POLICIES FOR INVESTING IN NIGERIA'S POWER DELIVERY CAPABILITIES

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Abstract

This thesis recommends a set of policies for investing in the Nigerian Electricity Supply Industry (NESI). First, it examines the electricity generation profile of the country for the year 2013, and then it identifies the bottlenecks in the electricity supply value chain. It goes on to show that it is inefficient to invest in increasing the country's available generating capacity before successful elimination of these bottlenecks and therefore, the primary goal of the NESI should be to increase the energy delivered to the customer. Finally, this thesis suggests three investment strategies, which are subsequently applied to different sample realizations of the country's electricity generation profile. Using the results of this analysis, this thesis ultimately recommends a robust investment policy to the key decision makers of the NESI.

Acknowledgements

I would like to thank my thesis advisor, Professor Powell, who never got tired of reminding me of the goal of my thesis and assuring me that I did have enough 'math' in it. I would also like to thank Mr. Niyi Olubiyi, who spent many hours helping me and giving me insight into the financial viability of generation plants in Nigeria. I would especially like to thank Seun Amoda and Muhammad Wakil of the Nigerian Electricity Regulation Commission (NERC), who provided me with my core data and information and were always available to answer my questions and prompt with their responses.

I am not sure that my journey at Princeton would have been possible without all of the prayers, love, encouragement and support from my parents. I cannot thank you enough for providing me with all I that I have needed and wanted without neglecting to teach me how to value things. I cannot imagine having a better set of parents, even if I tried. *Mo dupe lowo yin pupo. Olorun a d'emi yin si. Amin*

I also really appreciate all my friends that have lent a listening ear to my ever-talking mouth and brought laughter and good times to my Princeton experience. Thank you to my extra-amazing friends that helped me proofread this thesis. Many would have doubted my English-speaking abilities without you.

Thank you God for getting me through Princeton in one *peace*.

It has been real.

For Adun, because she opened Heaven's Gates for us ...

Glossary of Abbreviations

BPE	Bureau of Public Enterprises
CPCS	CPCS Transcom International Limited
DISCO	Distribution Company
EPSR ACT	Electric Power Sector Reform Act
GACN	Gas Aggregation Company of Nigeria
GAS	Gas Sales Agreement
GENCO	Generation Company
IPP	Independent Power Producer
MYTO	Multi Year Tariff Order
NBET	Nigeria Bulk Electricity Trading Plc
NEPA	National Electric Power Authority
NERC	Nigerian Electricity Regulatory Commission
NESI	Nigerian Electricity Supply Industry
NGC	Nigerian Gas Company
NIPP	National Integrated Power Project
NNPC	Nigerian National Petroleum Corporation
OCGT	Open Cycle Gas Turbine
OPEC	Organization of Petroleum Exporting Countries
PHCN	Power Holding Company of Nigeria
PPA	Power Purchase Agreement
SC	Successor Company
SO	System Operator
TCN	Transmission Company of Nigeria

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1 Chapter 1: Introduction

I recall the first day back at home in Nigeria on holiday from school in South Africa. Around 3 pm, I finally noticed that my phone battery had only about 5% battery life left. However, as I went to retrieve my charger, I realized why the windows in the house were open and why I had not been watching television: there was no ‘light’ (electricity) to power the air conditioner or the television. Suddenly, I realized that I was stuck in the sweltering heat, with a dying phone, no television and nothing else to do. I spent the rest of the afternoon frustrated until the generator was turned on at 7 pm. Despite my annoyance, all I could do was scream for joy at 7pm “there’s light!” because even I knew the generator was a luxury that many other Nigerians could not afford. They would come to meet their dark homes and worry about how they would go about ironing their clothes for work the next day, or thinking about how to handle all the food that would be going bad in their freezers. The power situation was terrible when I was younger and it is still bad now. It seeps into every crevice of our daily lives and is more of an issue to some than others, but an issue for all nonetheless. To the average Nigerian, three days without electricity is not out of the ordinary.

The Nigerian Government is fully abreast of the demand-supply gap in the Power sector and consequently, has made the development of power supply a key deliverable in its agenda. However, in the past 4-5 years, the Presidential Task Force on Power (PTFP) has repeatedly failed to meet its power generation capacity targets and this failure has been attributed to a number of setbacks. Nonetheless, there appears to be a trend in the plans for generating capacity ramp ups, which I believe is part of the underlying reasons for the halting progress in increasing Nigeria’s electricity supply. In planning for generation upgrades, it appears as though the bodies responsible for this task examine each aspect of the electricity value chain and treat each one as a separate entity. To be clear, there is an acknowledgement of the dependency of one part of the value chain on another: actual generation depends on gas availability, but also depends on the evacuation infrastructure and the ability of the transmission network to transmit all the electricity that is generated. However, this knowledge is not the driving force of the power sector reform plans, as it should be. For instance the revision of the Power Reform Roadmap written by the PTFP, indicates that there are ongoing plans to install new power plants and rehabilitate the old ones, thereby increasing the available generation capacity to about 9000MW in 2013. However, in the roadmap's projection for the same year, the transmission wheeling capacity stands at 5000 MW. Assuming the gas supply was able to meet the demands of the Installed Capacity, when the 9000MW of energy is being generated, what happens to the 4000MW that is not transportable? It translates to 4000MW worth of generation capacity investment lost and millions of Nigerians that will remain dissatisfied[1]. This is not to say that there are no plans to increase the transmission wheeling capacity, because those plans do exist and are being implemented. The point being made here is that in planning capacity expansions, the transmission capacity is mostly lagging behind the generation capacity and this will inevitably result in Available Capacity that remains stranded. The figure below shows the PTFP projections for these expansions.

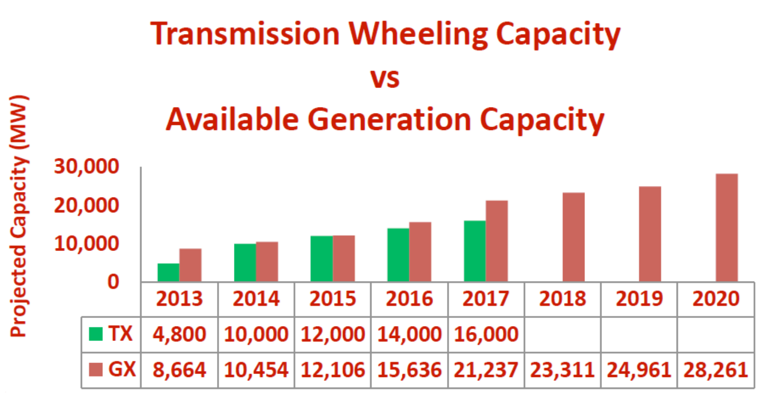

Figure 1: PTFP Projections for Transmission and Generation Capacity

[1] The Presidential Task Force on Power. (n.d.). Roadmap for Power Sector Reform- Revision 1, 33. Retrieved from http://www.nigeriapowerreform.org/content/Roadmap for Power Sector Reform - Revision 1.pdf

Furthermore, the 2013 revision of the Roadmap for Power Sector Reform claims that "there is no firm projection of the level of future investment required in transmission", indicating that the problems with the transmission network have not yet been fully identified and attended to. Perhaps it would be wiser to reduce the amount of money spent on increasing the generation capacity of the country and instead invest in ensuring that the gas supply can meet the available generating capacity and that all the generated energy can be transmitted to the end users. The problems of the Nigerian Power Sector cannot be solved by 'fixing' one part of the system or by making isolated investments in selective parts of the chain, without thinking about how the other parts will contribute to, or hinder the realization of, any potential value created by the investment. As such, by establishing this principle of interacting components, which shows that improving one component of the system cannot necessarily improve the entire system unless the other components can be improved, this thesis offers the PTFP, and other concerned parties, a different strategy for planning improvements in the power sector. This strategy is necessarily an integrated approach, where one does not think about investing in increasing the generation capacity without immediately thinking about increasing the availability of gas for these power plants as well as sufficient transmission wheeling capacity. These thoughts must translate into carefully planned actions. Otherwise, investors will continue to make large investments in capacity that cannot be fully utilized for years, essentially wasting the money that could have gone to increasing the amount of energy that is actually delivered to the electricity consumers. This thesis will provide examples of holistic investment policies for the power sector that are structured in such a way that all the parts of the system are considered, and thus greater value is created.

The following sections are structured as follows: The rest of this chapter gives a background of Nigeria and its Power Sector. Chapter 2 will introduce the data that has been used for this analysis and focus on setting up the context of energy flow through the system by identifying and quantitatively analyzing the bottlenecks and capacity constraints in the NESI. Chapter 3 will establish the background for the four investment policies that are to be suggested, introduce their goals and explain the investment policies that are to be evaluated as well as the four scenarios to which they are to be applied for comparison. It then ends with an explanation of the performance metrics with which the investment policies will be evaluated. Chapter 4 presents the results of applying each of the investment policies to each of the four scenarios and furthermore suggests that the best investment policy is one in which there is no introduction of new generating capacity to the system unless the gas supply and transmission network are able to accommodate the capacity increase. Chapter 5 presents the conclusion of this thesis, which will include final recommendations, limitations of the study and suggestions for further expansion of the analysis.

1.1 Background: Nigeria

With its population of 168 million people, Nigeria is Africa's most populous country and as at 2012, was the eighth largest member of the Organization of Petroleum Exporting Countries (OPEC)[2]. Despite its wealth in mineral resources and human capital, the majority of its population is below the poverty line. One of the major problems stagnating the growth and development in the country is the state of its Power Sector. Nigerians who are solely dependent on the national grid and cannot afford their own electricity generators mostly have to result to the hazardous use of firewood and kerosene as fuel for lighting and cooking. According to a recent study published in the Nigerian Journal of Technology, the minority that are able to afford to generate their own power do so at a cost four times larger than what they would have to pay if the connection to the national grid ensured a steady supply of electricity[3]. The lack of stable electricity supply consumes a major chunk of the nation's disposable income. The Nigerian government is aware of the country's electricity problems and so set about fixing it with the enactment of the Electricity Power Sector Reform Act (EPSRA) in 2005. The aim of this reform act is to engage the private sector in revamping the country's Power Sector. However, implementation of the EPSRA has been slow due to changes in governmental administrations. Nonetheless, the current administration under President Jonathan is focused on the expansion of the Power Sector and the implementation of the EPSRA. In the wake of ongoing Power Sector privatization there is a fair amount of optimism about the future state of electricity in Nigeria but there is a lot to be done to make this reform successful.

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[2] OPEC. (2012). OPEC: About Us. Retrieved from http://www.opec.org/opec_web/en/about_us/167.htm

[3] Ugwu, H. U., Nwankwojike, B. N., Ogbonnaya, E. A., & Ekoi, E. J. (2012). ENERGY AND ECONOMIC LOSSES DUE TO CONSTANT, *31*(2), 181.

1.1.1 Geography and Demography

Nigeria is located in West Africa and lies right above the equator. To the South it is bordered by the Gulf of Guinea and the Atlantic Ocean, with the Republic of Benin to the West, Cameroon to the East and Niger and Chad to the North.

Figure 2a: Map of Africa

Figure 3b: Map of Nigeria

Nigeria is a federal republic comprising of thirty-six states, and a Federal Capital Territory (FCT). The former state capital, Lagos, has a population of over 20 million people and is regarded as the country's commercial capital.

1.1.2 The Nigerian Economy

Nigeria has a fast-growing economy, with GDP growth between 6-8% percent in the past 5 years. The economy was recently rebased and Nigeria now has the largest GDP in sub-Saharan Africa. Nigeria receives most of its wealth from the sale of its crude oil and earned $95 billion in crude oil exports in 2013[4]. Although Nigeria is an oil-rich country which earns the majority of its government budget from the sale of Petroleum, Agriculture remains the primary contributor to the

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[4] Abdul-hamid, O. (n.d.). OPEC: Annual Statistical Bulletin,12.

country's GDP at thirty nine percent[5]; Crude Petroleum and Natural Gas related activities is the third largest contributor and supplies fourteen percent of the country's GDP[6].

1.2 Power in Nigeria

The Power Sector accounts for two percent of Nigeria's GDP and though its population size is similar to Brazil's, Nigeria only produces about 4% of the electricity Brazil produces. The figure below shows how far behind Nigeria is in terms of its ability to generate electricity relative to the size of its population. The line is based on an estimate that recommends 1Gigawatt of electricity per million people in the population. Nigeria is the furthest from this line, generating only two percent of what it should be generating for a country with a population of its size.

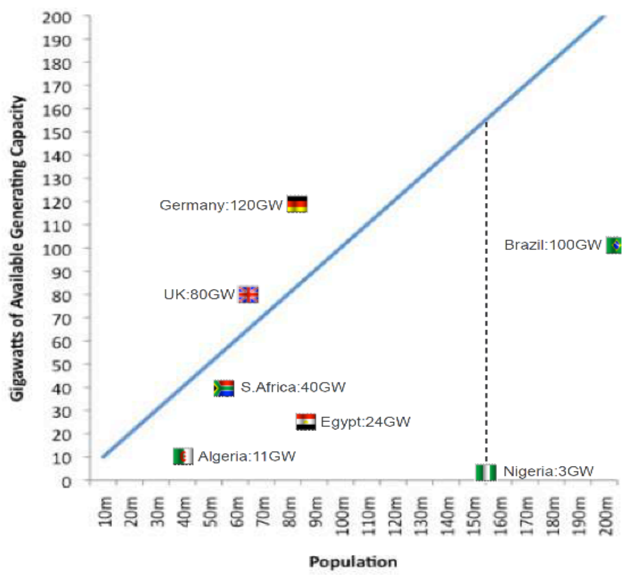

Figure 4: Population vs Generating Capacity of Select Countries.
Source: Roadmap for Power Sector Reform

The failure to generate sufficient amounts of electricity is not for want of the natural resources needed to generate the electricity. Estimated at 180 trillion cubic feet, Nigeria has the largest proven natural gas reserves in Africa

[5] Nigerian National Bureau of Statistics.
[6] Nigerian National Bureau of Statistics.

and the ninth largest in the World[7]. In addition to the use of natural gas as an electricity generation fuel source, Nigeria also has the potential to expand its hydro power generation. Hence, in Nigeria there is little risk of running out of power generation feedstock. The figure below illustrates the two major sources of the country's generation 'fuel'[8].

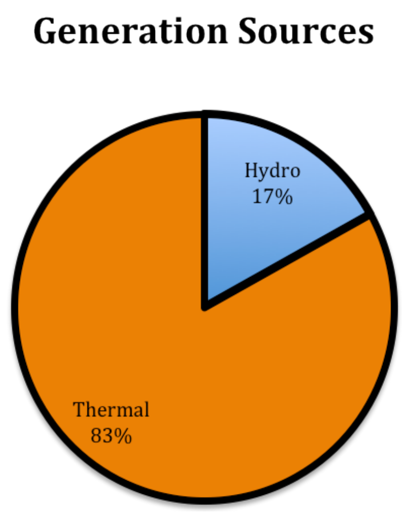

Figure 5: Types of Power Plants in operation in Nigeria

Furthermore, there is no lag in the demand for power; the opposite is the case. The Transmission Company of Nigeria (TCN) estimated a peak demand load of about 13,000MW in 2013, representing a 7000MW deficit. This is most likely a conservative estimate, but it shows a large supply gap nonetheless. The following figure illustrates the impact of the lack of electricity supply in the country. It shows the distribution of electricity as a source of lighting per state. Only seven out of the thirty-six states in the country have more than sixty percent use of the grid as a source of lighting.

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[7] US Energy Information Administration. (2013). Nigeria. Retrieved from http://www.eia.gov/countries/analysisbriefs/Nigeria/nigeria.pdf

[8] The 'Thermal' source is essentially made up of natural gas.

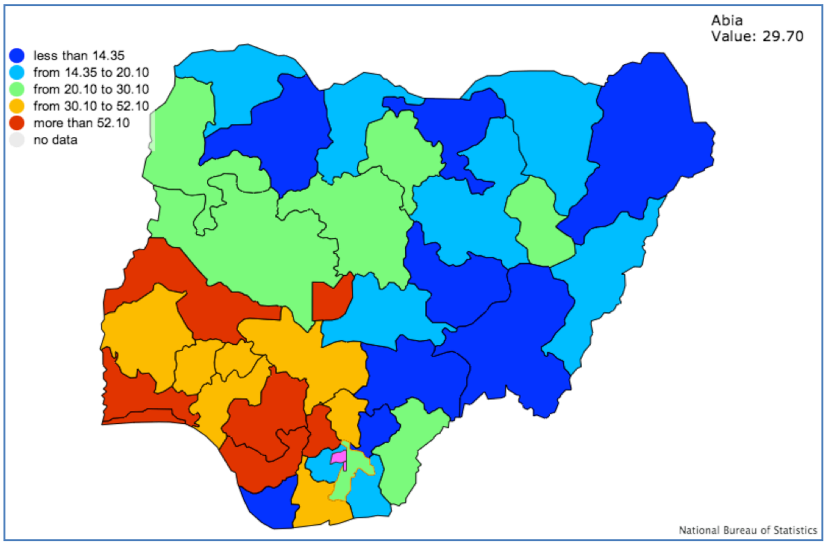


Figure 6: Percentage of Nigeria households that use electricity from the national grid for lighting. Source: National Bureau of Statistics

The state of the Nigerian Electricity Supply Industry is not a result of the lack of resources or demand but a clear absence of sufficient investment and proper planning for growth in the sector. This need engendered the Electricity Power Sector Reform Act (EPSRA), which aims to transform the industry by involving the private sector investment in it.

1.2.1 The Electricity Power Sector Reform Act (EPSRA)

Prior to the enactment of the EPSRA, the National Electric Power Authority (NEPA) was responsible for the generation, transmission and distribution of electricity to the Nigerian population. The reform act sought to change this, with a mandate that came in four parts:

1. Creation of the Power Holding Company of Nigeria (PHCN)
2. Creation of the 18 successor companies held by the PHCN, including:
    a. The Transmission Company of Nigeria (TCN)
    b. Six Generation Companies (GENCOs)
    c. Eleven Distribution Companies (DISCOs)
3. Development of a competitive electricity market by the creation of a Bulk Trader- Nigerian Bulk Electricity Trader (NBET)

4. Creation of the Nigerian Electricity Regulatory Commission (NERC)

The current administration's prioritization of the Power Sector has led to significant progress with the ESPR in the past two years:

- The Eleven DISCOs have been privatized
- The TCN is to be managed by the Canadian firm, Manitoba Hydro International
- The NBET has been incorporated
- The NERC has released the cost-reflective second Multi-Year Tariff Order (MYTO II)

The sector is now between what it calls its pre-transition and transition stages. In its transition stage, it will have the following structure[9]:

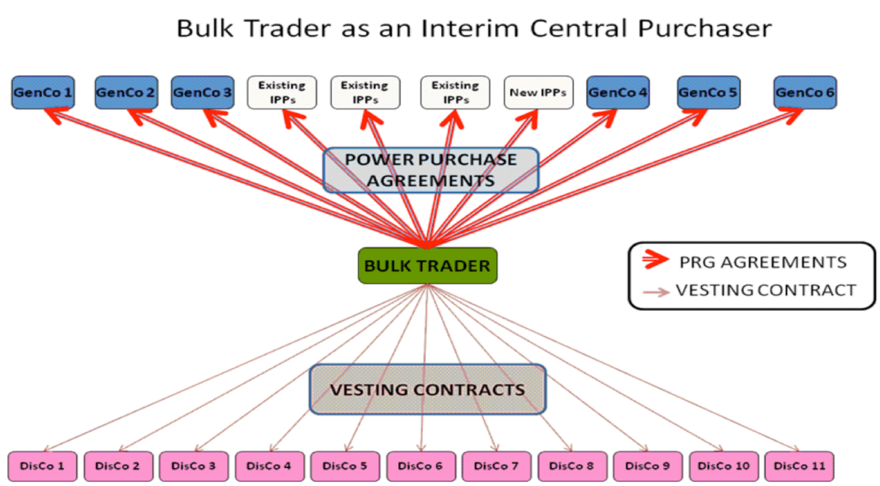
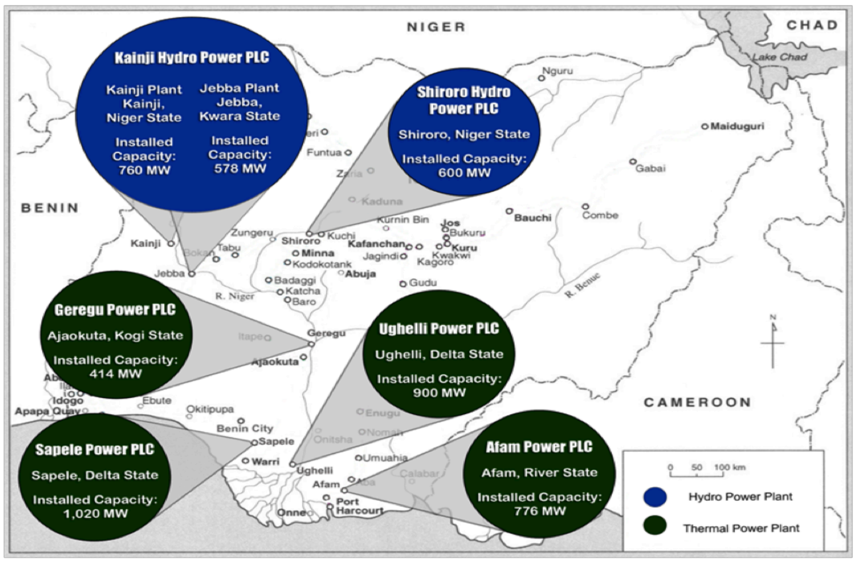


Figure 7: Nigerian Electricity Market in its Transition Stage

[9] This figure illustrates the contractual relationships in the market. The NBET purchases electricity from the power plants: GENCOs, Independent Power Projects (IPPs) and National Integrated Power Projects (NIPPs) under Power Purchase Agreements (PPAs). The NBET then sells this electricity to the DISCOS under vesting contracts. The electricity is then delivered from the GENCOs to the DISCOs by the TCN. It is expected that as the market grows and its participants become financially viable and independent. The GENCOS and DISCOS would enter PPAs without the need of he bulk trader.

1.2.2 Generation

The six successor GENCOs have a combined Installed Capacity of about 5,000MW but only operate at less than half of this capacity. Four of the GENCOs are located in the Southern part of the country and are thermal power plants, while the remaining two: Kainji and Shiroro are hydro power plants in the North of the country.



