60%	61%
	x	45%	26%	22%	74%	71%
	44%	x	8%	68%	47%	52%
	25%	20%	x	46%	74%	44%
	23%	68%	35%	x	88%	80%
	36%	9%	62%	58%	x	**108%**
	33%	12%	44%	55%	**112%**	x
Base, KAGU006, MPAN032, KABU16	24%	34%	27%	69%	86%	85%
	x	58%	37%	44%	**101%**	95%
	57%	x	13%	**106%**	65%	71%
	29%	29%	x	74%	**109%**	57%
	44%	**105%**	56%	x	**130%**	**115%**
	44%	14%	91%	91%	x	**153%**
	39%	19%	57%	85%	**159%**	x

Table 5.1.10: Case 1 and 3: Power lines only. "x" marks a broken connection.

	Sud-Ozone	SNEL-Sud	Nord-SNEL	RN1-Ozone	RN1-SNEL	RN1-Nord
Base, KAGU006	17%	21%	31%	27%	32%	16%
	x	38%	38%	12%	42%	22%
	37%	x	23%	49%	20%	9%
	23%	15%	x	32%	57%	21%
	13%	48%	32%	x	48%	27%
	25%	13%	55%	35%	x	39%
	20%	18%	19%	30%	44%	x
Base, KAGU, MPAN	18%	26%	36%	40%	45%	27%
	x	45%	44%	22%	56%	34%
	44%	x	25%	68%	29%	16%
	25%	20%	x	46%	74%	15%
	23%	68%	52%	x	70%	44%
	29%	15%	70%	51%	x	61%
	23%	22%	12%	45%	66%	x
Base, KAGU, MPAN, KABU	20%	37%	46%	65%	70%	49%
	x	58%	54%	44%	83%	58%
	57%	x	31%	**106%**	47%	34%
	29%	29%	x	74%	**108%**	9%
	44%	**104%**	74%	x	**111%**	78%
	37%	20%	99%	83%	x	**104%**
	29%	29%	3%	74%	**111%**	x

Table 5.1.11: Case 1: Power lines only. "x" marks a broken connection.

5.2 Cost estimations

Here data connected with the financial costs of equipment for the different cases is presented. For each scenario the losses in terms of GWh are presented and also the losses in momentary costs associated with the losses of energy. The costs are calculated in USD and a conversion factor to SEK of 6.75 is used. The losses in table (5.2.2) assume an electricity price of 0.2 USD/kWh and the costs in table (5.2.1) assume an electricity price of 0.17 USD/kWh. These prices are inline with a probable electricity price for the project, supplied by APW.

The total costs are calculated using Net Present Value with a discount rate of 15%, either with or without the addition of 7% inflation rate. The discount rate is based on economical return of the project and inflation is based on previous data for inflation [8]. For a detailed list of costs see appendix A.

Case 2a marked with bold text is the by REGIDESO suggested case.

	Equip. costs (MSEK)	Losses/year		Total costs	
		GWh	MSEK	Excl. inflation	Incl. inflation
Case 1a	20.05	2.59	3.5	42	86.88
Case 1b	24.29	0.81	0.93	31.18	45.3
Case 2a	**25.07**	**4.91**	**5.64**	**66.57**	**151.66**
Case 2b	52.32	0.16	0.19	53.7	56.52
Case 3a	12.12	1.39	1.6	23.89	48.02
Case 3b	9.92	1.04	1.19	18.69	36.66
Case 3c	13.50	1.16	1.33	23.33	43.48

Table 5.2.1: Costs associated with connection scenarios. The costs associated with losses are calculated using a price of 0.2 USD/kWh.

	Equip. costs (MSEK)	Losses/year		Total costs	
		GWh	MSEK	Excl. inflation	Incl. inflation
Case 1a	20.05	2.59	2.98	38.37	76.95
Case 1b	24.29	0.81	0.93	30.11	42.05
Case 2a	**25.07**	**4.91**	**5.64**	**60.37**	**132.76**
Case 2b	52.32	0.16	0.19	53.51	55.94
Case 3a	12.12	1.39	1.6	22.14	42.67
Case 3b	9.92	1.04	1.19	17.37	32.65
Case 3c	13.50	1.16	1.19	21.83	38.9

Table 5.2.2: Costs associated with connection scenarios. The costs associated with losses are calculated using a price of 0.17 USD/kWh.

6 Discussion and Analysis

The discussion and analysis is divided into two sections. The first section handles the energy system and consumption of electricity in Burundi, now and in the future. The second section analyze the results from the simulation of the grid connections together with losses and costs. The two sections are then merged together for a final recommendation in the Conclusion chapter.