	Genco	Type	Installed Capacity	Available Capacity
1	Afam Power Plc	Gas-fired	776	90
2	Geregu Power Plc	Gas-fired	414	276
3	Sapele Power Plc	Gas-fired	1,020	100
4	Ughelli Power Plc	Gas-fired	972	300
5	Kainji Hydroelectric Plc	Hydro	760	480
	Jebba Hydroelectric Plc	Hydro	540	450
6	Shiroro Hydroelectric Plc	Hydro	600	450
	Totals	-	5,082	2,146

Figure 8: The Successor GENCOs. Source: CPCS Transcom

The GENCOs are not the only source of electricity generation in the country. There are also Independent Power Producers (IPPs) and National Integrated Power Projects (NIPPs). Three IPPs are owned by International oil companies -Agip and Shell, one owned by the Lagos State government, and three owned by the Akwa Ibom and Rivers State governments.

The six IPPs have a combined capacity of 1,695MW. The actual power generated from these IPPs stands at about 1484MW indicating a higher efficiency than the GENCOs.

Name of Power Plant	Year Built	Location	Installed Capacity (MW)	Available Capacity (MW)
AES Power Station	2000	Egbin, Lagos State	224	224
Shell- Afam Vi Power Station	2008	Afam, Rivers State	650	650
Agip – Okpai Power Station	2005	Okpai, Delta State	480	480
ASG- Ibom Power Station	2007	Akwa Ibom State	155	76
RSG- Trans Amadi Power Station	2009	Port Harcourt, Rivers State	36	24
RSG- Omoku Power Station	2005	Omoku, Rivers State	150	30
Totals			**1,695**	**1,484**

Figure 9: Operating information for IPPs. Source: CPCS

Furthermore, there are ten NIPPs being constructed by the Federal Government and they are expected to have a combined capacity of 4,775MW. In the time after the figure below was created, five of the NIPPs below have become operational, although they are operating much below full capacity.

Name of Power Plant	Year Built	Location	Installed Capacity (MW)	Available Capacity @ Feb. 2011(MW)
Calabar Power Project	Under Construction	Calabar, Cross River State	563	Nil
Egbema Power Project	Under Construction	Egbema, Imo State	338	Nil
Ihovbor Power Project	Under Construction	Ihovbor, Edo State	451	Nil
Gbaran Power Project	Under Construction	Gbaran, Bayelsa State	225	Nil
Sapele Power Project	Under Construction	Sapele, Delta State	451	Nil
Omoku Power Project	Under Construction	Omoku, Rivers State	225	Nil
Alaoji Power Project	Under Construction	Alaoji, Abia State	961	Nil
Olorunsogo –Phase-2 Project	Combined Cycle under construction	Olorunsogo, Ogun State	676	224
Omotosho-Phase-2 Project	Under Construction	Omotosho, Ondo State	451	Nil
Geregu-Phase-2 Project	Under Construction	Geregu, Kogi State	434	Nil
Totals			**4,775**	**224**

Figure 10: Operating Information of NIPPs. Source: CPCS

The five NIPPs in operation are:

1. Ihovbor Power Project
2. Sapele Power Project
3. Olorunsogo- Phase 2 Project
4. Omotosho- Phase 2 Project
5. Geregu- Phases 2 Project

The Roadmap for Power Sector Reform indicates that it expected the country's generation capacity to increase to 14,000MW by the end of the 2013, but as at the 31st of December 2013 the country's actual generation capability stood at 4372 MW. Apart from the gap between the Installed Capacity of the power plants and their available capacities, there is also the issue of restricted gas supply to these power plants, which further reduces the generation of electricity. Thus the problem with electricity generation in Nigeria is both the lack of generation capacity and the deficiency in the gas supply for the capacity that is available.

1.2.3 Transmission

The Transmission Company of Nigeria (TCN) will remain a Federal Government owned entity. However, it will be managed by the Canadian enterprise, Manitoba Hydro International. The TCN is split into three operational functions:

1. Transmission Service Provider (TSP)
2. System Operator (SO)
3. Market Operator (MO)

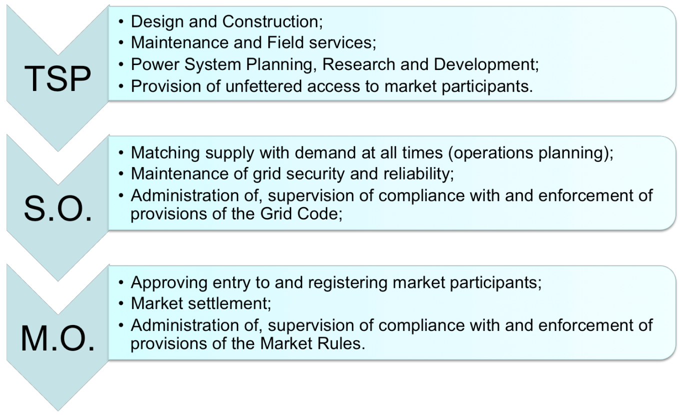


Figure 11: Structure of the TCN. Source: Presentation on "The Future of the TCN"

The current transmission network in the country is radial, meaning that the power is delivered from the main branch to sub-branches and then is split from the sub-branches again. It is the cheapest system but also the most unreliable and is often avoided for networks in densely populated areas due to the lack of alternate routes should a part of the system become faulty. The unreliable structure of the system is one of the issues that the TCN is currently dealing with. The figures below show the current transmission network and the plans to build a 'super-grid'. The main barrier to achieving this goal has been access to funding.

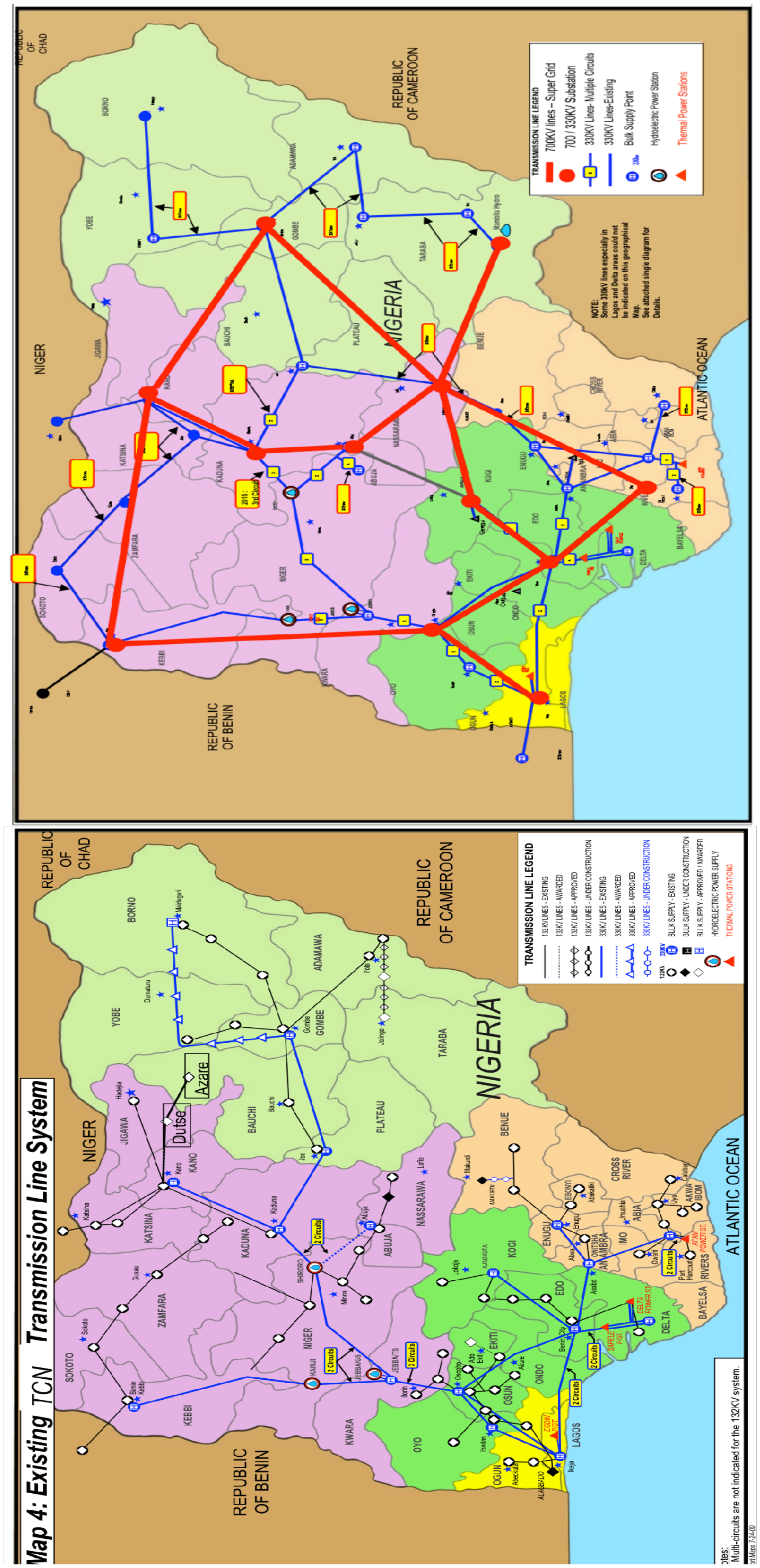


Figure 11: Transmission Network with Planned Expansions

1.2.4 Distribution

The DISCOS were created on a regional basis. The following map shows which states each DISCO is responsible for servicing. Due to its high levels of commercial activity, two separate DISCOS operate in Lagos State and the remaining nine DISCOS each supply multiple states simultaneous.

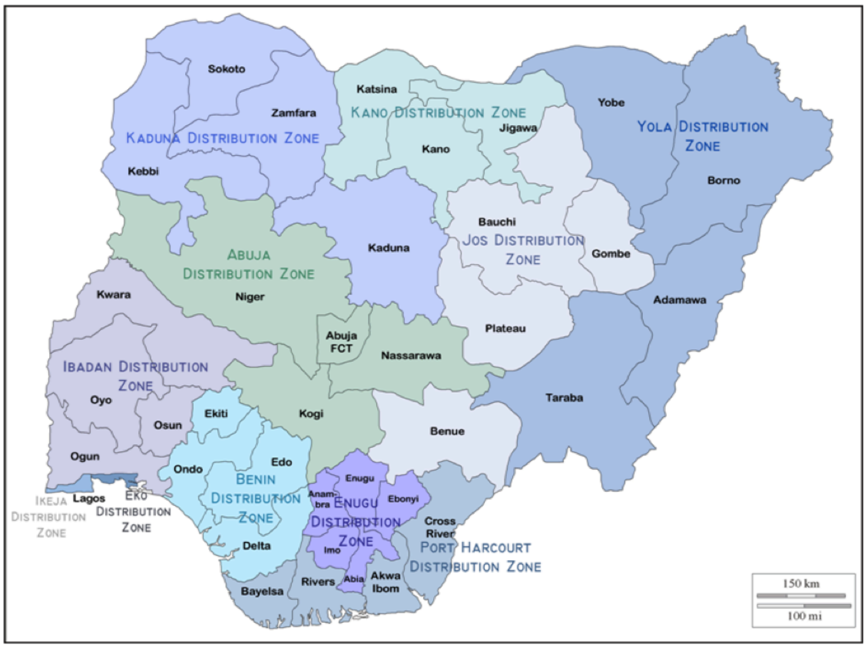


Figure 12: Geographical Boundaries of the DISCOs

Each of the DISCOS face similar problems with dilapidated distribution infrastructure and insufficient metering of customers for billing purposes. However, this thesis does not extend its analysis to the distribution system.

1.2.5 Nigerian Bulk Electricity Trader (NBET)

The transition stage of the power reform, as shown in figure 7 highlights the role of the NBET as the middleman. Its role is to enter into, or continue existing PPAs with the GENCOS and IPPs in order to buy electricity. The NBET will also enter into vesting contracts with the DISCOS to whom they would sell the electricity. These contracts are long-term contracts with approximately twenty-year life spans. However, in the long run, it is expected that the NBET will be phased out, as the market becomes fully competitive since the sector is not yet mature enough to handle.

1.2.6 Nigerian Electricity Regulation Commission (NERC) & The Multi- Year Tariff Order 2 (MYTO2)

The NERC is the industry regulator and is responsible for creating an efficient structure for the market. As the regulator it also manages the relationship between the different parties in the sector. For example, it decides the price, which the GENCOS and DISCOS pay the TCN for their use of its transmission network. It also sets the penalty paid to the DISCOS by the TCN for exceeding a pre-specified efficiency loss. Also included in its duties is the enactment of the Multi-Year Tariff Order (MYTO). This is a cost reflective tariff set with the aim of allowing all interested parties to recover their costs while being fair to the consumer. The MYTO is a fifteen-year program that is reviewed every five years. The second tariff order, MYTO2 began in 2012 and is to last till 2017. The need for the MYTO was highlighted by the fact that the electricity tariffs were far below production costs and they have stayed stagnant over time. The adaptation of the MYTO has also had the effect of making the sector more attractive to private investors who can then be more confident about the chances of recovering their electricity supply costs.

This chapter has introduced Nigeria and its electricity supply industry. The industry is in its growing phase, with increased needs for proper investment and planning. This thesis aims to make a contribution by suggesting the policies to be used when making investments in the sector to create the most value with a focus on the generation and transmission aspects of the electricity supply value chain.

2 Chapter 2: Data and Energy Flow Analysis

In order to be well informed before evaluating different investment decisions for Nigeria's power sector it is necessary to understand the details of the current generation profile of the country. We examine the sector during the whole of 2013, using the daily reports compiled by the Transmission Company of Nigeria. These reports include pertinent information such as the generation capacity of each power plant, the faults with their turbines, the gas constraints and the quantity of energy sent out of each power plant. We compile the data from the first day of each of the 52 weeks in the year, only including the power plants that were in operation, of which there were seventeen. There are more power plants in operation now than there were as at December 2013, but this thesis restricts its definition of 'current generation profile' to mean the generation profiles of the power plants that were operating at one point or the other in 2013. The following points explain the exceptions I have made from my data selection:

- We only consider the gas fired power plants and not the hydro plants. This is because roughly 80% of all the power generated is through gas-fired power plants.
- We do not include all the gas power plants reported. Some power plants were listed, however they were still undergoing commissioning tests, or not operating at all. Of these, three power plants were excluded:
    - Trans Amadi: It was out of service for over ninety-five percent of the year.
    - Omoku Gas: It was not generating due to collapsed towers on a mains 132kV line
    - Alaoji NIPP: A new power plant that had not been commissioned.

The seventeen power plants that are included in the analysis are:

1. Sapele Power Plant
2. Sapele NIPP

3. Delta/Ughelli Power Plant
4. Afam IV-V Power Plant
5. Geregu Gas Power Plant
6. Geregu NIPP
7. Omotosho Gas Power Plant
8. Omotosho NIPP
9. Ihovbor NIPP
10. Okpai Gas
11. AfamVI Power Plant
12. Ibom Power Plant
13. Rivers IPP
14. Olorunsogo Gas Power Plant
15. Olorunsogo NIPP
16. A.E.S Power Plant
17. Egbin Power Plant

The pieces of information I have used in performing the analysis in this thesis include:

- ***Installed Capacity (MW):*** This is the original capacity of all the gas turbines in the power plant
- ***Available Capacity (MW):*** This is the portion of the power plant's Installed Capacity that is available for power generating operations
    - The difference between the Installed Capacity and the Available Capacity is caused by the turbines that are not in operation due to long-term faults
- ***Actual Capacity (MW):*** This is the portion of the power plant's Available Capacity that can be used.
    - The difference between the Available Capacity and Actual Capacity is caused by deficiencies in the gas supply to that power plant.

- ***Energy Sent Out (MW):*** This is the total energy that has been sent out from the power plant in that day.
    - It is recorded in MWh, however we use its capacity (MW) value, in order to be able to compare it to the actual and available capacities.
    - The difference between the Actual Capacity and the Energy Sent Out is indicative of the efficiency of the power plant's turbines. A large difference would suggest that the turbines are not running efficiently and require upgrades or better maintenance practices.

The information above was reported for each of the seventeen power plants considered. A portion of a page of the Daily Reports from which this information was extracted is shown below. It lists the power plants, the turbines that are in operation, the different capacities mentioned above and brief explanations of the problems with the faulty turbines or capacity constraints due to gas supply.

A B C D E F G H I J K L M N O P Q R S T U V W X Y

POWER HOLDING COMPANY OF NIGERIA

1.5 NEW SCADA RTU STATUS :- 330kV :17 Out of 26 stations available.

1.8 GENERATION POSITION AT 0600HRS WEDNESDAY 23/10/2013

	STATIONS	AVAILABLE	INSTALLED AVAILABLE CAPACITY (MW)	ACTUAL GENERATION CAPABILITY (MW)	UNITS ON BAR	GENERATION AT 06:00HRS	REMARKS
PHCN	KAINJI HYDRO	1G6 1	120	110	1G6 1	105	1G5 – Rehabilitation on going . 1G7 – Out on stator winding E/F. 1G8 – Out on fault. 1G9 - Out due to upper guide bearing temperature problem. 1G10 - Out due to thrust bearing temperature but available for station service. 1G11 - Out on maintenance. G12 – Out on rehabilitation.
	JEBBA HYDRO	2G2 - 5 4	389	389	2G2 - 5 4	389	2G1 - Out on annual maintenance. 2G6 – Burnt generator winding and AVR.
	SHIRORO HYDRO	411G2 - 4 3	450	450	411G2 - 4 3	450	411G1 - Out due to stator winding insulation break down. Undergoing repair and overhaul (work commenced 12/8/13).
	EGBIN STEAM	ST1 - 5 5	1100	1100	ST1 - 5 5	523	ST1 - 5 - Generation reduced due to low gas pressure. ST6 - Out on high turbine rotor vibration Rehabilitation work in progress.
	SAPELE (STEAM)	ST2 1	90	75	ST2 1	73	ST1 - Tripped on lube oil pressure low and turbine trip. ST3 - Tripped on control oil failure. ST4 - Out on generator winding soldering failure. ST5 - Out on fault. ST6 – Out on high turbine rotor vibration.
	DELTA (GAS)	GT8, 12, 16 & 20 4	240	230	GT8, 12, 16 & 20 4	175	GT3 & 5 – Generator winding fault. GT4 - Out due to abnormal noise from the exhaust. GT6 – Out on generator differential. GT10 – Out due to high vibration. GT11 - Out due to unit transformer that is out on maintenance. GT13 – High vibration awaiting check and repair. GT14 – Out on maintenance. GT15 – Turbine blade failure. GT 17 - Tripped on high exhaust temp. spread. GT19 - Undergoing maintenance work.
	AFAM IV-V (GAS)	GT18 1	75	65	GT18 1	65	GT2 – Out on generator differential. GT4 –On fault. GT5 – Out due to burnt generator breaker. GT6 - Out on major inspections/Repairs in progress. GT17 - Out on fault.
	GEREGU GAS	GT13 1	138	138	GT13 1	110	GT11 & GT12 - Out for maintenance.
	OMOTOSHO GAS	GT1 & 7 2	84	76	GT1 & 7 2	51	GT2 - Out on generator differential. GT4-Out due to generator differential problem. GT 3 & 5 - Out due to excitation problem. GT6 - Out on vibration problem. GT8 - Out due to pieces of metal falling from the chimney.
	OLORUNSOGO GAS	GT1 & 2 2	84	76	GT1 & 2 2	40.4	GT3 - Shut down for mtce on the 105MVA 0.5/330kV main transformer 2. GT4 - Shut down due to wheel space separator differential high. GT5 -Shut down for mtce work by NGC on gas pipeline. GT6 – Out on blade failure problem. GT7 - Inspection on the generator hydro racheting pump & to carry out inspection on the generator. GT 8 - Out due to gas constraint.
NIPP	GEREGU NIPP	GT 23 1	152	152	GT 23 1	152	GT21 & 22 - Out on gas constraint..
	SAPELE NIPP	GT2 1	125	120	GT2 1	117.5	GT1 - Out due to gas constraint. GT3 - Out due to civil work on the basement.
	ALAOJI NIPP GAS	0 0	0	0	0 0	0	GT1 - Out due to gas constraint.
	OLORUNSOGO NIPP GAS	GT2 & ST1 2	250	240	GT2 & ST1 2	105.3	GT3 & 4 Out on maintenance. GT1 - Out due to as contraint.
	OMOTOSHO NIPP GAS	GT1 - 4 4	500	480	GT1 -4 4	431	All available units are on bar.
	IHOVBOR NIPP	0 0	0	0	0 0	0	GT1 & 2 - Out due to gas constraint.
	OKPAI GAS/STEAM	GT11, 12 & ST1 3	480	450	GT11, 12 & ST1 3	367	All abvailabe units are on bar.
	AFAM VI GAS/STEAM	GT11 & 13 2	303	303	GT11 & 13 2	303	GT12 - Out as C2 inspection. ST1 - Out due to tube leakage on the heat recovery steam generator.

Figure 13: Sample of Daily Report Prepared by the Transmission Company of Nigeria

The following sections use the information introduced above in order to analyze the flow of energy in the electricity supply value chain.

2.1 Examining the Flow of Electricity in Nigeria

The value-chain of the electricity supply industry in any country is complex because of the interdependency of all the different components therein. Nigeria is no exception. In order to develop a clearer picture of the value chain of Nigeria's power industry, we created a spreadsheet model that attempts to replicate the aggregate flow of energy in the country from the fuel source, to generation, through to the national grid (transmission) just before it gets distributed to the end user. The spreadsheet aims to quantitatively highlight the bottlenecks caused by each part of the value chain. Due to time limits, the complexity of the system and restricted access to data, it does not consider the flow of energy through the distribution system to the end user. Instead, the focus is on using the final amount of energy generated by the power plants and sent out to the national grid to show:

- The limitations in the fuel supply and fuel supply infrastructure to these power plants: "Gas Constraints"
- The gap between the Installed Capacity of the power plants in the country and the current generating capacity of the country: "Generation Gap"
- The limits of the energy that could be sent through the transmission system: "Transmission Constraints"

Thus, the three parts of the electricity system in consideration in this thesis are the gas supply, generation capacity and transmission capacity.

2.1.1 Energy Flow Data

The first part of the energy flow analysis is to record the capacity of the electricity generating system at each of the three parts mentioned above. These are the Installed Capacity, Available Capacity, actual generating capability, or Actual Capacity, and the equivalent capacity of the energy sent out of each power plant, which were introduced earlier in the chapter. The subsections that follow detail how these pieces of information have been used to illustrate the flow of energy from gas to electricity delivered to the distribution zones.

2.1.2 Gas Supply

The gas supply is the starting point of the energy flow, as it is the fuel with which the energy is generated. Although Nigeria has the largest natural gas reserves in Africa, it still has a problem with its gas production and supply infrastructure. It is not always possible to predict the amount of gas that will be supplied to the power plant because the gas supply does not have the support of a robust framework and the Nigerian Gas Company (NGC) operates on a best endeavor basis, where it supplies as much as it can[10]. The price of gas supplied to the generating companies is a disincentive to increasing gas production levels. The current market price of natural gas is roughly $4/MMBtu, but in Nigeria, it is about $2.40/MMbtu[11], which fails to reflect the true cost and as such is not sustainable for gas supply growth. Consequently, the potential for a viable natural gas market in Nigeria is not being realized. In Nigeria the government, through the NGC is the gas supplier to the power sector and is also responsible for the transportation of the gas. Under normal circumstances, a third party is responsible for the transportation of the gas. However, in order for this service to thrive there must be a gas plant in place that will provide the gas that is to be transported and an off-take, or power plant with Available Capacity that would

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[10] CPCS Transcom International Limited. (2011). Information Memoradum Volume 1,p 47.

[11] (NERC), N. E. R. C. (2012). MYTO Financial Model. Abuja.

receive the gas. Given that both those things are in uncertain supply, private pipeline providers are rare. As such, the gas supply network is not as expansive as one would expect for a country with such levels of natural gas resources. Nonetheless, this situation is changing with the increased level of activities in the Power Sector.

A simple way to visualize the network of gas pipelines that supply the power sector, is by separating it into two categories, Western Network and Eastern Network, which cover the South of the country. This restriction is due to the geographical placement of the gas fields in the South East and South-South regions of the country and the fact that the power plants in the north are hydro powered[12]. The Western network consists of the Escravos Lagos Pipeline System (ELPS), which is a group of gas plants that supply the power plants in the South Western part of the country. The Eastern network is not a connected network per se, but instead separate gas plants that supply one or two power plants in the South East of the country. The maps below shows this system, although it includes more power plants and gas plants than are in consideration in this thesis and it is also a plan for future pipeline projects as well as on-going ones[13].

[12] There are plans in place to build gas pipelines that would transport gas from from the Southern Niger Delta to the Northern region of the country.
[13] The gas supply network is slightly more expansive than this, but this is the main network that currently supplies the power plants in the country.

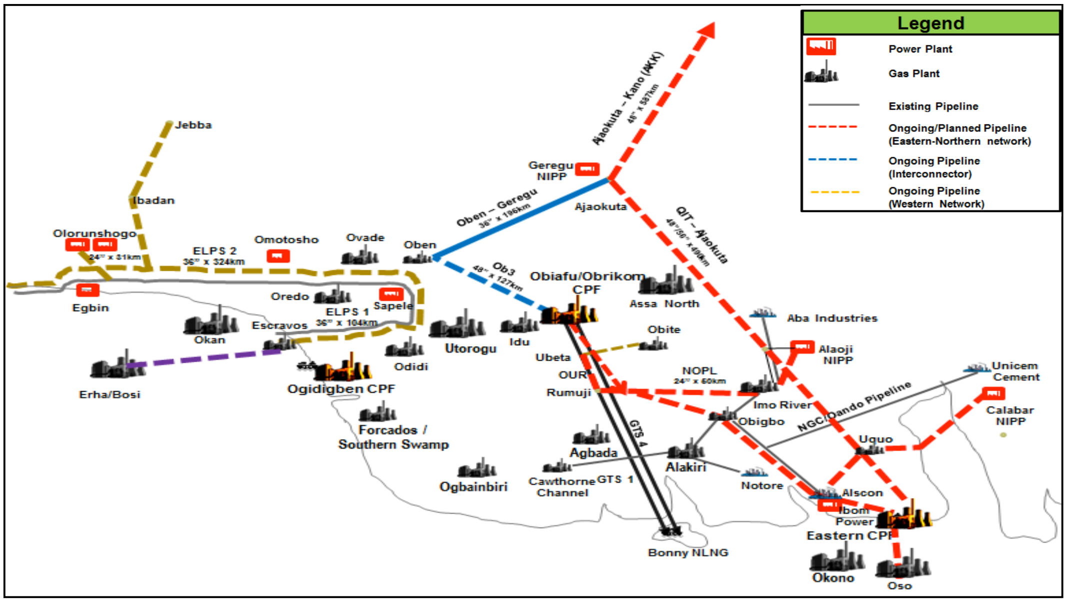


Figure 14: Critical Gas Pipeline Infrastructure. Source: NNPC

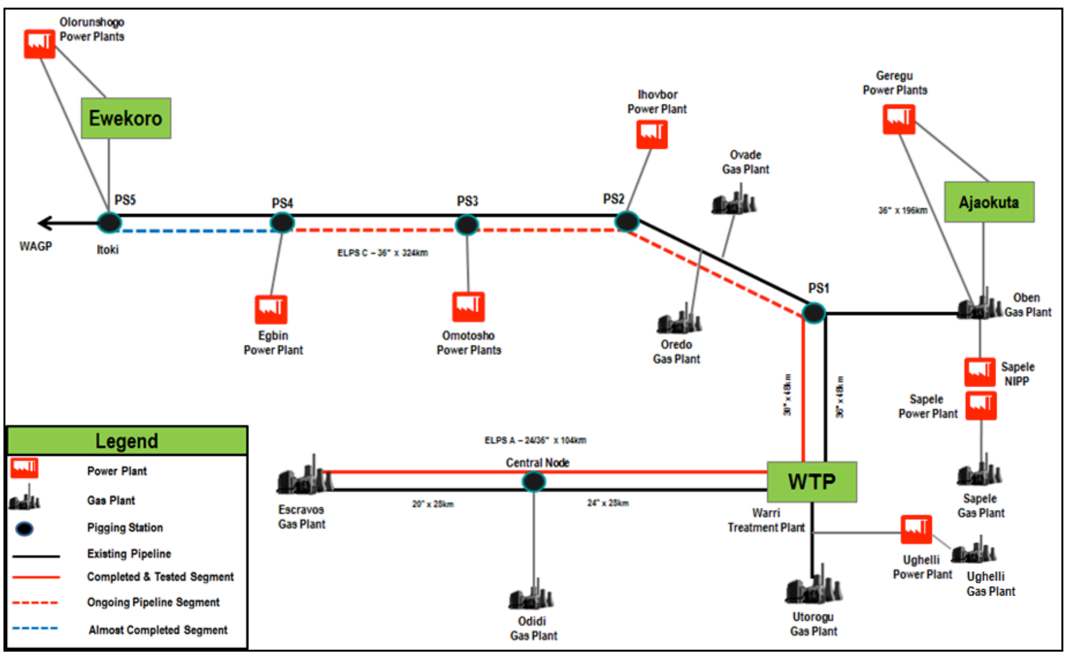


Figure 15: Western Gas Network (ELPS). Source: NNPC

The two maps above emphasize the deficit in gas pipeline infrastructure. Excluding the ELPS, majority of the pipelines displayed are planned pipelines or only in the process of being constructed. Pipelines are perhaps the most crucial part of the system because without them there would be no means of getting the gas to the power plants for generation. Apart from the limited pipeline infrastructure, there is also the problem of pipeline vandalism, which renders the plant unable to generate electricity until the pipeline is fixed.

2.1.3 Gas Supply Variables

In analyzing the gas supply, each power plant under consideration has been paired with its respective gas plant. The table below shows a few of the paired gas plants and power plants.

Gas Plant	Power Plant
Sapele Gas Plant	SAPELE (STEAM)
Ughelli Gas Plant	DELTA (GAS)
Okoloma Gas Plant	AFAM IV-V (GAS)
ELPS Network	GEREGU GAS
ELPS Network	GEREGU NIPP
Oben Gas Plant	SAPELE NIPP
Imo Gas Plant	ALAOJI NIPP GAS

Figure 16: Gas Plant to Power Plant Pairing

It was necessary to make some assumptions concerning the source of gas for a few of the power plants, as the specific information was unavailable. However, this does not have a material effect on the analysis since it is not designed to fully capture the complexities of the system, but instead look at the different parts of the system on an aggregate level. The following variables are represented in the energy flow analysis:

$$i \in I,\ I = \{\text{All gas plants that supply the power plants}\}$$
$$j \in J,\ J = \{\text{All seventeen power plants under consideration}\}$$

Hence we have the random variables:

$$\hat{g}_{ij}\ \forall\ i \in I, j \in J$$

They represent the supply of gas from gas plant i to power plant j for all the gas and power plant pairings. The gas supply is considered to be random because:

- Pipeline vandalism is a random occurrence. No one knows when or where it will occur.
- Gas production levels tend to vary each day, as the NGC has limited gas supply.

The gas supply variables are derived from the realization of the daily generation figures, which will be explained in the next section. Before that, it is necessary to introduce the variables that represent the pipelines.

$$\hat{p}_{ij}^{vandalized} \sim Bernoulli(\tau_{ij})$$

The pipeline random variable $\hat{p}_{ij}^{vandalized}$ is a Bernoulli random variable, where the 'success' occurs when the pipeline connecting gas plant i to power plant j has been vandalized. The probability of success for each pipeline τ_{ij} is different because of the regional differences of the locations of these pipelines. For example, in many cases it is the disgruntled members of the pipeline's host communities that attempt to sabotage the pipelines. So for each pairing of the gas and power plants, we make estimated assumptions about the probability of acts of vandalism on the pipeline based on news on such events. For example the oil rich South-South region, which is prone to oil pipeline vandalism incidents, would have more frequent occurrences of such events, whereas in the South Western part of the country, although vandalism does exist, it would probably not be as frequent. This thesis also assumes that when a pipeline p_{ij} has been vandalized, it means that power plant j has no gas supply and thus stops all production for that day.

2.1.4 Generation Capacity and Output

As explained earlier, the generation capacity and output are values reported daily from the systems operator. They are represented by the variables below:

$$C_j^{Installed}$$

This is the Installed Capacity, in Megawatts (MW), of power plant j. It is constant and only included as a means of comparison to Available Capacity of the power plant.

The Available Capacity of a power plant j, which is random due to the uncertain reliability of the gas turbines

$$\hat{C}_j^{Available}$$

The actual generating capability of the power plant given the gas supply levels

$$\hat{C}_j^{Actual}$$

The energy (MWh) sent out from power plant j

$$\hat{O}_j^{SO}$$

Although it is the capacity of the power plants that we extract from the data, the energy flow analysis uses the energy output of those capacities. This is a means of smoothening the variation in Actual Capacity that occurs throughout the day.

We define:

$$\hat{O}_j^{potential} = \hat{C}_j^{Available} \text{ x } 24hrs$$

The potential energy output of plant j given the Available Capacity

$$\hat{O}_j^{GC} = \hat{C}_j^{Actual} \text{ x } 24hrs$$

The potential energy output of plant j given the gas supply constraint

It was difficult to obtain the gas supply quantities from each gas plant to its respective power plant, so these figures were inferred from the energy output of each power plant. We calculate the amount of gas needed per day in each of the grid-connected power plants. In order to do so we need to know:

1. The efficiency/heat rate
   - This is the rate at which the plant is able to transform the energy from gas to electricity.
   - At a 100% heat rate, we assume an efficiency of 3412Btu/KWh (British Thermal Unit/Kilowatt hour)

- Given the assumptions in the Multi Year Tariff Order II (MYTO II) stipulated by the Nigerian Electricity Regulation Commission (NERC), we assume a heat rate of about 32%, which implies an efficiency of about 10,600Btu/KWh

2. The capacity of the power plant (MW)
   - In this computation, we use the Available Capacity of the power plant, in order to see how much gas would be sufficient to enable all the available turbines in the power plant to run at its Available Capacity.
3. 1 Million cubic feet = 1,020 Million British Thermal Units

Hence, the calculation for determining the amount of natural gas needed per day by a thermal generation plant, with the above assumptions in place, can be calculate with the equation below.

$$\hat{g}_{ij}^{demand} = h \text{ x } \hat{O}_j^{potential} \text{ x } 1000\text{MW x } \frac{1cf}{1020Btu} \text{ x } 10^{-6}$$

This represents the day's MMscf of gas needed by power plant j from gas plant i

$$\hat{g}_{ij}^{delivered} = h \text{ x } \hat{O}_j^{GC} \text{ x } 1000\text{MW x } \frac{1cf}{1020Btu} \text{ x } 10^{-6}$$

This represents the day's MMscf delivered to power plant j from gas plant i

2.1.5 Transmission Network

There has been a gradual increase in generating capacity but the rate of this increase is higher than the transmission network can currently accommodate. This is because of the lacking infrastructure within the transmission network and absence of the funds with which to provide it. The image below shows the current transmission network in Nigeria. It also includes the planned network expansions. The network is a radial system with no redundancies, which puts more strain on the transmission wheeling capacity. As in the pipeline network, most of the lines on the map are planned. The existing lines are the black bold lines with no white-filled shapes on them.

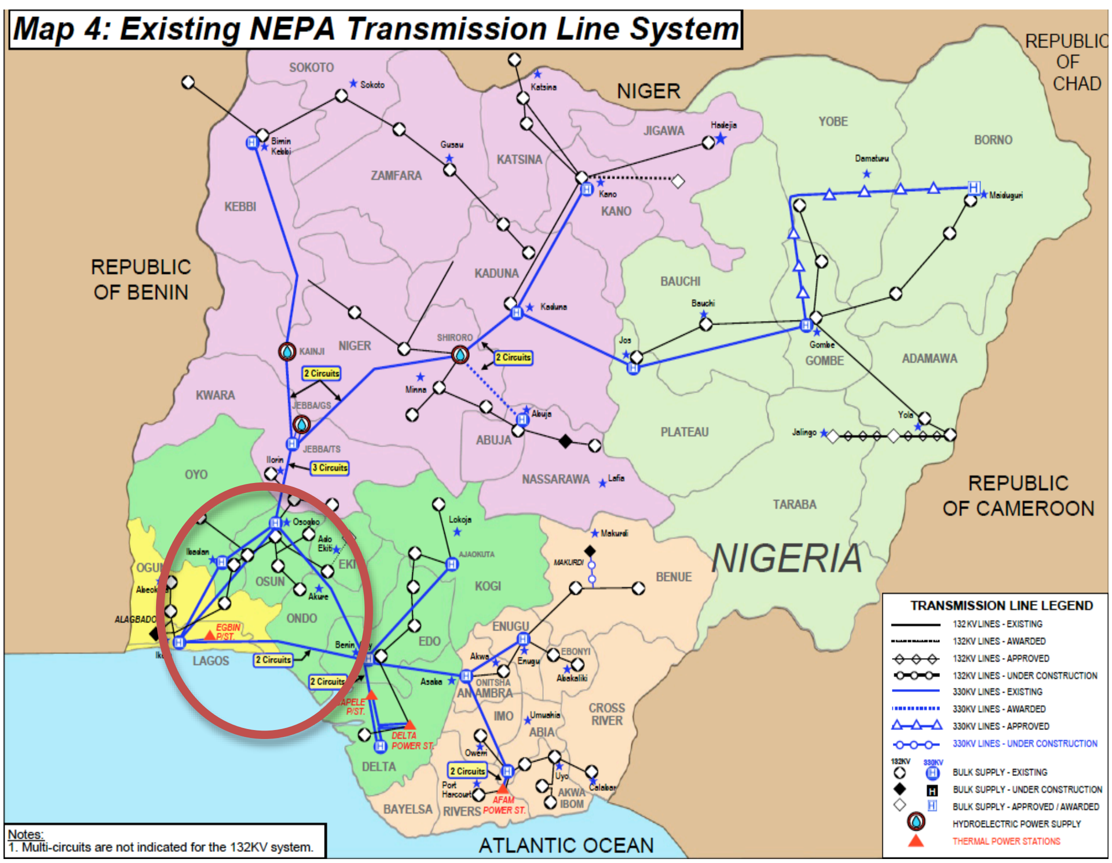


Figure 17: Current Transmission Network with Planned Improvements

The transmission network considered in the energy flow analysis is a highly simplified version of the actual transmission network. It is explained by the illustration below. The main network connecting the major transmission stations is illustrated by a triangle with vertices representing the three main transmission stations in Lagos, Osogbo and Benin and the respective power plants that we assume deliver electricity directly to them. The red circle in Figure 17 pictured above, highlights this triangle. We also make the assumption that each of these transmission stations represents the points through which the energy is transmitted to the eleven distribution zones before getting to the final customer.

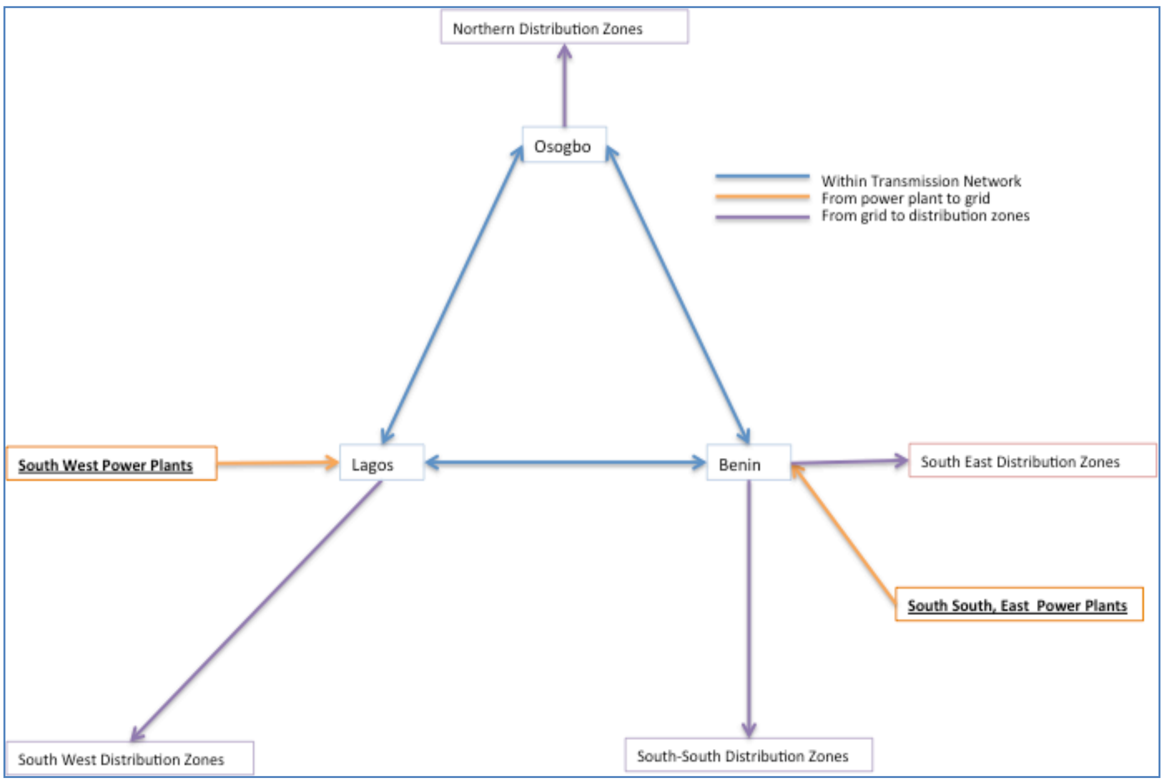


Figure 18: Simplified Transmission Triangle

The country's eleven distribution zones have been grouped into three: North, South-West, South-South, which represents both the South- South and South-East regions. The country map of the distribution zones is pictured in Figure 12 above, and a table of their groupings is shown in the figure below.

The transmission triangle assumes that all Northern zones receive electricity through the Osogbo transmission station, all South-West zones receive electricity through the Lagos transmission station and all South-South zones receive electricity through the Benin transmission station.

Distribution Zone	Equivalency	Zone Group	Transmission point node
Abuja	North	North	Osogbo (from Benin and Lagos)
Jos		North	
Kaduna		North	
Kano		North	
Yola		North	
Ibadan	South West	Lagos	Lagos
Eko		Lagos	
Ikeja		Lagos	
Portharcourt	South South	Benin	Benin
Benin		Benin	
Enugu		Benin	

Figure 19: Distribution Zone Groups and Respective Pairings to the Transmission Stations

We also make the assumption that power plants in the South-South region send all their electricity directly to the Benin transmission station while the power plants in the South-West send all their electricity to the Lagos transmission station. The electricity is then transmitted to the distribution zones from these transmission stations. The Osogbo transmission station is different as it is the point of contact for transmission of electricity between the power plants in the northern and southern regions of the country.

There are limitations to this transmission network triangle beyond its simplification:

- The Benin transmission station appears to be the first point of contact for power plants in the regions from which it collects power. However, the electricity goes from these power plants directly to smaller transmission stations within the regions *in addition* to going to the Benin transmission station. This is the same case with the Lagos transmission station.
- The network also appears to have electricity going from Benin to both Lagos and Osogbo and not the other way round. In reality, the electricity travels between these two power stations both ways, depending on the available transmission lines. The flow of electricity

is not as straightforward as is assumed here since electricity travels between Lagos, Osogbo and Benin in any directions. It is further complicated because the hydro plants are also producing in the North.

- Nonetheless, the spreadsheet has analyzes the transmission flow on an aggregate level so the absence of these details in the model does not significantly hinder the analysis.

Each of the eleven distribution zones has been allocated a load that determines how much power is transmitted to them. It is with this allocation that we determine how much energy is sent out to the Benin and Lagos transmission stations and to the different distribution zones.

2.1.6 Energy Flow to Transmission Triangle

We define d_k as the percentage allocation of total sent out energy to the distribution zone k, $k \in K = \{\text{North(N), South-West(SW), South-South(SS)}\}$. The allocation of energy (MWh) to each distribution zone group is computed thus:

$$\hat{E}_k = \sum_{k \in K} d_k \hat{O}^{SO}$$
$$\hat{O}^{SO} = \sum_{j \in J} \hat{O}_j^{SO}$$

Based on the assumptions made, Lagos and Benin transmission stations are the only ones that receive electricity directly from the power plants. The following equation describes the energy expected at each transmission station

$$\hat{T}_n^{\exp} = \sum_{\substack{All \text{ plants} \\ j \text{ delivering} \\ \text{to station } n}} \hat{O}_j^{SO} \text{ x (1-Transmission Loss Factor)}$$
$$n \in \{\text{Benin(B), Lagos(L), Osogbo(O)}\}$$
$$\text{Transmission Loss Factor} = 8\%$$

However, the constraint in the transmission network appears in the capacity limits of the transmission lines. First we define:

$$P_n = \{\text{Power Plants transmitting to station } n\}$$

$l^{P_n} =$ Line limit between station n and P_n

$$\hat{T}_n^{rec} = \min(\hat{T}_n^{\exp}, l^{p_n})$$
$$\hat{T}_n^{lost} = \hat{T}_n^{\exp} - \hat{T}_n^{rec}$$
$$T_O = 0$$

Thus the energy received by each transmission station n from its respective power plant is the minimum of the energy that was expected at the transmission station (based on its allocation) and the transmission line limit between that transmission station and the power plant sending energy out to it. The lost energy is the difference between the expected energy and the energy that was actually received by the transmission station. The Osogbo transmission station receives no energy directly from the gas-fired power plants.