6.1 Energy system and electricity consumption

From figure (2.1.3) it is possible to identify three stages of electricity consumption: base load, daily load and peak load. The base load is during the night (22-06), the daily load is from 06-18 and a peak during the evening (18-22). The figure shows that the base load is just above 20 MW, the daily load is around 30-35 MW and the peak load is around 40 MW.

It is possible to identify each of the three loads with real world applications. The base load can be associated with standard consumption such as lightning, air condition and various other applications running 24/7. The daily load from 06-18 is most likely connected with office hours when most factories are running and people are working. The peak load is probably associated with the usage of lightning in buildings (street lights are more or less non existent) since it coincides very well with the time the sun is setting. The shape in figure (2.1.3) is also important for how the overall energy system needs to be developed.

The deficit in the grid (20 MW) is according to official documents represented during all times of the day. The load disconnection that REGIDESO is using to control the deficit is larger during the night than day which is likely a result from the fact that the largest HPP, Rwegura, is a peak power plant and needs to refill its reservoir during the night to handle daily and peak loads. The scheduled running of the Rweguera HPP therefore likely have an effect on the distribution of the daily load as seen in figure (2.1.3). The operation of Rwegura will also affect the operation of KAGU006 since its outlet affects the Kaganuzi river. The hourly discharges from Rwegura was not available or measured in the latest feasibility study and the hourly impact is therefore not known. If Rwegura fills up its reservoirs during the night, the output of KAGU006 could be reduced as well. So the impact of the scheduled running of the Rwegura power plant would imply that KAGU006 could see a similar generation curve with higher peak during the day and a lower generation during the night. This could further increase the difference between base and peak load and continue to require a larger load disconnection during the night. The power output of KABU16 and MPAN032 is likely to be enough to compensate this behavior if needed. Their total output is over 30MW which is likely to be enough in a short term perspective. However no plans over their scheduled running were available nor if they can be affected by the running of Rwegura or other hydropower plants.

Since KAGU006 will sell all their generated power it is of great importance that there is an available load that they can supply to, both when it is taken online in 2014/2015 but also in the future.

According to the projections there will be a considerable increase in electricity demand until 2015 which is roughly when KAGU006, KABU16 and MPAN032 will be taken online. Together they will increase the available power with 39.1 MW. Considering the current 50 MW maximum capacity a sudden connection of almost 40 MW might create problems since there has to be a comparable increase in load. Making estimates for 2012 based on the generation from June it seems like the estimations of 395 GWh for 2015 are optimistic. However, it should be noted that June is in the beginning of the long dry season in Burundi and generation are likely to be less than the annual average. But there is a risk that there might be a period when not all power plants can supply at their full capacity. APW should take measures to make sure that during no circumstances will KAGU006 be disconnected or operated on a lower capacity because there is a lack of a load.

In the longer perspective the access to electricity needs to be expanded to a larger part of the population. Currently only a few percent have access to electricity, 98% of the households are outside the electrical system and base their energy consumption around wood and charcoal. Wood and charcoal are also most commonly used for cooking and other energy forms that are not easily replaceable by electricity. An expansion of the usage of electricity is therefore not only a question of access to the electrical grid or capacity but a question regarding a change in the energy system. A change that will require a noticeable investment for the poorest who lack the equipment to utilize electricity other than for simple utilities. In order to replace their use of charcoal and wood in this sector they would therefore need to invest in equipment that is based on electricity. Considering the economical status of the majority of the population, such an investment is not possible at the moment. Therefore an increase in the electricity consumption would also require economical development.

Because of the lack of consistent data, there are big uncertainties when the future energy system and electrical grid is analyzed. When even the current and historical data is uncertain, it is hard to make qualitative and quantitative projections on the transition in the energy system. Since it neither exist any detailed master plan for how the electrical grid in Burundi is to be developed in the long term together with power generation and estimated load, it is hard for new stakeholders to start projects. The plan for 2025 is a good start, but it needs to be expanded to take into account planned power plants and their impact on the grid. Since there are no connection between the change in the energy system with how the grid is to be expanded, the projections will be even more uncertain. This is especially vital since the electrification rate in Burundi is so low and therefore the potential impact on the grid is very large. It it also important to note that it's not only which governmental body or organization that makes the master plan that is important, but that they are responsible for the implementation and preferably have responsibilities to the users. The chain of responsibility between planners and the users needs to be clearly defined and set up. The problem with the chain of responsibility is especially visible with the use of aid. Since the aid is acquired externally and not from the tax payers, the population have no direct interest in that the money are being spent optimally. However, when the money originates from the tax payers, they have a larger self interest that there money are spent in the best possible way and they would therefore demand responsibility from the government or organization that are in charge of the expenditures.