2.1.7 Energy Flow within Transmission Triangle

Based on the assumption that the Benin transmission station receives electricity from all the power plants in the South-South and South-East region of the country, and the fact that these power plants represent the majority of the country's generation capacity, the flow of energy between transmission stations would be from Benin to Lagos and Osogbo. Given that the Osogbo transmission station does not receive any power directly from the gas-fired power plants, we assume that the excess power from Benin is first allocated to Osogbo. Thus, the energy expected at the Osogbo transmission station is

$$\hat{X}_o^{\exp} = \min(\hat{T}_B^{rec} - \hat{E}_{SS}, \hat{E}_N)\ \mathrm{I}_{\{\hat{T}_B^{rec} > \hat{E}_{SS}\}},$$

the minimum between the leftover energy at the Benin transmission after it has satisfied its allocation and the allocation to the Northern distribution zones. The 'I' in the equation represents the indicator function whose value is 0 if the South-South region's allocation is greater than the amount of energy sent to the Benin Station. If this is the case, no electricity is sent to Osogbo from Benin. The energy flow analysis also assumes that whatever is left over after the electricity has been sent to the Osogbo station, would flow from the Benin transmission station to Lagos. This assumption is represented mathematically in the equation below.

$$\hat{X}_L^{\exp} = \max(\ 0\ ,\ \min(\hat{T}_B^{rec} - \hat{E}_{SS} - \hat{X}_O^{\exp}, \hat{E}_{SS} - \hat{T}_L^{rec}))\ \mathrm{I}_{\{\hat{T}_B^{rec} - \hat{E}_{SS} - \hat{X}_O^{\exp} > 0\}}$$

This just says the amount transferred to Lagos from Benin is capped at the available energy after Osogbo's allocation has been satisfied. If there is no leftover, Lagos would receive nothing from the Benin station. However, since these formulae are based on the allocations of the sent out energy, this should not be the case. There are also transmission constraints when electricity travels between transmission stations:

$$l^{B-L}, l^{B-O}$$

These represent the line limits between the transmission stations. Consequently, the electricity transfer from Benin to the other transmission stations in the triangle:

$$\hat{X}_O^{rec} = \min(l^{B-O}, \hat{X}_O^{\exp})$$
$$\hat{X}_L^{rec} = \min(l^{B-L}, \hat{X}_L^{\exp})$$

The energy flows through the transmission network assumes that the other parts of the grid have enough capacity to enable the flow of electricity without constraint.

2.1.8 Generation Loss Analysis

Apart from the needed expansion of the country's generating capacity, which is emphasized in Chapter 1, the data also shows that Nigerians are not benefitting as much as they could be from the current Available Capacity in the country. This is because there is a series of capacity losses in the power generation process. These losses have been described mathematically above. The losses specific to the generation part of the value chain are shown in the diagram below:

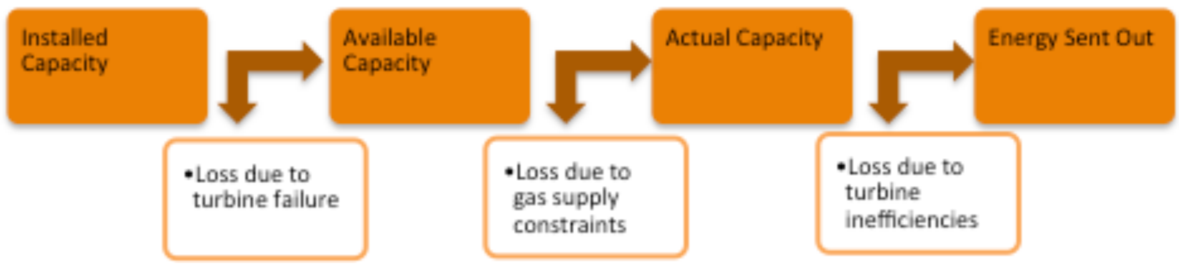


Figure 20: Sources of Generation Capacity Loss

We want to find out how much each type of generation loss contributes to the total loss of generating capacity. We look at this information for each of the days representing the fifty-two weeks of 2013. Thus, we define our sample realization

$$\rho = \{1,2,...52\},$$

the generation profile from the reports of week one to day fifty-two. For each power plant j under week/scenario ρ, we define:

Loss A: Loss due to turbine failure

$$\delta_j^{A,\rho} = (C_j^{installed,\rho} \text{ x } 24hrs) - O_j^{potential,\rho}$$

Loss B: Loss due to gas supply constraints

$$\delta_j^{B,\rho} = O_j^{potential,\rho} - O_j^{GC,\rho}$$

Loss C: Loss due to turbine inefficiencies caused by low maintenance levels

$$\delta_j^{C,\rho} = O_j^{GC,\rho} - O_j^{SO,\rho}$$

Total Loss: The total lost generation capacity between Installed Capacity and the MW equivalent of the energy sent out of each power plant on that day.

$$\delta_j^{Total,\rho} = \delta_j^{A,\rho} + \delta_j^{B,\rho} + \delta_j^{C,\rho}$$

We give each loss m, $m = \{A,B,C\}$ a 'blame factor' $\beta_j^{m,\rho}$, which is the portion of the total loss in plant j under scenario ρ, which is due to loss m

$$\beta_j^{m,\rho} = \frac{\delta_j^{m,\rho}}{\delta_j^{Total,\rho}}$$

With this information, we hope to have a better indication of how the investment budget might be allocated to the different parts of the supply value chain. The budget allocations would be made with the goal of reducing the generation capacity losses in a way that brings about the greatest overall increase in the final amount of energy that is sent out to the transmission network at the end of the generation process.

Given the stochastic nature of the generation profiles, we need to get a sense of the distribution of the generation capacity losses over the course of the year. The purpose of using the distributions and not just picking a particular number is to learn more about how much of the time a constraint is actually a constraint. For example, some power plants have gas constraints. Sometimes the gas constraint is responsible for more than half of the energy loss and sometimes it is responsible for less than one percent. If the latter occurs more often, we would be in a better position to decide that we won't invest in the gas supply for the particular power plant because gas is only a problem 1% of the time. Furthermore, we evaluate the contribution of each power plant to the final amount of energy that is sent to the grid, how much of the total system loss is caused by the power plant and rank the sources of its capacity loss based on the source of the biggest reduction from the Installed Capacity. Below, we present the analysis performed on two of the power plants. We do not include all seventeen as there is little variance in the trends of their generating profiles. We only aim to get a better sense of how the generation capacity is lost before it gets sent to the transmission stations.

2.1.9 Geregu Gas Power Plant

Geregu gas is a formerly owned Federal Government power plant that began operations in 2007. As at the period of the data used in this thesis, it was only six years in operation. It is located in Kogi State, in the Southwestern region of the country and is supplied gas from the ELPS network. In examining Geregu gas's generation loss profile, we see that:

- for majority of the year between 80-100% of its total capacity loss i.e. difference between Installed Capacity and the MW equivalent of sent out capacity, is caused by unavailable turbines, while
- gas accounts for mostly 10% of this loss and
- the other 10% lost from the inefficiencies of the turbines that in operation

Even when we compare the portion of gas constraint losses and inefficiency losses based not on Installed Capacity, but Available Capacity of the power plants, the results are still similar, where we see that they are each responsible for about 20% of the capacity loss most of the time. This indicates that any investments in Geregu gas should be directed at rehabilitating the faulty turbines. However, the investment will have to be split between ensuring an increased gas supply to the plant and reclaiming the lost generating capacity as one investment is essentially useless without the other.

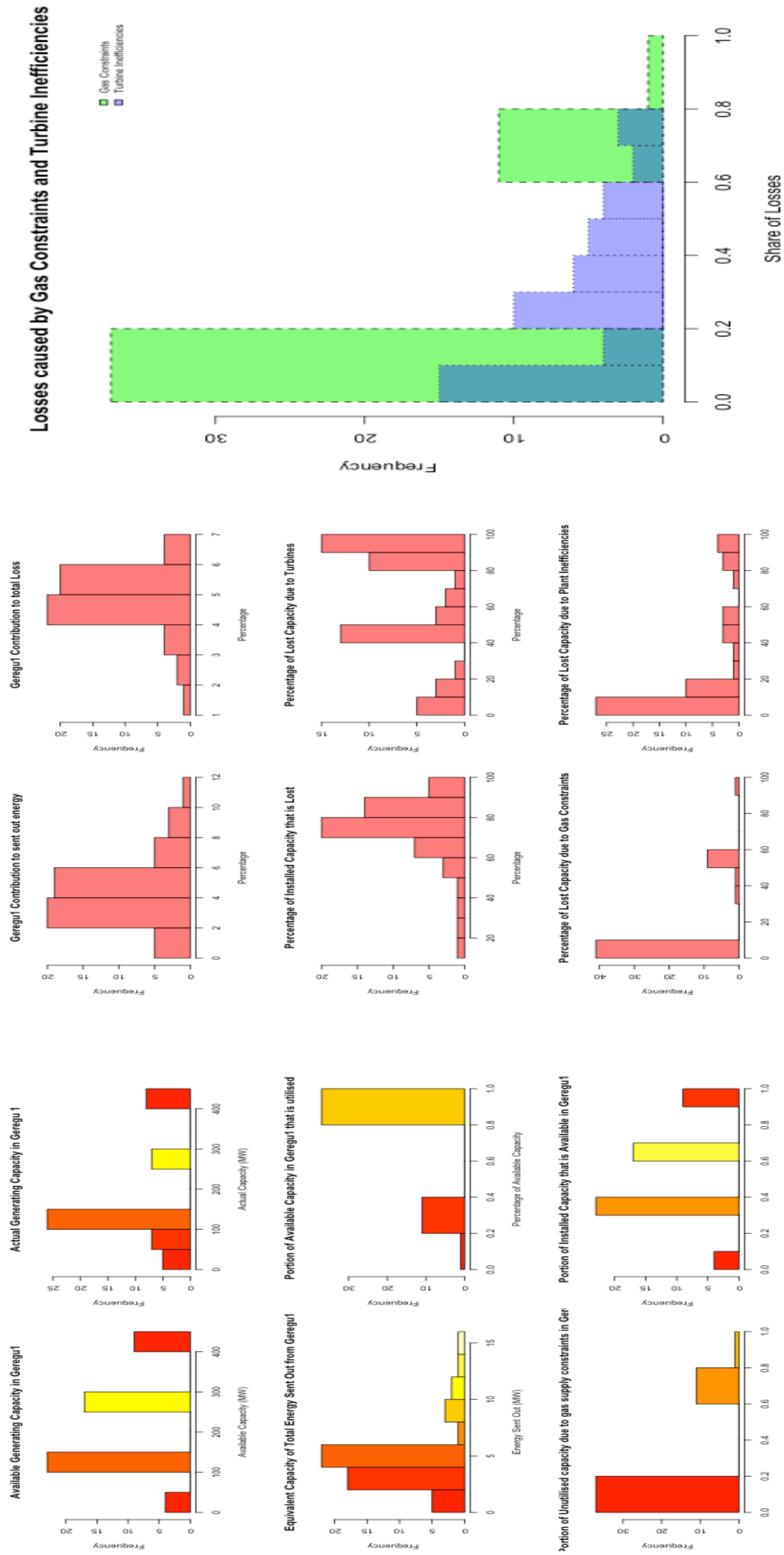


Figure 21: Distribution of the Generation Profile and Generation Capacity Losses of Geregu Power Plant

2.1.10 Egbin Power Plant

Located in the country's commercial capital, Lagos State, the Egbin Power Plant has been in operation since 1985, making it twenty-eight years old as of 2013. It is supplied gas from the ELPS network. It has the largest Installed Capacity in the country- 1320MW and contributes 20-30% of the energy sent out to the grid, it is responsible for a large chunk of generation output, but also contributes between 10-15% of the total capacity loss. The distributions of each of the capacity losses are more or less evenly spread. From the plots we can see that 30-70% of the Installed Capacity is lost by the time the final energy is sent out, with 60-70% of lost capacity appearing the most frequently. The largest source of capacity loss lies in the faulty turbines, which reduce the Available Capacity. The next appears to be plant inefficiencies while gas is the lowest source of loss. However, looking carefully at the gas constraint plot, we can see that there is roughly and even spread between the 10-80%. If we weigh the capacity losses with respect to the Available Capacity of the plants, we see that half the time, the gas loss takes away 10% of Available Capacity; so do the turbine inefficiencies, with the inefficiencies accounting for more of the losses. However, at higher capacity losses, more specifically losses that are between 40-60% of Available Capacity, the gas constraints account for the higher portion of the losses more frequently than the inefficiencies do. This suggests that although half the time the gas constraints take away 10% of Available Capacity, 20% of the time the plant can't use over half of its Available Capacity because it has no gas. Nonetheless, the capacity loss graphs indicate that the first use of any investment should be on maintaining the turbines, which tend to cost the plant 70% of its capacity half the time. However, we must not neglect the fact that increased Available Capacity translates to higher demand for gas. Given that the gas demand is not fully satisfied, these investments will have to come together.

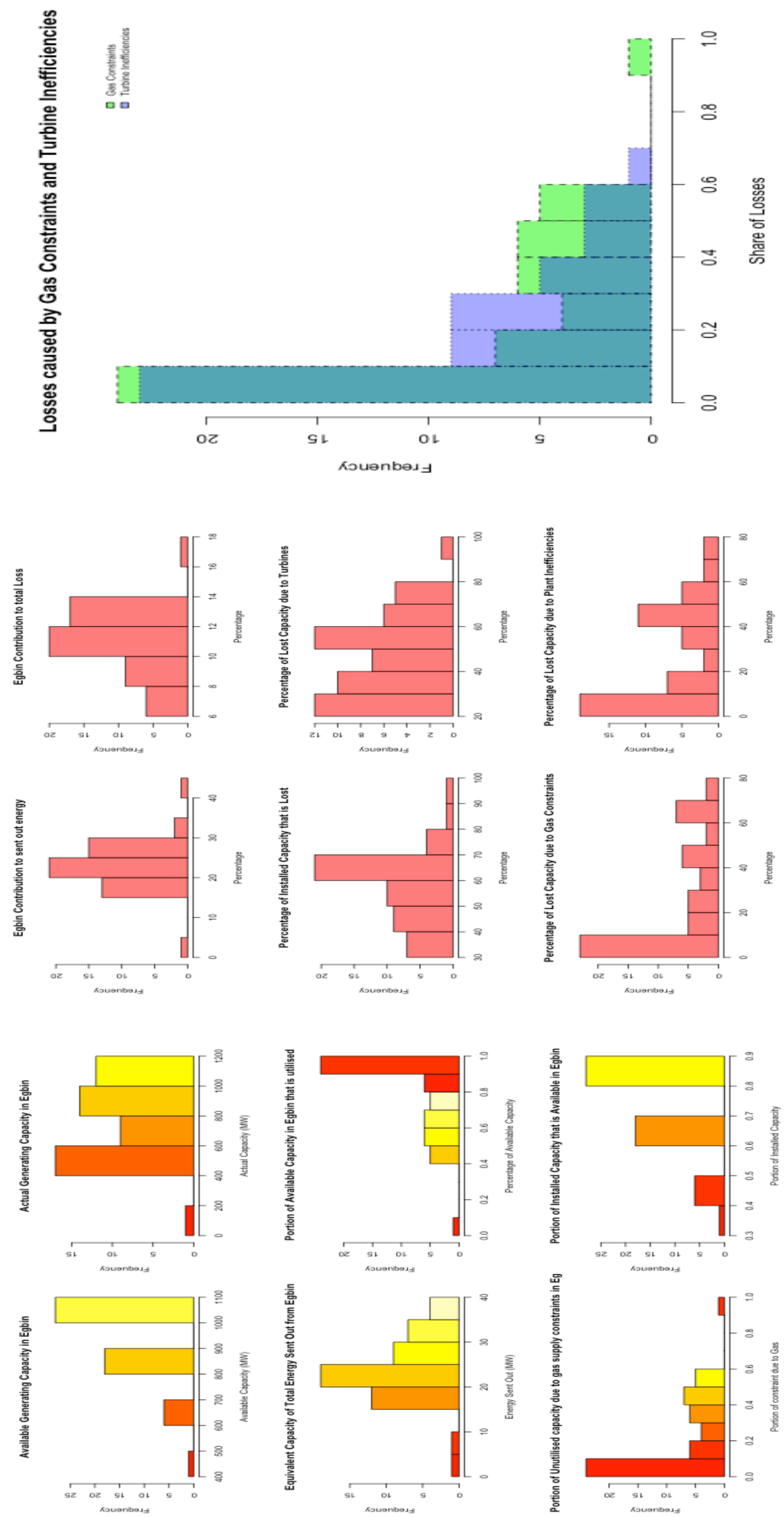


Figure 22: Distribution of Generation Profile and Generation Capacity Loss of Egbin Power Plant

The rest of the power plants exhibit similar trends. The biggest sources of generation capacity loss in each power plant are from the inefficient turbine operations. This trend will appear again when we implement our investment policies in the following chapters. Even though the numbers point to the turbines as the biggest source of capacity loss, the fact that the gas supply does not match the Available Capacity in all the power plants shows that when the turbines do begin to work, more gas will be needed. So if the gas supply in not increased as the Available Capacity is increased, the generation capacity loss problem will not be solved even when the capacity loss due to the turbine failures and inefficiencies has been eliminated. We will go more into detail about this in the next chapter.

2.2 Stochastic Energy Flow

We have mentioned the sources of uncertainty in the system- gas supply and the gas turbine reliability and efficiency. Thus it is important that any worthwhile analysis acknowledges the stochastic nature of the system. A method of doing this would be to analyze the effects of investment strategies under the fifty-two different scenarios. However, given the time constraints and limitations of excel spreadsheet analysis, we can shrink this sample space by picking four sample realizations out of the original fifty-two week sample space. Having analyzed our data using the fifty-two week data available, we choose the following sample realizations:

- **Sample Realization 1 (SR1)**: This is the generation profile that averages all the data over the fifty-two weeks given. It gives us the expected generation profile of the system.
- **Sample Realization 2 (SR2)**: This is day in which the lowest Energy Sent Out occurs- 10th April 2013
- **Sample Realization 3 (SR3)**: This is the day in which we see the lowest Actual Generating Capacity- 14th August 2013
- **Sample Realization 4 (SR4)**: This is the day in which we have the lowest Available Capacity – 13th November 2013

We have specifically chosen these sample realizations because when implementing the different investment strategies in the following chapters, we want to be able to account for worst-case scenarios. The average case has been included to provide a 'normal' scenario.

We define our sample space as

$$\omega \in \{1,2,3,4\}$$

And adjust the generation variables in order to represent the generation profile of each power plant j in each sample realization:

$$G(\omega_j) = \{g_{ij}^{demand,\omega}, g_{ij}^{delivered,\omega}, O_j^{potential,\omega}, O_j^{GC,\omega}, O_j^{SO,\omega}\}$$

These are the same variables as described earlier, only now without the randomness. They now represent sample realizations of the data. In the following chapter, we will explore investment strategies over these sample realizations.

We add another layer of uncertainty to the energy flow analysis through the stochastic nature of the Bernoulli pipeline vandalism indicator variable $\hat{p}_{ij}^{vandalised}$ introduced earlier. The event of an attack on pipeline ij is occurs with probability τ_{ij}. These events are simulated using the following method:

$$
\begin{aligned}
&\text{Generate } U \sim Uniform(0,1) \\
&p_{ij}^{vandalized} = \mathrm{I}_{\{U<\tau_{ij}\}} \\
&O_j^{GC,\,\omega} = \mathrm{I}_{\{p_{ij}^{vandalized}=0\}} \text{ x } (\mathrm{C}_j^{actual,\,\omega} \text{ x } 24\text{hrs}) \\
&g_{ij}^{delivered,\omega} = \mathrm{I}_{\{p_{ij}^{vandalized}=0\}} \text{ x } h \text{ x } \mathrm{O}_j^{GC,\omega} \text{ x } 100\text{MW x } \frac{1cf}{1020Btu} \text{ x } 10^{-6}
\end{aligned}
$$

We generate a uniform random variable between zero and one, if the number generated is less than the probability of the pipeline being vandalized; we say that the pipeline has been vandalized. Furthermore, if p_{ij} is vandalized this implies that there will be no gas delivered to power plant j from gas plant i, meaning no electricity is sent out from power plant j. Modeling the pipeline vandalization like this appears extreme, but it is purposely so in order to emphasis the large impact of the pipeline vandalization on the amount of electricity is able to produce.

2.3 Money Flows

So far we have not considered the fact that money flows as energy flows. As such, the energy flow is reflected in financial terms using the MYTO II tariffs/prices for gas, generation and transmission. At each step of the value chain: gas, generation and transmission, we compute the revenues and the funds that have been lost due to capacity constraints.

$$R_i^{gas,\omega} = t^{gas} \sum_{j \in J} g_{ij}^{delivered,\omega}$$
$$L_i^{gas,\omega} = t^{gas} \sum_{j \in J} g_{ij}^{demand,\omega} - g_{ij}^{delivered,\omega}$$

The above formulae compute the gas revenues that are earned and lost by each gas plant i based on the amount of gas that is delivered and the difference between this and the amount of gas that is demanded by the plant (based on its Available Capacity).

$$R_j^{generation,\omega} = C_j^{available,\omega} t^{capacity} + O_j^{SO,\omega} t^{energy}$$
$$L_j^{generation,\omega} = t^{energy} \left(O_j^{potential,\omega} - O_j^{SO,\omega} \right)$$

These show the revenues the power plant earn and lose based on the amount of energy that is sent out and the difference between this amount and the potential energy, based on the plant's Available Capacity. One thing to notice is that there are two types of charges for generation. The first is the capacity charge, which is paid to the power plant based on its Available Capacity and the second is the energy charge, which is the amount it is paid per MWh of electricity sent out. As such, the financial implications of the capacity losses described earlier are considerably reduced for generation.

Transmission revenue flows:

$$R_n^{trans,\omega} = t^{transmission} \sum_n T_n^{rec,\omega} + X_n^{rec,\omega}$$
$$L_n^{trans,\omega} = t^{transmission} \sum_n (T_n^{\exp,\omega} + X_n^{\exp,\omega}) - (T_n^{rec,\omega} + X_n^{rec,\omega})$$

The transmission revenues are calculated based on the energy that is transmitted from the power plants to the transmission stations and the energy that is delivered from one transmission station to another. The lost revenues are calculated in the same vein and are as a result of the transmission line limits described above.

Although the flow of money in the system is equally as important as the flow of energy, due to limitations in data, we are not able to fully capture this flow of money in as much detail as we do the flow of energy. The financial flows in the value chain consist of multiple contracts, which we do not have the room to analyze in this thesis. As such, we stop the analysis of the flow of money here, acknowledging that it is important, but also more complicated than we have had the time to analyze in this thesis.

This chapter has presented the data with which we perform our analysis and make our investment policy decisions. It has also explained the context and modeling of the flow of energy in the system, including especially, a description of the losses, constraints and bottlenecks in the system. It introduced the stochastic nature of the data and explained how it will be taken into account while performing our analysis. All this has been done with the aim of preparing the groundwork to enable us design the most relevant and useful investment policies, which will be expanded upon in the following chapter.

3 Chapter 3: Investing in the NESI

Thus far, we have closely examined the flow of energy in the NESI and highlighted the bottlenecks in the different parts of the system that cause a large disparity between the available capacities of the power plants and the final amount of energy that is sent to the distribution zones. In this chapter, we provide the background for the investment plans with which we hope to reduce or eradicate, where possible, the bottlenecks in the NESI. We assume that we are at the end of 2013 and want to make investment plans to be applied to the NESI in the coming year. We introduce the investment goals and explain the context in which these investments are being made. We will also explain four investment policies and the four scenarios in which these investment policies will be applied. Finally, we define the performance metrics with which we determine the value created by each of the four investment policies.

3.1 Goals of Investment Policies in the NESI

When investing in the NESI, the main goal is to achieve a substantial increase in the ratio of the energy sent to the electricity consumers every day to the available generating capacity of the country, we will call this the 'energy delivered' ratio. Consequently, the focus should be less on the separate capacity milestones made by the 'fuel-to-power', 'generation' and 'transmission' sections of the value chain and more on the combined effects of their capacity improvements on the final energy that gets delivered. It is with this in mind that we decide on good investment policies for the electricity supply value chain. While comparing investment policies, we will establish the principle of interacting components, where we show that we cannot fix the system by investing in only one part of the value chain or even by investing in multiple parts, without considering how the investment in each part of the system affects the added value to the whole system. In comparing investment policies for the NESI, this chapter proposes that the goal of investing in the Nigerian Power Sector should be twofold:

The first and arguably the most important goal, is to remove all the sources of generation capacity losses. These are the losses identified in the previous chapter:

- Loss due to turbine failure
- Loss due to gas supply constraints
- Loss due to turbine inefficiencies
- We will also include here the loss due to the transmission wheeling capacity constraints

In other words, the core investment objective should be to 'fix' the current system so that it is operating with minimal losses such that the electricity that is received by the consumer is reflective of the Available Capacity of the power plants. This sets a good foundation for any necessary future capacity expansions. If the current system were barely able to support itself, any expansion plan would require inflated investments in order to compensate for the inefficiencies in the unfixed system.

After we have ensured that the current system is delivering as much electricity as it physically can, the next move is to address the electricity supply-demand gap. This is the second goal. The capacity expansions should be done with the primary goal in mind. If we have a budget with a certain dollar amount, it would be split so that we have enough extra fuel to satisfy the capacity being added and enough wheeling capacity in the transmission network, to send it all out. This is all to ensure that we are not left with 10,000 MW of Available Capacity, 5000MW worth of gas supply and 3000 MW that is finally sent out to the distribution zones. We would have wasted the cost of the 7000 MW generation capacity when the funds could have been applied to expanding *the whole* chain by 4000 MW, from which 3800MW would be delivered to the customer. This would ensure that no part of the investment is stranded in unused capacity. The rest of the chapter discusses the implementation of these goals in detail.

3.2 Setting Up To Fix the Current System

As described above, this part of the investment plan is the most important and is aimed at freeing up the bottlenecks in the electricity supply value chain in its present state. In the analysis, we make the assumption that there is no time lag when investments are made. This means that we assume all investments and their resulting capacity increases, are implemented immediately. Although this assumption does not account for time lags, it does not stop the analysis from establishing the value of considering all parts of the system when making investments in any part of the system.

3.2.1 Budget and Areas of Spending

We will assume that we have a budget of $7,000,000,000. This amount has been chosen because it is small enough to constrain our spending, but large enough to make a considerable impact in the system. It will be represented by the variable B^{fix}. Based on the identified areas of capacity constraints and losses, we will define five areas of spending.

1. **Gas Supply Investments**
   - Gas Pipeline Security:
     - Vandalized pipelines are a big cause of reduced gas supply. Our model assumes that once the pipeline supplying a power plant is vandalized, there is no electricity sent out from that power plant. It is not an unreasonable assumption as this does occur.
     - Investments in pipeline security will have the effect of reducing the probability of the event that a pipeline is vandalized.
   - Gas Production
     - The problem with the insufficient gas supply is not limited to the gas supply infrastructure, but also the levels of gas supply itself.

- Investments in gas production will have the effect of increasing the gas supply to the power plant, which means that the gap between the plant's Available Capacity and Actual Capacity is reduced.

2. **Generation Capacity Investments**

- Increasing Available Capacity:
  - Majority of the power plants are not operating at Installed Capacity because one or more of their turbines are out of order and not available for use.
  - This investment effectively decreases the gap between Installed Capacity and Available Capacity by fixing the faulty turbines. Although the amount of the capacity increase would depend on the capacity of the turbine that is being fixed, we assume that the increases in Available Capacity can be made in steps of 1MW[14].
- Increasing Turbine Efficiency
  - We have seen in the previous chapter that the energy sent out of the power plant, is between 50%-75% of the actual generating capability of the plant.
  - In this analysis, we assume that the cause of the reduced efficiency of the power plant is from a lack of maintenance. Consequently, this investment improves maintenance of the gas turbines and decreases the gap between the actual generation capacity of the plant and the equivalent capacity of the energy sent out.

3. **Transmission Wheeling Capacity**

- Due to the transmission line limits, not all the energy sent out from the power plants can be delivered to the transmission stations or the distribution zones.

[14] This is technically improbable but has been used here in order to capture the marginal value of the investment in increasing the generation capacity of a power plant.

- This investment increases the wheeling capacity of the transmission lines in order to decrease the gap between the energy sent out from the power plants and the energy delivered to the three main transmission stations and distribution zones.

The investment policies to be described are aimed at reclaiming lost capacity. The goal is to reduce the amount of energy that is lost along the supply chain. At this point we do not consider the introduction of new capacity to the system.

3.2.2 Spending Costs and Effects: Assumptions and Variables

This section explains the set-up of the model with which we will apply our investment strategies into the system. In each area of spending, we estimate a cost per unit increase in the respective areas of investment. Given that the model is a highly simplified version of the true electricity supply system, the cost estimates are not to be mistaken for their true values, which could be more or less than has been assumed in this thesis. However, this is not a major limitation because the aim of this thesis is not to find out how much of a financial investment the Power Sector needs, but how best to use an allocated budget, given the generating profile of the country. The methodology can easily be applied to the true costs. Below we define the different prices of the investments in each of the following areas:

Let P^r represent the cost per unit of improvement in spending area r

where r = {Gas Pipeline Security (GPS), Gas Production Capacity (GPC),
Available Generating Capacity (AGC), Turbine Maintenance (TM),
Transmission Wheeling Capacity (TWC)}

We assume the following costs:

Pipeline Security

$$P^{GPS} = \$1{,}000{,}000 / \%$$

For every \$1 million invested in gas pipeline security, we assume that the probability τ_{ij} of pipeline ij being vandalized reduces by a percentage. Mathematically speaking, the result of a \$1 million investment is

$$\tau_{ij}^{I} \rightarrow 0.9\tau_{ij}$$

Gas Production Capacity

$$P^{GPC} = \$45{,}000 / MWh$$

An investment of \$45,000 in the production capacity of a gas plant generates enough gas to produce 1MWh of electricity.

Generation Capacity

$$P^{AGC} = \$1{,}500{,}000 / MW$$

With an investment of \$1.5 million, we can increase the Available Capacity of a power plant by a MW. Technically, an increase in Available Capacity would call for the repair of a whole gas turbine, which can be of any capacity; this mode of pricing depicts the marginal value of the capacity expansion.

Turbine Maintenance

$$P^{TM} = \$15{,}000 / MW$$

For every \$15,000 invested in turbine maintenance, we increase the equivalent generating capacity of the energy sent out of the turbines by a MW. However, this is a one-time investment because we assume that after the turbines have been restored to generating at their full capacity, the future maintenance costs will become part of the operating costs of the power plant. Furthermore, when new capacity is restored to the plant, it is expected that the turbine operates at its full capacity and will thus have no need for a restorative maintenance investment.

Transmission Wheeling Capacity

$$P^{TWC} = \$500,000 / MW$$

With an investment in the transmission network of $500,000, we assume that we can increase its wheeling capacity by a MW. Although we do not take into consideration the length of the transmission lines, we can assume that the cost above is the average marginal cost of improving the wheeling capacity of the network.

3.2.3 Budget Allocations and 'Post Investment' Energy Flows

As indicated earlier, the budget with which we plan to fix the system is $B^{fix} = \$7,000,000,000$. There are also two further levels of budget allocation that need to be described:

- The budget allocation to the five different spending areas listed above, represented by:

$$\mu^r, \forall r, \text{ where } \mu^r \in (0,1)$$

- The budget allocation to each of the individual power plants:

$$\lambda_j, \forall j, \text{ where } \lambda_j \in (0,1)$$

These allocations are not predetermined, but recorded after the investment figures have been calculated. This enables tracking of which spending areas and plants require the most money while being fixed.

3.2.4 Pipeline Security Investment

The investment in pipeline security is different from the others because there is no fixed price of pipeline security. The range of damage, time till damage is resolved, and frequency of the occurrence of the pipeline vandalizations are too varied to have one definitive estimate on the costs of pipeline security. However, we will allocate $7,000,000 (0.01%) of the budget as a contingency plan in the event of a pipeline being damaged. The pipeline budget is represented mathematically below:

$$I_{ij}^{GPS} = B^{fix}\mu^{GPS}\lambda_j,$$
$$B^{fix}\mu^{GPS} = \$7{,}000{,}000\ ,$$

It says that the pipeline security investment made on the pipeline connecting gas plant i to power plant j is the product of the budget allocated to fix the system, the share of the budget allocation to gas pipeline security and the share of the pipeline security budget that has been allocated to plant j. We define the value created by this investment in the equation below. It represents the post-investment probability of an event of the vandalization of pipeline ij:

$$\Delta_{ij}^{GPS} = \max(\zeta, \left(1 - \left(\frac{\frac{I_{ij}^{GPS}}{P^{GPS}}}{100}\right) \text{ x } \tau_{ij}^{vandalisation}\right),$$

where ζ is a number very close to 0,

$\tau_{ij}^{vandalisation}$ is the pre-investment probability of a pipeline vandalisation event occuring

3.2.5 Available Generation Capacity Investment

The investment in increasing the available generation capacity is

$$I_j^{AGC} = B^{fix}\mu^{AGC}\lambda_j$$

The investment is computed the same way as in the pipeline security case. In order to measure the value of the investment on that part of the system, we compute:

$$\Delta_j^{AGC} = \frac{I_j^{AGC}}{P^{AGC}} \text{ x 24hrs}$$

$$\mathrm{O}_j^{potential,\omega,I} = \min(\Delta_j^{AGC} + O_j^{potential,\omega}, C_j^{installed} \text{ x 24 hrs})$$

$\mathrm{O}_j^{potential,\omega,I}$ is the post investment potential output of power plant j.

It gives us in MWh, the increased daily potential output of the power plant. However, since we are not adding any new capacity here, the most we can increase the potential output of the power plant is up to its original Installed Capacity.

3.2.6 Gas Production Capacity Investment

The gas supply investment computations are similar to those above. Although we have to consider the increased Available Capacity, or potential output as this will increase the demand for gas supply.

$$g_{ij}^{demand,\omega,\mathrm{I}} = O_j^{potential,\omega,\mathrm{I}} h \text{ x } 10^{-3} \text{ x } 1020^{-1}$$

The equation above gives us the MMscf/d of the gas that is demanded from gas plant i to be sent to power plant j, given its increased Available Capacity. The investment in gas production capacity,

$$I_{ij}^{GPC} = B^{fix} \mu^{GPC} \lambda_j$$

Causes an increased production capacity of

$$\Delta_{ij}^{GPC} = \frac{I_{ij}^{GPC}}{P^{GPC}}$$

But the actual increase in the gas production capacity has an upper limit at the production capacity that would satisfy the post investment Available Capacity of the power plant:

$$g_{ij}^{delivered,\omega,\mathrm{I}} = \min(g_{ij}^{delivered,\omega} + \Delta_{ij}^{GPC}, g_{ij}^{demand,\omega,\mathrm{I}})$$

Which allows us to compute what we previously referred to as the "gas-constrained output"

$$O_j^{GC,\omega,\mathrm{I}} = \frac{g_{ij}^{delivered,\omega,\mathrm{I}} \text{ x } 10^6}{h \text{ x } 10^3 \text{ x } 1020^{-1}}$$

3.2.7 Turbine Maintenance Investment

The same sets of equations follow for the turbine maintenance investment

$$I_j^{TM} = B^{fix} \mu^{TM} \lambda_j$$

$$\Delta_j^{TM} = \frac{I_j^{TM}}{P^{TM}}$$

$$O_j^{SO,\omega,I} = \min(O_j^{GC,\omega,I}, (\Delta_J^{TM} \text{ x } 24hrs) \text{ x } 0.98 + O_j^{SO,\omega})$$

$$U_j^{TM} = (\Delta_J^{TM} - O_J^{SO,\omega,\mathrm{I}}) P^{TM}$$

The post-investment energy sent out to the grid is capped by the post-investment gas constrained generation capacity, $O_j^{GC,\omega,\mathrm{I}}$. We multiply the increase in energy sent out by 98% to account for the plant's 2% auxiliary factor, which is the amount of energy needed to power the plant.

3.2.8 Transmission Wheeling Capacity Investment

The investment in the transmission wheeling capacity goes directly to increasing the transmission line limits described in the previous chapter. We defined two types of transmission lines, the first set consist of the transmission lines that transport the electricity from the power plants to the transmission stations while the second set of transmission lines consist of those running between the main transmission stations.

We previously defined the line limits: $l = \{l^{P_n}, l^{B-L}, l^{B-O}\}$

Thus we have the investment allocation to line l ,

$$I^l = B^{fix} \mu^{TWC} \lambda_l$$

$$\Delta_l^{TWC} = \frac{I^l}{P^{TWC}}$$

$$\Rightarrow l^{p_n,I} = l^{P_n} + \Delta_{l^{Pn}}^{TWC}$$

$$\Rightarrow T_n^{rec,\omega,\mathrm{I}} = \min(T_n^{\exp,\omega}, l^{P_n,I})$$

Resulting in the post-investment electricity transmitted to the transmission station n . We have a similar line limit increase in the lines between the transmission stations.

$$l^{B-O,I} = l^{B-O} + \Delta^{TWC}_{l^{B-O}}$$
$$l^{B-L,I} = l^{B-L} + \Delta^{TWC}_{l^{B-L}}$$
$$X_o^{rec,\omega,I} = \min(l^{B-O,I}, X_o^{\exp,\omega})$$
$$X_L^{rec,\omega,I} = \min(l^{B-L,I}, X_L^{\exp,\omega})$$

Here we continue to assume the transmission lines between the transmission stations and the different distribution zones have sufficient capacity to withstand the post-investment capacity increases.

3.2.9 Post - Investment Money Flows

Given that the investments should create an increase in capacity and output, the revenues at each part of the value chain will also see an increase:

Gas Revenues:

$$R_i^{gas,\omega,I} = t^{gas} \sum_{j \in J} g_{ij}^{delivered,\omega,I}$$
$$L_{i,}^{gas,\omega,I} = t^{gas} \sum_{j \in J} g_{ij}^{demand,\omega,I} - g_{ij}^{delivered,\omega,I}$$

Generation Revenues:

$$R_j^{generation,\omega,I} = C_j^{available,\omega,I} t^{capacity} + O_j^{SO,\omega,I} t^{energy}$$
$$L_j^{generation,\omega,I} = t^{energy} \left(O_j^{potential,\omega,I} - O_j^{SO,\omega,I} \right)$$

Transmission Revenues:

$$R_n^{trans,\omega,I} = \sum_n T_n^{rec,\omega,I} + X_n^{rec,\omega,I}$$
$$L_n^{trans,\omega,I} = \sum_n (T_n^{\exp,\omega,I} + X_n^{\exp,\omega,I}) - \ (T_n^{rec,\omega,I} + X_n^{rec,\omega,I})$$

However, as previously mentioned we will not include the money flow analysis in this thesis. We have mentioned it in order to indicate the importance of thinking about the flow of money as well as the flow of energy.

The image below shows a part of the spread sheet in which we have extended the ‘Energy Flows’ analysis in order to show how the investments made in each spending area increases its value.

Generation Capacity Investment ($)	Additional Potential Output MWh	After Investment Potential Output (MWh)	Gas Requirements (MMscf/d)	Additional Gas Requirements (MMscf/d)	Increased Gas Requirements (MMsfc/d)	Implied Gas Supply (MMscf/d)	Budget Allocation to Gas Production	Gas Production Investment ($)	(Additional) Implied Gas Supply MMscf/d	After-Investment Gas Supply (MMscf/d)	Gas Constrained Output MWh
0	0	0	0	0	0	0	0%	0	0	0	0
0	0	5,280	55	0	55	54	0%	5,400,000	1	55	5,160
0	0	0	0	0	0	0	0%	0	0	0	0
441,000,000	7,056	10,416	35	73	108	33	10%	324,000,000	75	108	3,216
450,000,000	7,200	10,800	37	75	112	25	12%	378,000,000	87	112	2,400
0	0	0	0	0	0	0	0%	0	0	0	0
261,100,000	4,178	7,178	31	43	75	25	7%	214,560,000	50	75	2,410
489,000,000	7,824	10,824	31	81	112	27	11%	368,496,000	85	112	2,645
0	0	11,520	120	0	120	28	12%	396,252,000	91	120	2,714
0	0	0	0	0	0	112	0%	0	0	0	10,800
232,500,000	3,720	3,720	0	39	39	0	5%	167,400,000	39	39	0
270,000,000	4,320	4,320	0	45	45	54	0%	0	0	45	5,155
330,000,000	5,280	7,296	21	55	76	19	8%	246,240,000	57	76	1,824
0	0	1,008	10	0	10	5	1%	23,328,000	5	10	490
0	0	0	0	0	0	0	0%	0	0	0	0
0	0	5,376	56	0	56	0	7%	241,920,000	56	56	0
330,000,000	5,280	31,680	274	55	329	123	27%	893,160,000	206	329	11,832

Figure 23: Part of the Energy Flow Spreadsheet Adjusted to Include Investments

3.3 Fixing the Current System: Investment Policies

Our goals in fixing the current system are similar to the overall goals outlined earlier in the chapter. The first goal is to increase the energy delivered ratio. This is equivalent to removing as many of the bottlenecks in the value chain as our budget will allow. The second goal, much like reducing the supply-demand gap, is to increase the generating capacity with the effect of reducing the gap between the installed and available capacities of the power plants. We present one investment policy with which we illustrate the effects of focusing on investing only in increasing generating capacity and three investment policies with which we aim to achieve the first goal of fixing the current system and increasing the energy delivered to the consumers. These policies present investment plans made at the end of 2013, for investments to be made in the year 2014.

3.3.1 Investment Policy 1: The Bad Strategy

Investment Policy 1 (IP1) has been included only for illustrative purposes as it presents an extreme action plan. IP1 uses the whole budget to increase the Available Capacity of the power plants. Given that we are assuming these investment plans are planned for the following year, it means that the Available Capacity of the power plants will be higher, and in some cases, even close to their installed capacities, but there will be no provisions made for gas supply, turbine maintenance or transmission wheeling capacity beyond their current capacities. The results of this investment policy will be discussed in the next chapter, but it is clear that the goal of increasing the ratio of Available Capacity to energy delivered will not be achieved. While this plan seems rather extreme, it is not far from the current generation profile of Nigeria. It appears the country is witnessing a faster rate of increasing Available Capacity than increasing energy delivered to the customer.

3.3.2 Investment Policy 2-4: The Better Strategies

In the other three suggested investment policies, there is a common rule that has been put in place so that the policy stays in line with the goal of increasing the energy delivered ratio. The rule is simply that no investment will be made in increasing the generating capacity unless there is also enough money to increase the gas supply and transmission wheeling capacity to a level that will accommodate the generation capacity increase. Furthermore, when investing in increasing the generation capacity, we assume that the minimum amount that can be invested at a time is the amount of money that is needed to support a generation capacity increase of 1 MW. This could range from $3,000,000 - $3,500,000. Any funds leftover after implementing the investment strategy to the limitations of the budget will added to the gas pipeline security allocation.

3.3.2.1 Investment Policy 2: Fixing the Weakest Link First

In Investment Policy 2 (IP2), we start by investing in the area that causes the biggest capacity loss, which in most cases is the loss caused by the absence of proper turbine maintenance, and we move forward to invest in the parts of the value chain that follow the first investment. Once we have reached the end of the chain, we repeat the process, only this time, the investment is made starting with part of the chain that precedes the first investment we made and we do this recursively until there is no money left. The schematic below provides an illustration of this investment policy.