6.2 Grid connection and losses

From the cost assumptions that are found in Chapter 5 it is seen that there are considerable differences in costs for the different cases, both in terms of equipment costs and losses. Case 3, using a T-off connection on the passing 110 kV power line, shows the lowest costs both in terms of equipment and total costs (incl. and excl. inflation) while case 2b shows the by far lowest losses. The proposed connection scenario from REGIDESO (case 2a) have equipment costs inline with previous assumptions made by APW but it also shows the highest losses of all cases. The difference in losses between case 2a and 3a, 3b and 3c is 3.5-3.9 GWh, this should be seen as a reference to the annual production of 49.83 GWh. Case 1a don't show any benefits from case 2 or 3, but case 1b shows very low losses. Because of the low losses in case 1b the total costs are low. but not as low as in case 3. Case 1 could be interesting if there are problems not discussed here (such as juridical) associated with the T-off connection of the passing 110 kV line.

As seen in table (5.1.10) and (5.1.11), case 2 shows load advantages in Bujumbura's transmission grid. The advantage is especially visible during failure on one component and primarily occurs with the connection of KABU16 and MPAN032. Case 2 shows less overload than case 1 and case 3, but power lines are still being overloaded. It is interesting to see that the power lines in Bujumbura that are being overloaded are the same for all cases and scenarios. It is only the amount of overload that differs. Therefore all cases would require the upgrade of the following power lines: SNEL-Sud, RN1-Ozone, RN1-SNEL and RN1-Nord if a n-1 criteria is to be obtained. Normal operation don't show any overload in Bujumbura for any case or scenario.

The results for the power line connecting Bubanza and RN1 in Bujumbura is slightly different. The power line is loaded with 101% during the peak load from the simulations for case 1 and 3 and together with the connection of KABU16 and MPAN032 in Bubanza. This is compared to case 2 when the maximum load of the power line is 86%. The extra load between case 2 and case 1 and case 3 also affects the 30/110 kV transformers in RN1. There are currently 2x20 MVA transformers installed to handle the power. In case 1 and 3 these are loaded at 141% with the connection of KABU16 and MPAN032. But since they are also over loaded in case 1 in the same scenario (123%) the transformers need to be upgraded (or another connection between Bubanza and Bujumbura will be needed) regardless of KAGU006.

The other solution to installing a new transformer in RN1 would be the construction of a new power line between Bubazna and Bujumbura. REGIDESO have plans on a 110 kV line between Bubazna and Poste Nord, however no details about this power line is known or when it might be operational. And even if it will be constructed there are still redundancy benefits with installing one more transformer in RN1 considering the capacity of the power line from Bubanza to RN1 is rated for roughly 60 MVA and the transformers can currently handle 40 MVA. A new 25 MVA transformer costs roughly 4 MSEK and considering that the cost difference between case 2a and case 3 is around 15 MSEK. One option for APW would be to partly finance a new transformer in RN1 using a fraction of the money that is saved on equipment costs. This would both improve overall capacity at RN1 but also redundancy in case of a transformer failure. Another fraction could also be used to help REGIDESO improve capacity on the overhead transmission lines in Bujumbura. The upgrade would mean that Bujumburas transmission grid would reach a n-1 contingency criteria. However, no economical estimations of such costs have been done.

According to REGIDESO the owner and maintainer of the power line can be decided in the contract signed between APW and MWEM. Because of Burundi's situation it can be hard to find qualified personnel that can maintain the line during 20 years and subletting the maintenance to REGIDESO seems like a viable option.

The environmental benefits for case 1,2 and 3 are very different. Since case 3 uses the already existing lines (except the short 1 km line from the power house to the connection point) the environmental impact will be at a minimum. Since both case 1 and 2 will require new power lines to be built (either 15 km or 40 km) the impact will obviously be larger. Because of the high level of deforestation and the climate in Burundi no or very little clearing of trees needs to be done. This means that the new power lines will have considerable visual impact from a larger distance then it the land would had a larger forest cover. Since the Burundian government have adopted measurements to preserve forests there might be issues constructing a new power line if it would cross sensitive or important areas for reforestation.