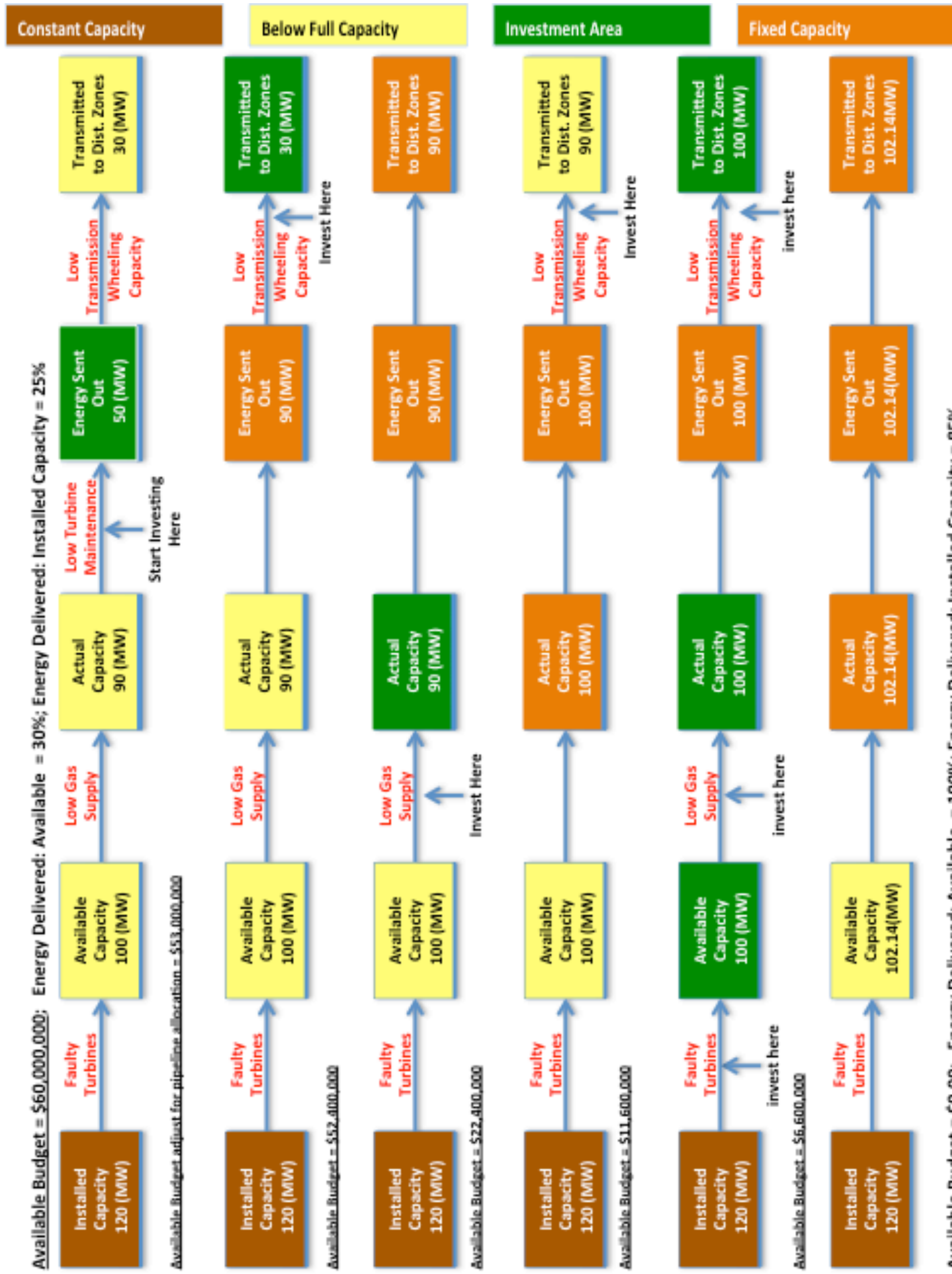


Figure 24: Investment Policy 2 Schematic

3.3.2.2 Investment Policy 3: Investing in Closing the Biggest Gaps

The strategy involved in Investment Policy 3 (IP3), is that we invest in only a few power plants, which are chosen based on their installed capacities. They have the largest installed capacities, but also the biggest gaps between the Installed Capacity and the Available Capacity. This means that, a large portion of their turbines is faulty. The idea behind this investment strategy is that if the focus were on a few power plants with large Installed Capacity, the potential for expanding this capacity would be huge. However, in closing the generation capacity gap, there is also the added expense of gas supply and transmission wheeling capacity to consider. Since these are added expenses to increasing the generation capacity, it is likely that not all of the Installed Capacity will be recovered. The results of Investment Policy 3 will be shown with that of the other three investment policies in the next chapter.

3.3.2.3 Investment Policy 4: Investing in one Regional Network

In Investment Policy 4 (IP4), we shrink the current system into the ten plants connected to the ELPS network. This investment policy only invests in the ELPS network and aims to increase the energy generated from the plants connected to that network, the gas supply levels in that network and also ensure the transmission wheeling capacity is on par with the electricity that would be generated and sent out after the investments have been made. The motivation for this investment strategy is simply that if the budget would not allow for the whole system to be fixed, it might be more effective to focus all the funds into fixing one part of the system. That way, we can try to fix the system on a regional basis, with the energy delivered ratio still remaining high.

3.3.3 Sample Realizations

The four investment policies need to be applied to a generation profile. Given that the generation profile is stochastic, we introduced four sample realizations of the generation profile data. These sample realizations include:

$$\omega = \{1,2,3,4\}$$

- **Sample Realization 1 (SR1)**: This is the generation profile that averages all the data over the fifty-two weeks given.
- **Sample Realization 2 (SR2)**: This is day in which the lowest Energy Sent Out occurs- 10^{h} April 2013
- **Sample Realization 3 (SR3)**: This is the day in which we see the lowest Actual Generating Capacity- 14^{th} August 2013
- **Sample Realization 4 (SR4)**: This is the day in which we have the lowest Available Capacity – 13^{th} November 2013

From SR1, we get a sense of what we can expect on average as a generating profile. However, it is also important to understand what happens in the more extreme cases. This is why we include the other three sample realizations; the focus is on the effects of investments in the worst-case scenarios for each type of capacity mentioned above. The lowest sent out energy, although other factors contribute to it, could have been caused by the low efficiency of the operating turbines. Similarly, the lowest actual generating capacity points to low levels of gas supply, while the lowest Available Capacity, indicates instances of more failed turbines that normal. Given the varied nature of the generation profiles of these four sample realizations, we want to compare the performance of each of the investment policies in each of the different scenarios. This comparison is necessary because it can indicate whether or not different generation profiles do better with a particular investment strategy, or whether there is a robust investment strategy that consistently produces the best results regardless of the initial generation profile. As such, we compare a total of four sets of four investment strategies.

3.3.4 Performance Metrics

In order to compare the investment strategies, we need performance indicators with which to compare them. These performance indicators have been created based on the goal of ensuring that as much as is possible, all the generated energy is delivered to the final customer and that the gap between the Available Capacity and the Installed Capacity of the power plants in the system is decreased.

1. Progress to Increasing Delivered Energy

   In order to measure how well the investment plan improves upon the system's performance in this area, we compute the following ratios:

   - Actual Capacity : Available Capacity – This tracks the gas supply performance
   - Energy Sent Out: Available Capacity – This tracks the performance indicator above and the turbine maintenance performance
   - Energy Delivered to Distribution Zones: Available Capacity – This tracks the two performance indicators mentioned above and the transmission wheeling capacity
   - Actual Delivered Energy – Although this is not a ratio, we want to see the absolute equivalent capacity that is being delivered to the distribution zones. Beyond the percentages, it is important that we know what the end product actually is.

2. Progress to Reclaiming Capacity

   With this indicator we are able to measure the progress that was made in increasing Available Capacity while maintaining the energy delivered ratio

   - Available Capacity: Installed Capacity – This tells us how much of the Installed Capacity has been reclaimed
   - Energy Sent Out: Installed Capacity – This tells us how much is actually being generated, relative to the Installed Capacity
   - Energy Delivered to the Distribution Zone: Installed Capacity -This tells us how much of the Installed Capacity is getting delivered to the customers.

The first of these three is most important because it offers a direct evaluation of the performance of the Available Capacity, as opposed to the other two that are constrained by the losses in the parts of the value chain preceding them. However, it is still informative to know the difference between what is supposed to be generated or distributed, if everything was in working order.

At this point we have fully established the goals, set-up and methods of the investment policies. In the next chapter, we present the results of each of the four policies, under each of the four scenarios.

4 Chapter 4: Investment Policy Results

In the previous chapter, we defined our investment goals and introduced four investment policies and the four scenarios in which they would be implemented. This chapter presents the results of those policy implementations. In order for us to assess the investment policies on the spending areas that are within their control, we have decided to exclude the pipeline vandalizations from our analysis from this point, as we will need a more complex framework to fully analyze the effects of investments in this area. This is because the control of pipeline vandalization is a social issue as well as a financial one. We have included the pipeline vandalism in the analysis thus far for the sake of completeness. Nonetheless, we make allocations to gas pipeline security in each investment policy, as it remains an important issue in the sector, just not one that can be 'fixed' in purely financial terms. At this point, the emphasis is on establishing the best use of the budget by focusing on the spending areas in which we can directly influence the outcomes.

4.1 Investment Policy 1

IP1 has a simple strategy- invest all the money in increasing the Available Capacity of all the power plants. Given that this strategy does nothing to reduce the capacity constraints and losses, it is only able to increase the Installed Capacity but not the amount of energy delivered to the distribution zones.

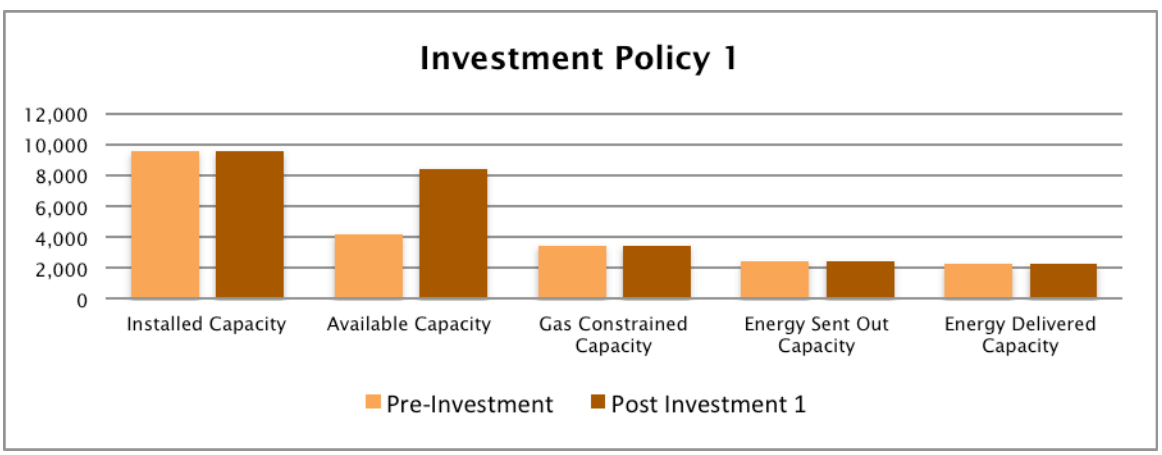


Figure 25: Illustration of the Effects of IP1

The chart above illustrates the effect of IP1 on SR1. Although the gap between the installed and available capacities has decreased considerably, there is the added problem of stranded generation capacity. This is especially so because not all the Available Capacity was being delivered to the distribution zones before the investment took place. IP1 appears to be an extreme example, but it does well in illustrating that increasing the available generation capacity before sufficient gas supply and transmission infrastructure is in place, does little to increase the energy delivered ratio. It represents the current state of the Nigerian Power Sector, where large investments have been made in generation capacity before the gas supply and transmission network have been fully attended to. In IP1, the distribution zones will have to wait till the next round of financing where investments can be made in the other areas of the value chain before they can experience the benefits of the generation capacity investment. The other three investment plans show that this not need be the case if we focus on the primary goal of increasing the energy delivered ratio. Given that the effects of IP1 do not go beyond this, we will not be discussing it further.

4.2 Sample Realization (SR) 1: The Average Generation Profile

SR1 assumes that the sample realization of the generation profile is simply the expectation of all the generation profiles of the seventeen power plants over the fifty-two week period. The figure below shows the generation profile of SR1.

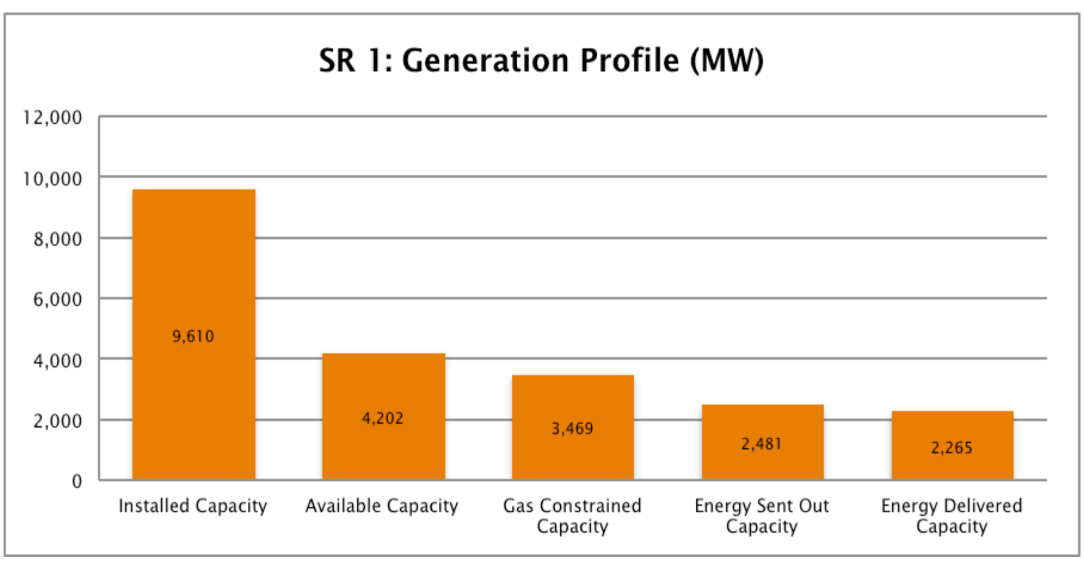


Figure 26: Generation Profile of SR1

Apart from the large gap between the installed and available capacities, the biggest source of energy loss seems to be during the energy generation itself, pointing to a large portion of lost capacity due to a lack of turbine maintenance. This corresponds to what we learnt in the second chapter, where we analyzed the generation profiles and capacity losses of the individual power plants. In this pre-investment stage of SR1, only fifty-four percent of the Available Capacity is delivered to the distribution zones.

4.2.1 Investment Policy 2 in SR1

The following charts illustrate the budget allocation recommended by IP2 and its performance in SR1.

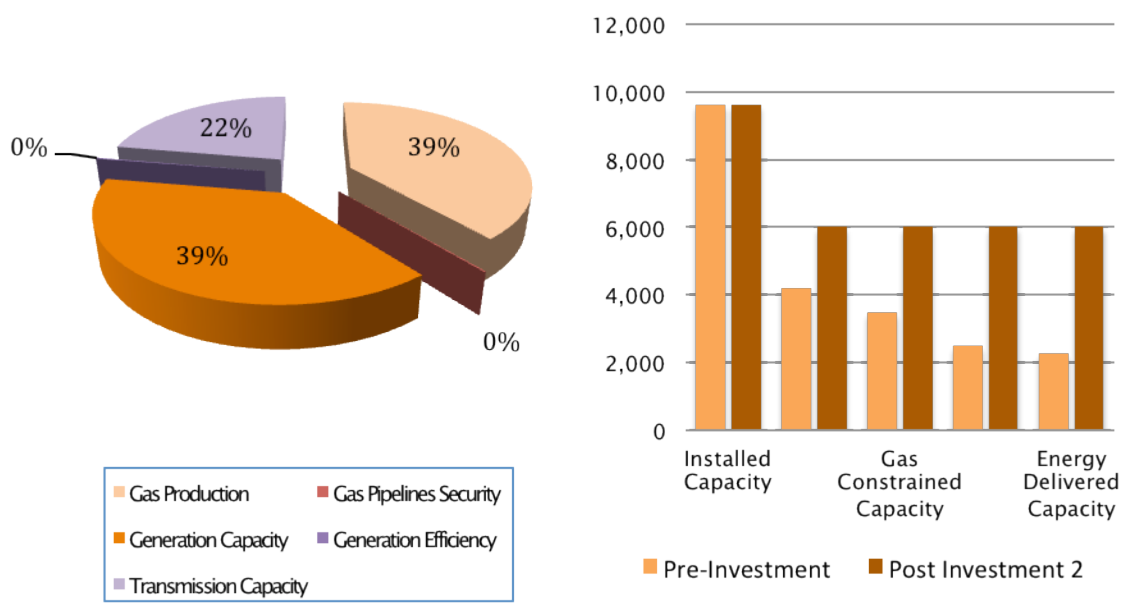


Figure 27: Budget Allocation and Results of IP2 in SR1

IP2 is the only one of the investment policies that invests in the supply chain of every power plant. As was described in the previous chapter, IP2 plans its budget allocation by starting with removing the capacity losses from the point at which the loss is the highest, that is, between the Available Capacity and the Energy Sent Out. However, as per the universal rule, whenever IP2 fixes one part of the chain, the policy ensures that the next part of the chain is able to accept the increased energy, as far as the budget will allow. This is why the distribution zones receive all the electricity that is expected from the Available Capacity- all the bottlenecks have been fixed to accommodate the increased available generation capacity. However, because IP2 focuses on the parts of the chain that keep the energy flowing and not on increasing the capacity, the Available Capacity is only sixty-two percent of the Installed Capacity. Nonetheless, it delivers more energy than IP1 does, which has a post-investment Available Capacity that is eighty-eight percent of the Installed Capacity.

4.2.2 Investment Policy 3 in SR1

IP3 focuses on investing in the power plants with the largest capacities, but the biggest gaps between the installed and available capacities, the budget allocation and results are presented below.

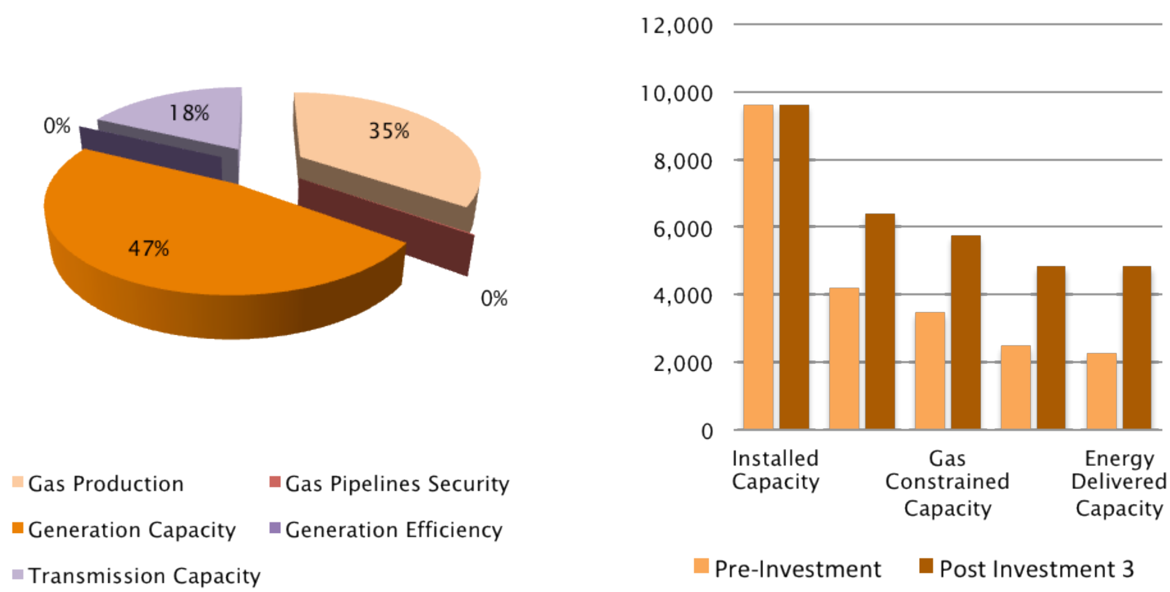


Figure 28: Budget Allocation and Results of IP3 in SR1

While IP3 regains more of the Installed Capacity than IP2 does in SR1, it also delivers a smaller percentage of the Available Capacity to the distribution zones. The smaller budget allocations to gas production and transmission capacity explain this occurrence. It is important to notice a few things when comparing IP3 and IP2 results:

- The extra generating capacity gained by IP3 is only marginally larger than that of IP2
- The energy delivered by IP3 is smaller than that of IP2 and we can see that generation capacity losses are still a problem, one that has been eradicated in IP2.
- Given that the budget of IP2 and IP3 are the same, but IP2 delivers more energy to the distribution zone, even though it has less Available Capacity, we can conclude that IP2 is better than IP3 in SR1.

4.2.3 Investment Policy 4 in SR1

The difference between IP4 and the other two investment policies is that it invests in more power plants than IP3, but fewer power plants than IP2; it invests in the supply chain of the power plants in the ELPS network, which consists of ten power plants. Thus we expect that IP4 would perform slightly better than IP3, but not as well as IP2.

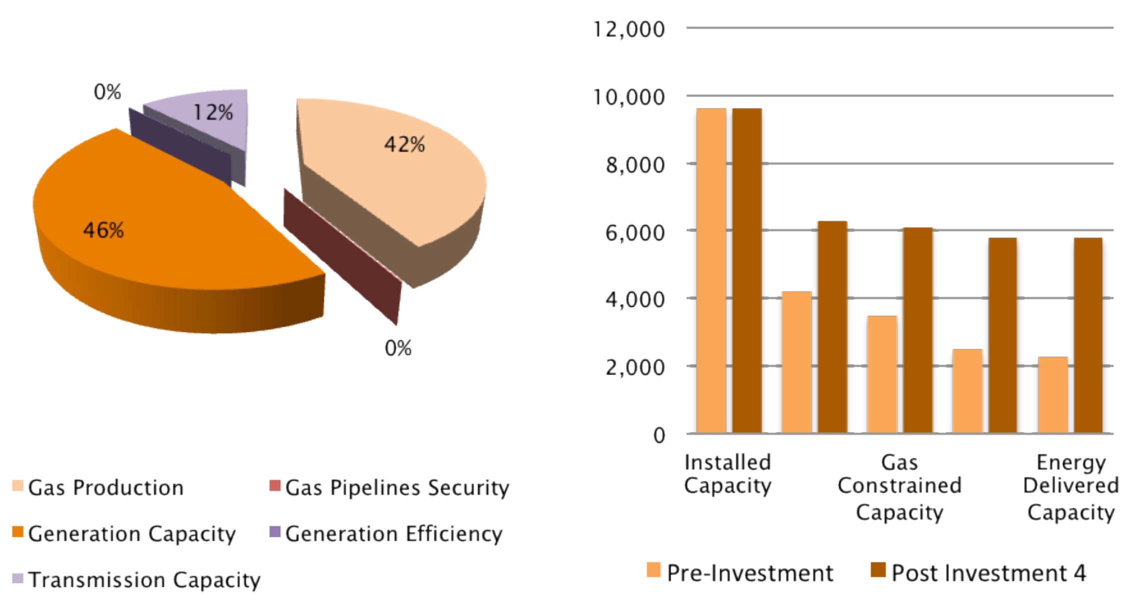
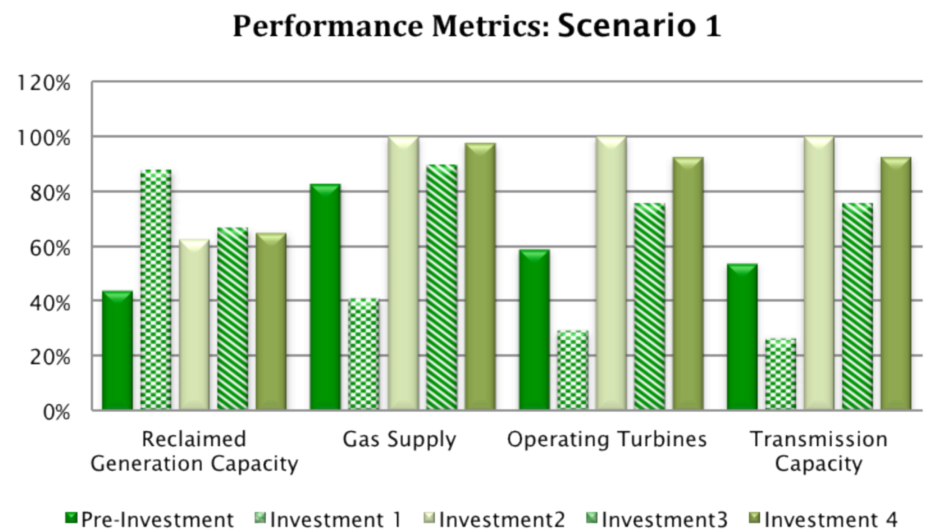


Figure 29: Budget Allocation and Results of IP4 in SR1

The results chart above shows that in terms of increasing Available Capacity, IP4 is only slightly lower than IP3, but higher than IP2. However, its level of energy delivery is closer to that of IP2 than IP3, meaning that it delivers more energy to the distribution zones than IP3 does, but less than IP2. The following charts compare the three investment plans and their performance metrics more closely.



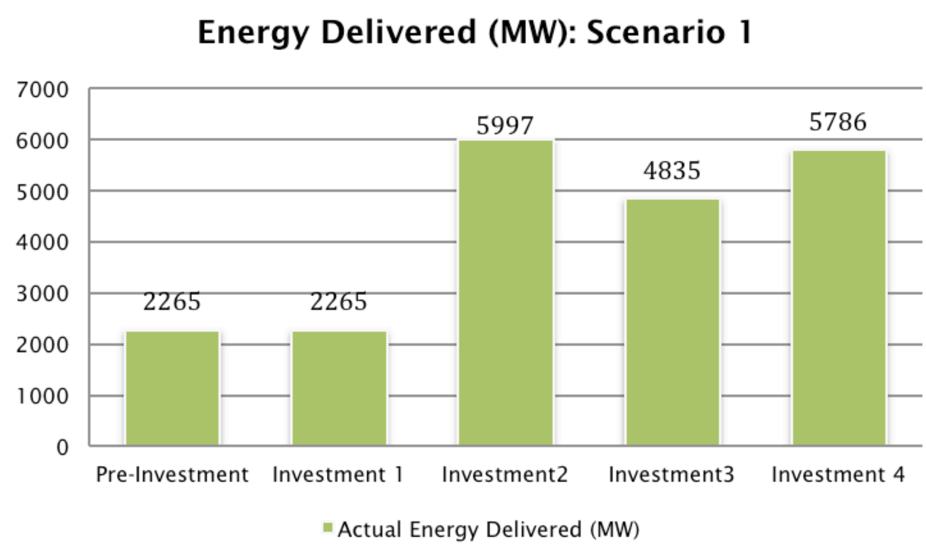


Figure 30: Comparison of Investment Policies in SR1

Given that each IP uses the same budget of $7,000,000,000 and IP2 delivers the most energy and loses none of its capacity in the energy flow process, it is the best strategy for this particular scenario. However, the results are close enough between IP2 and IP4 for us to use either of them in the event that there are other factors to consider. At this point, we can conclude from the extreme effects of IP1, and the more subtle differences between IP2, IP3 and IP4, that the tradeoff when making investments is between making allocations to increase the generating capacity and allocations to the rest of the chain: gas production and transmission wheeling capacity. Nonetheless, these results are for SR1, we need to see how the three IPs perform under different pre-investment generation profiles[15].

4.3 Sample Realization 2: The Lowest Turbine Performance

SR2 has a generation profile that is constrained by both the operations of the turbines and the transmission wheeling capacity. The turbine inefficiencies are a major source of capacity loss. This fact is made clearer when we consider that the Gas Constrained Capacity (Actual Capacity) in SR2 is higher than that of SR1 but the energy sent out is considerably lower in SR2. The loss is made even worse by the transmission capacity constraints, which have stranded over half of all the energy that has been sent out.

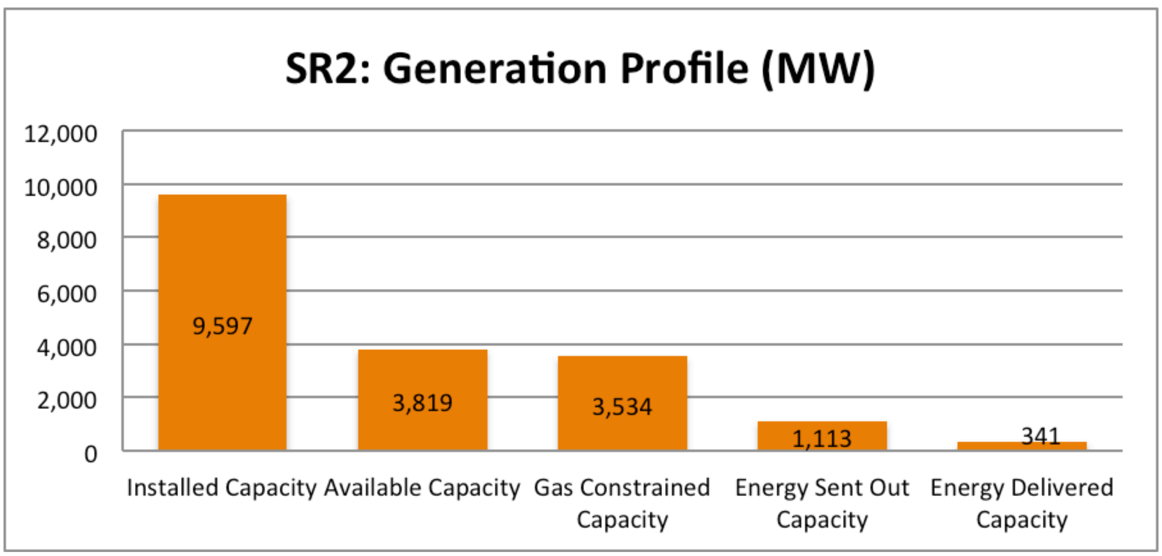
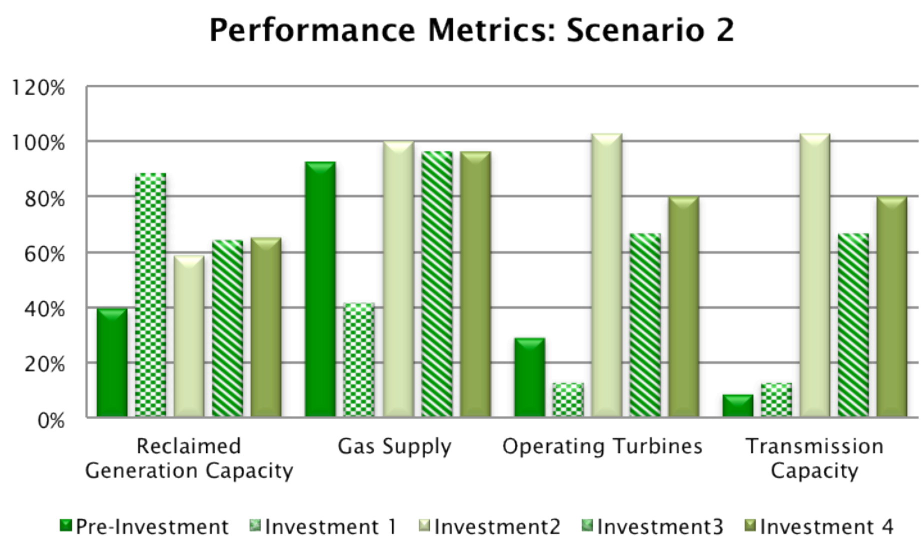


Figure 31: Generation Profile of SR2

[15] The charts showing the budget allocations and results of the investment policies in the three scenarios to follow can be found in the appendix.

The charts below compare the investment policies in SR2.



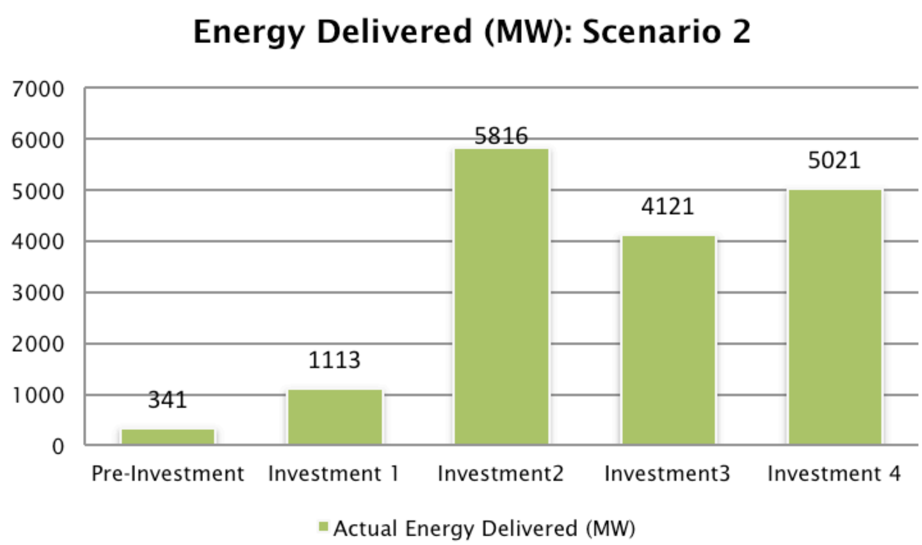


Figure 32: Comparison of Investment Policies in SR2

While in SR1, the difference between IP2 and IP4 is small enough to choose either and be comfortable with the results, in SR2, the superiority of IP2 over IP3 and IP4 is very clear. Perhaps this suggests that in situations whereby the generation capacity loss is disproportionately high near the end of the chain, it is best to use IP2. The Available Capacity achieved is similar in all the Investment Policies, but the energy delivered is markedly higher in the implementation of IP2.

4.4 Sample Realization 3: The Lowest Actual Generating Capability

SR3 is the generation profile with the lowest Gas Constrained Capacity in the year:

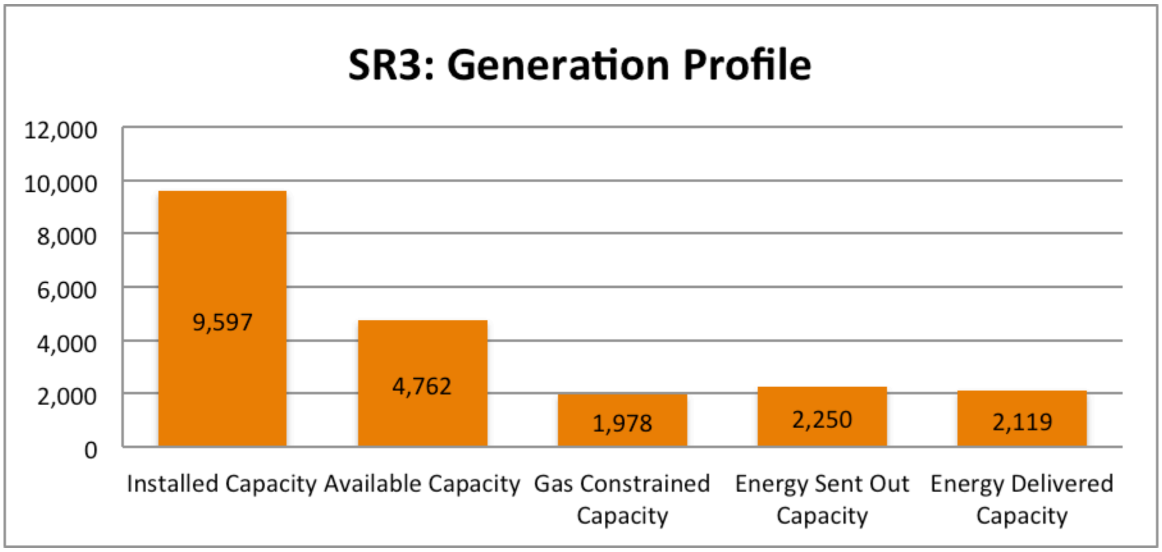
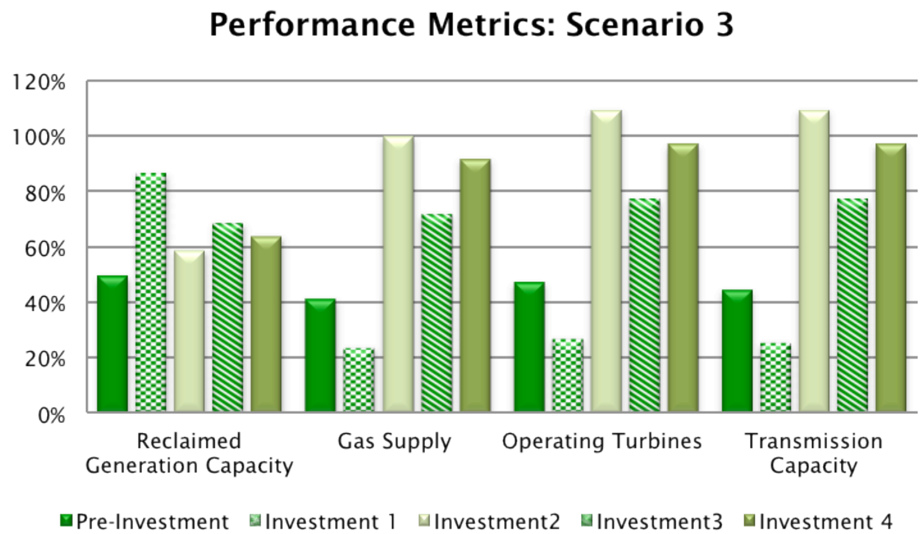


Figure 33: Generation Profile of SR3

Unlike the generation profile of SR2, the Energy Sent Out in SR3 is not the major cause of the lost capacity, but the gas supply constraint is. We also notice that the energy that is generated and delivered is higher than the gas constrained capacity of the power plant[16]. The evidence of the constrained gas supply is in the fact that the budget allocates the most money to gas production, higher than has been allocated in all the previous scenarios thus far[17]. The results of the implementation of the investment policies in SR2 suggested that the difference in the performance between IP2 and IP4 became clearer because the energy loss occurred at a stage near the end of the energy flow. However, similar results in SR3 suggest otherwise. In SR3, the generation loss occurs from gas production constraints, which is arguably the beginning of the energy flow. So we cannot conclude that the area in which the most energy is lost determines the performance of IP2 relative to IP4. The chart below compares the results of the investment policies in SR3.

[16] It is not impossible that the capacity of the Energy Sent Out is higher than the Gas Constraint Capacity because of the variations of energy levels in the course of the day.
[17] See figures 53, 66 in Appendix



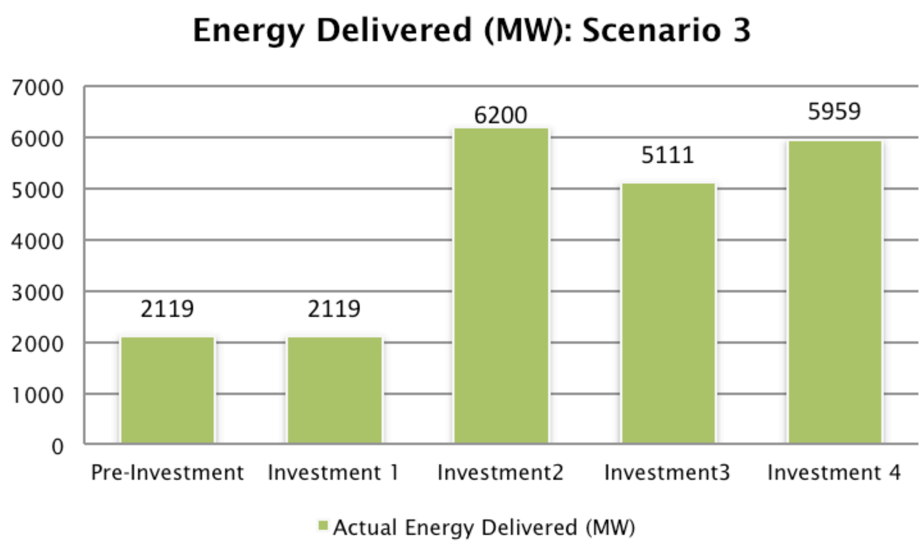


Figure 34: Comparison of Investment Policies in SR3

At this point, we can introduce the notion that IP2 performs well over the three scenarios because it is a robust investment policy. However, in order to test that claim further, we shall examine the performances of these three investment plants under sample realization 4.

4.5 Sample Realization 4: The Lowest Available Generating Capacity

In SR4, we have the generation profile of the week with the lowest Available Capacity.

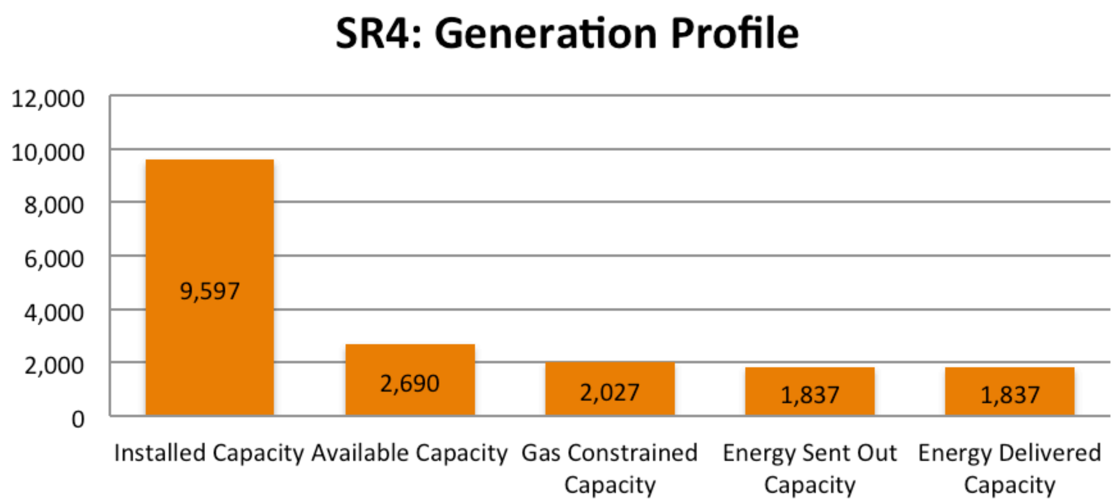
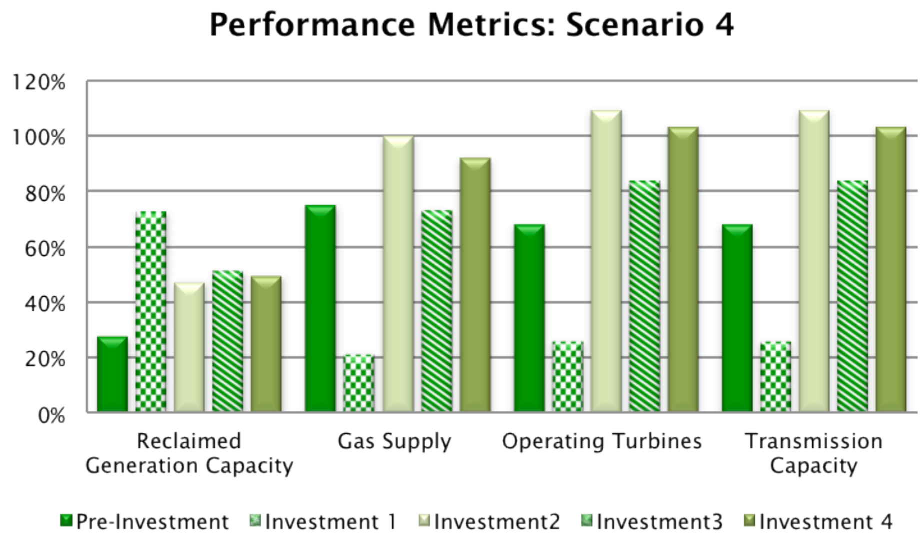


Figure 35: Generation Profile of SR4

The generation profile of SR4 indicates that the loss between the Installed and Available Capacity is the greatest capacity loss in the value chain. This is not different from what we have seen in all the other sample realizations. However, the distinguishing factor here is that the capacity lost in the following parts of the chain is relatively small compared to the other scenarios, where the gap between Available Capacity and Energy Sent Out could be as large as 2000MW. The results over all investment policies in SR4 indicate that IP2 is still the best investment policy of the three. This is illustrated by the charts below.