7 Conclusion

From a technical and economical point of view there are clear benefits with a T-off connection. By using already existing power lines the environmental impact is minimized as well as the financial investments associated with constructing a new power line. Therefore the total costs are held at a minimum. In order to compensate for the increased load on some components, part of the gain in costs compared to the other cases could be used to support the upgrade of transmission lines in Bujumbura and the transformer in RN1. In order to achieve a balanced total output on the grid during all hours of the day and compensate when possible for the scheduled running of the Rwegura HPP, a run-of-the-river peak power plant would be preferable. The lack data and access to it is a large problem when analysis is done but also for possible new investors in the power production market in Burundi. The current plan for the electrical grid for 2025 is vague and Burundi would benefit if there was a detailed plan of the transition of the energy system and expansion/upgrade of the electrical grid.

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A Detailed cost estimations for connection cases

Case 1 (Site - Bubanza-Bujumbura, 15km)

a) **30kV Line**

	Amount	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses (15+27km)		0,4527	2,5928783					3500385,67	
Equipment									
Transformers	1			10	6,6-30		2638000		55
	1			10	30-110		3519000		23
Transformer compartments	1				6,6-30		457000		53
	1				30-110		1956000		13
Lines	1			10	30	15	7590000		15
Housing	0								
Clearing	0								
Backup power	0								
Line bay	1				110		2154000		11
	2				30		750000		52
	3				6,6		981000		

b) **110kV Line**

	Amount	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses		0,1418	0,812172					1096432	
Equipment									
Transformers	1			10	6,6-110		3519000		23
Transformer compartments	1				6,6-110		1956000		13
Lines	1			10	110	15	13530000		1
Housing	0								
Clearing	0								
Backup power	0								
Line bay	2				110		4308000		11
	3				6,6		981000		67

Figure A.0.1: *Costs and losses associated with case 1.*

Case 2 (Site - Bujumbura, 40km)

a) **30kv Line**

	Amount	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses		0,8578	4,9131					6632717	
Equipment									
Transformers	1			10	6,6-30		2638000		55
Transformer compartments	1			10	6,6-30		457000		53
Lines	1			10	30	40	20240000		15
Housing	0								
Clearing	0								
Backup power	0								
Line bay	2			10	30		750000		52
	3			10	6,6		981000		67

b) **110kV Line**

	Amount	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses		0,0288	0,165					222689	
Equipment									
Transformers	1			10	6,6-110		3519000		23
	1			10	110-30		3519000		23
Transformer compartments	1				6,6-110		1956000		13
	1				110-30		1956000		13
Lines	1			10	110	40	36080000		1
Housing	0								
Clearing	0								
Backup power	0								
Line bay	2				110		4308000		11
	3				6,6		981000		67

Figure A.0.2: *Costs and losses associated with case 2.*

Case 3 (Site - 110kV Cibitoke-Bubanza line, 1km)

a) **6,6kV Line**

	Amounts	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses (1+15+27km)		0,2428	1,39066					1877388	
Equipment									
Transformers	1			10	6,6-110		3519000		23
Transformer compartments	1				6,6-110		1762000		12
Lines	1			10	6,6	1	3100000		14
Housing	1						461000		72
Clearing	0								
Backup power	1						145000		81
Line bay	1				110		2154000		11
	3				6,6		981000		67

b) **110kV Line**

	Amounts	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses (1+15+27km)		0,1815	1,03956					1403402	
Equipment									
Transformers	1			10	6,6-110		3519000		23
Transformer compartments	1				6,6-110		1762000		12
Lines	1			10	110	1	902000		14
Housing	1						461000		72
Clearing	0								
Backup power	1						145000		81
Line bay	1			10	110		2154000		11
	3			10	6,6		981000		67

c) **30kV Line**

	Amounts	MW	GWh	MVA	kV-kV/kV	Km	SEK	SEK/year	Löpnr
Losses (1+15+27km)		0,2029	1,16213					1568872	
Equipment									
Transformers	1			10	6,6-30		2638000		55
	1			10	30-110		3519000		23
Transformer compartments	1				6,6-30		391000		68
	1				30-110		1956000		13
Lines	1			10	30	1	506000		14
Housing	1						461000		72
Clearing	0								
Backup power	1						145000		81
Line bay	1			10	110		2154000		11
	2				30		750000		52
	3			10	6,6		981000		67

Figure A.0.3: *Costs and losses associated with case 3.*

B Parameters for bare overhead power lines calculations

Parameter	Value
Windspeed	0.61 m/s
Emissivity	0.5
Solar absorptivity	0.5
Ambient air temperature	40 °C
Maximum allowable conductor temperature	75 °C
Atmospheric conditions	1040 W/m^2
Azimuth	90°
Latitude	3.5°
Viscosity of air	0.0000188 Pa·s
Thermal conductivity of air	0.0269 $W/(m \cdot^{\circ} C)$

Table B.0.1: Parameters for calculations of capacity for bare overhead power lines.