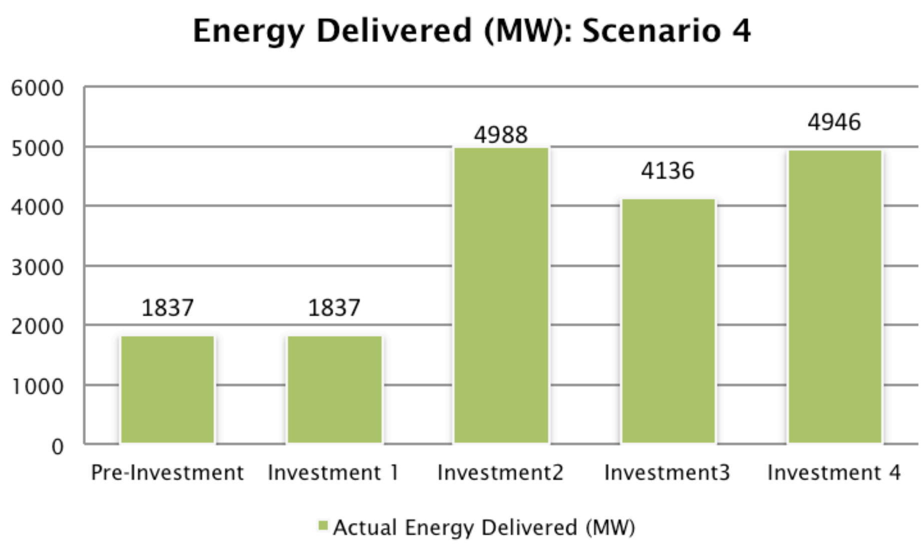


Figure 36: Comparison of Investment Policies in SR4

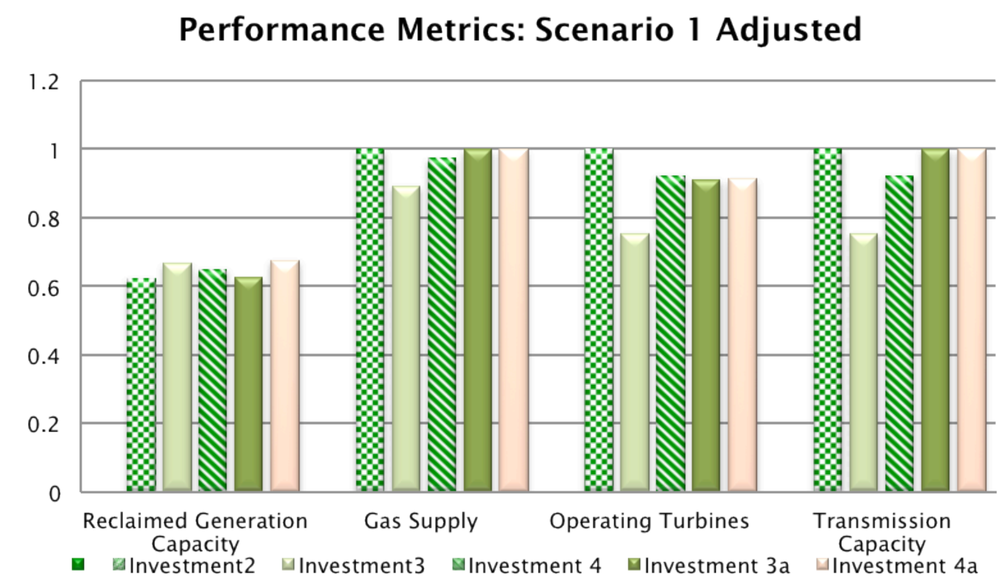
As in the case of SR1, the difference between the performance of IP2 and IP4 in SR4 is similar enough to consider choosing IP4, as the difference between the two Investment Policies is only about three percent. However, given the fact that each IP uses up the same budget and IP2 consistently delivers more energy to the customer, even with a lower Available Capacity in all cases, it is fair to conclude that IP2 is the most robust and efficient use of the budget allocated to fixing the system. The benefit of IP2 is that it plans its budget by working recursively backwards in order to make the decision on how much of its budget can be spent on increasing the Available Capacity of the whole system, while delivering the entirety of whatever generating capacity becomes available[18]. Although the other two investment policies do not add any new capacity to the system without ensuring that the gas supply and transmission wheeling capacity are able to take it on without any capacity loss, where they fail is that they ignore the generation losses in the other power plants that are outside their focus. IP4 performs relatively well in most cases but it is possible that it does so because over half of the power plants in this study are part of the ELPS Network, so the budget is more spread across the whole system than in the case of IP3.

Hence, there is a suggestion that it might be a better strategy to 'fix' the whole system before any capacity is reclaimed, than to focus on fixing the supply chains of a few specific power plants, as is the case in IP3. We can test this suggestion on Scenario 1 and see whether it produces better results than IP3 and IP4 do.

[18] It is understood that not all the energy will be delivered because of the heat loss in any mechanical system. However, we emphasize a perfect delivery in order to show the effects of budgeting for the outcomes of the system that we can control.

4.6 Adjusting IP3 and IP4

In the new versions of IP3 and IP4, we fix the bottlenecks in the current system first. After this has been completed, we focus on the prescribed power plants for IP3 and IP4 respectively. Given the consistence in the performance of IP2, we are testing the notion that it is superior to IP3 and IP4 because they both ignore the bottlenecks of the 'other' power plants. On the other hand, IP2 first tries to fix the bottlenecks in the whole system and then it begins to expand the Available Capacity over as many plants as possible while still ensuring that all the expected energy from the Available Capacity is delivered to the distribution zones. The charts below illustrate the results of this adjustment under scenario 1. We can reasonably expect similar results in the other scenarios. So we do not present them here.



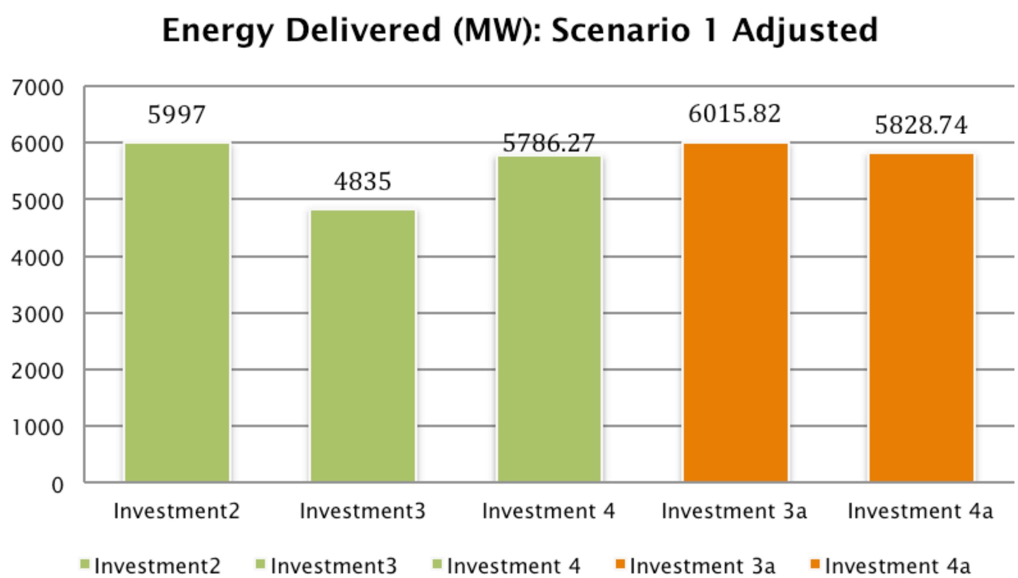


Figure 37: Comparing Results of the Adjusted Investment Policies

These results show that adjusting IP3 and IP4 so that they become, in a sense, subsets of IP2, positively transforms the investment policies. The performance metrics illustrated in the Performance Metrics chart above, shows that in each part of the value chain, the output is maximum for IP3a and IP4a as it is in IP2. This was not the case for IP3 and IP4. Furthermore, we witness an increase in energy delivered, especially in the case of IP3. This is not surprising because the IP3 budget is focused on 3-4 of the 17 power plants. Understandably, the increase is less drastic in the case of IP4a because the power plants in the ELPS Network cover a large part of the system.

Given the illustrations above, we can develop a more flexible investment policy. In addition to the rule that no generation capacity expansions should take place without simultaneously ensuring the ability of the gas supply and transmission network capacity to accommodate this expansion, we will add that before increasing the Available Capacity in the first place, all the bottlenecks in the system must be eradicated. This is essentially the same rule from the previous chapter regarding building new power plants but now we also make it a rule for reclaiming lost generation capacity of old power plants. Given this new rule, we are no longer restricted to implementing IP2 specifically, but can alter it to have a more focused area of investment, as is the case in IP3a and IP4a, only with the caveat that the rules above must be followed.

Essentially, the best Investment Policy is one that frees up the stranded capacity before it adds or reclaims any new capacity to the system. Such an Investment Policy ensures that the electricity consumers feel the effects of the budget implementation through higher levels of electricity supply.

5 Chapter 5: Conclusion

The Nigerian Power Sector is seeing major investments in its generation capacity expansions. These investments are being made in order to close the wide electricity supply-demand gap, which has been a major issue in the country for decades. In this thesis, we have closely examined and analyzed Nigeria's generation profile over the course of 2013. From this analysis, we identified the major bottlenecks through which the electricity delivered to the final consumer is significantly reduced from the original available capacity. In view of the analysis, we propose that the first and most crucial goal while making investments in the Power Sector should not be to increase the available capacity in the country, but rather to ensure firstly, that all of the capacity that is already available, is delivered to the end users. This is a more challenging and involved task than increasing the available capacity because it requires both the expansion of natural gas production and supply infrastructure and the expansion of the transmission network wheeling capacity. However, the alternative of focusing on building a number of power plants or buying new turbines for existing ones before restoring the rest of the value chain to their required capacities, is at risk of having an extended period of unusable generation capacity. Given the time value of money, this is a waste.

In order to illustrate that our goal is indeed the crucial first step to efficiently reducing the supply-demand gap in the Power Sector, we compared investment policies that adhered to this goal and one that did not. In the case of the investment policy that used up the given budget to increase the available capacity without simultaneously considering the required capacity increases in the rest of the value chain, there was an increase in available capacity, but none of it was delivered to the consumer because the bottlenecks were still present in the system. Conversely, the result of the investment policies that had this goal as its driving force, was that even with a lower available capacity than the previous investment policy created, the energy delivered to the final consumer was higher and stranded capacity minimal. This is because all the bottlenecks in the system had been eliminated, allowing a free flow of electricity with no major losses occurring along the value chain. Consequently, our final recommendation is that in order to effectively increase the supply of electricity in the country, there should be no investment in increasing the available generating capacity until there are sufficient funds to simultaneously increase the gas supply and transmission wheeling capacity to the extent that none of the available capacity would be stranded. Instead, whatever funds are available should be applied to removing the current bottlenecks in the system.

5.1 Limitations

While we believe that this thesis has made a clear recommendation using the results of its analysis, we also acknowledge that in performing the analysis, there have been some limitations which we have outlined below and made suggestions for improvement.

5.1.1 Limitations in Energy Flow Analysis

- The major limitation in our energy flow analysis appears in the way we model the transmission of electricity from power plant to transmission station to the distribution zones. We assume that the power plants deliver to either Lagos or Benin and that Benin then supplies the other transmission stations. While this is true, it is not the full picture. It would be more useful to have a clearer sense of the transmission flow so that the appropriate line limits may be applied in order to see where the system really needs investments. Nonetheless, the thought process behind the model can easily be adjusted to accommodate a more detailed transmission network flow.
- In the course of our analysis, we had limited access to information on the gas supply to the power plants so all the information we have reported about gas supply is inferred

from the Actual Capacity of each power plant. While this is a reasonable assumption to make, it might be overstating the gas supply constraints in some plants and understating it in others. A good replacement would be to input the actual amount of gas that is supplied, or at least a very close estimate. This way, we can compare it to the energy that is sent out and develop a fuller picture of the portion of the constraints that are caused by gas and the portion of the constraints that are caused by turbine operational issues.

- As mentioned in the thesis, we did not develop a full picture of the financial flows within the sector. This is an important omission as there can be no flow of energy without the flow of money. Although we recognized the different tariffs and the revenues made based on output, we could have gone further to understand the structure of the contracts between the parties in order to develop a detailed analysis of the financial flows. This way we could also use the financial benefits as an additional performance metric of the investment policies.

5.1.2 Limitations in Analyzing the Effects of Investments

- A major part of evaluating the investment policies is based on the value that can be created within a given budget. However, in our model the prices of each of the spending areas are not the true values and we are not sure how close to the true values they really are. While the prices will not significantly change the results of the comparative analysis of the investment policies, they will provide more information on what exactly is feasible within a given budget. This would help us make more informed comparative value judgments of the investment policies. Fortunately, this can easily be fixed by replacing the estimates in the model by their true values, or at least with better estimates and then perform the same analysis.

5.1.3 Limitations in replicating the structure of the NESI

The analysis performed in this thesis makes the assumption that the investments in the NESI are made by a central body. However, this is not the case as the gas suppliers are independent of the generation companies, which are independent of the Transmission Company of Nigeria. In this vein, it will be more difficult to make central investment decisions as have been illustrated in this thesis. Nonetheless, this limitation can also be seen as an implicit recommendation for the parties involved in the Power Sector to have a more coordinated and cooperative relationship, whereby even though each part makes its own investment decisions, it makes them with the full consideration of the other parts of the sector.

5.2 Further Research and Analysis

An important area of further analysis for this thesis topic is the inclusion of a time dimension in our model. We would introduce the time lags involved in raising the funds for the required investments and waiting for the completion of the capacity expansions after the investments have been made. Including a time dimension would provide a robust means of testing the performance of the Investment Policies suggested in the thesis, as it will necessarily involve the evaluation of those policies on the basis of their abilities to plan ahead and their energy delivery performance over time. Furthermore, with the addition of a full analysis of the financial flows, we would also be able to determine how quickly the implementation of the policies earns the original investment back. Aside from presenting an interesting problem to model, it will also depict a more realistic version of the analysis that could easily be adopted by the key decision makers in the sector.

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7 Appendix

Distribution of Generation Profiles of Power Plants

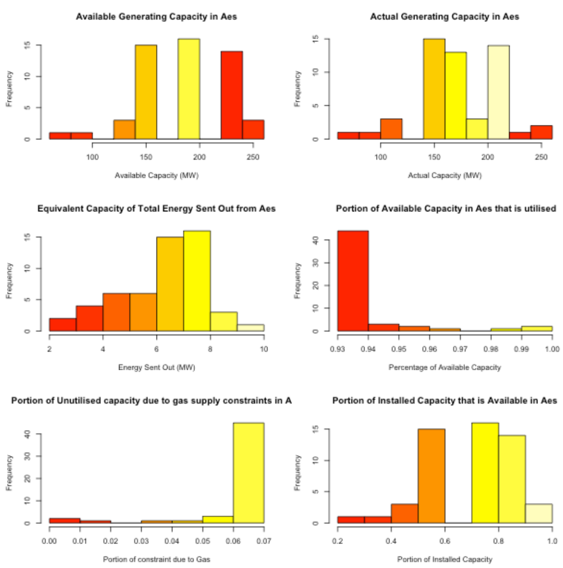

Figure 39: A.E.S Generation Profile

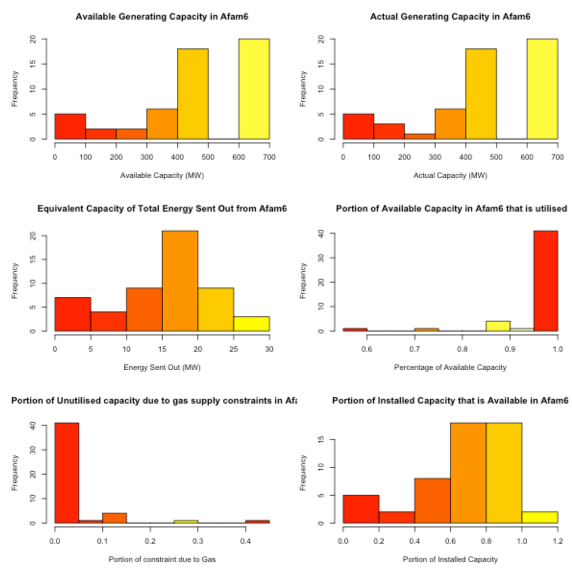

Figure 38: Generation Profile of Afam VI

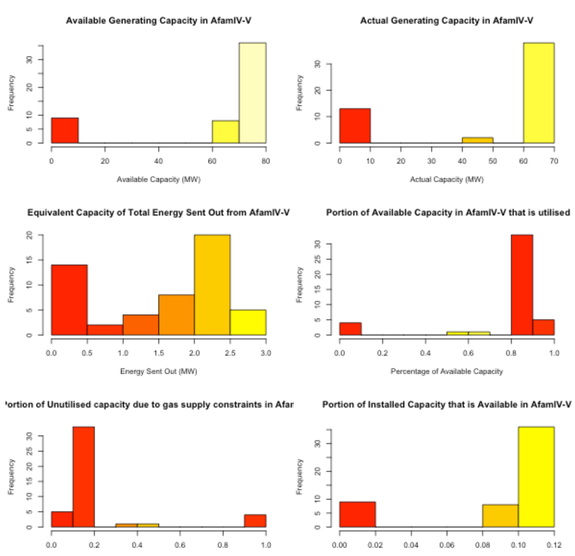

Figure 41: Generation Profile of Afam IV-V

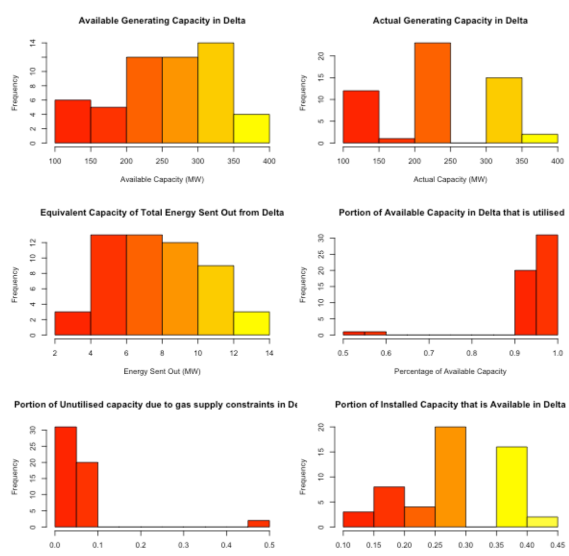

Figure 40: Generation Profile of Delta

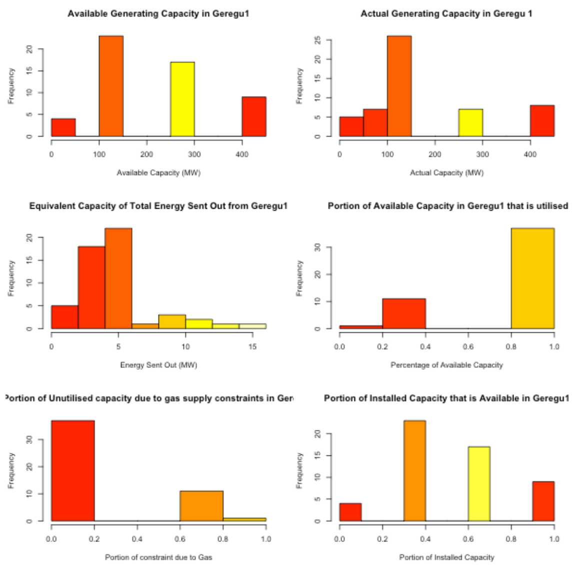

Figure 42: Generation Profile of Geregu 1

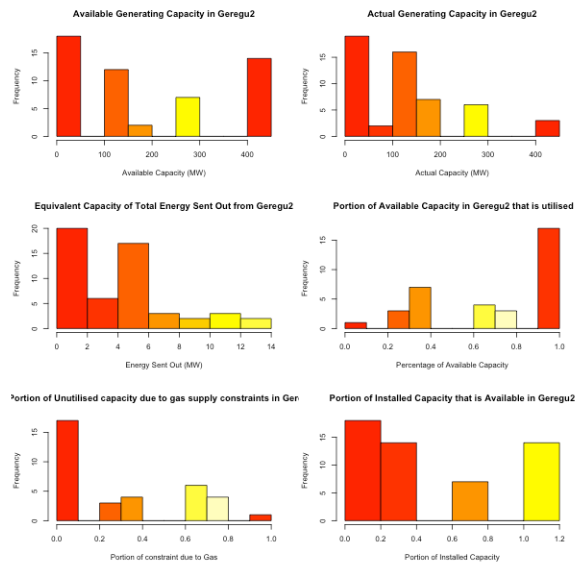

Figure 43: Generation Profile of Geregu 2

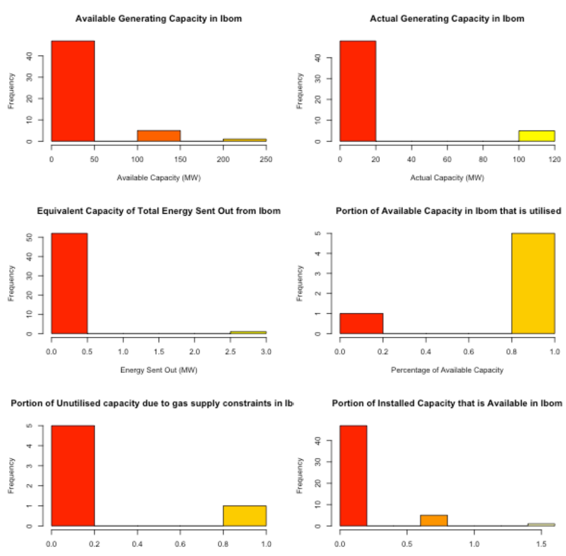

Figure 45: Generation Profile of Ibom

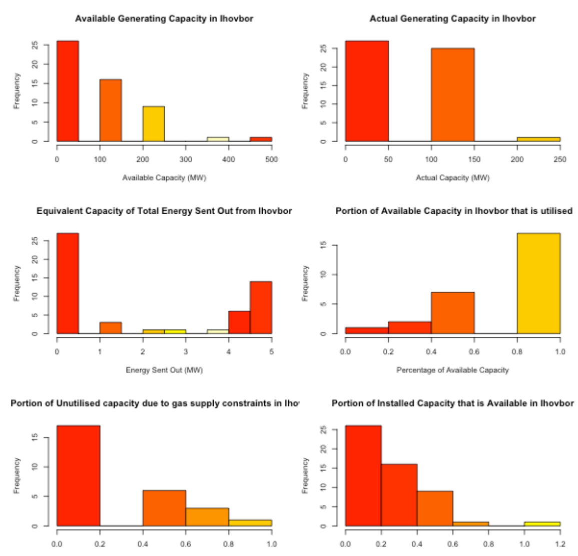

Figure 44: Generation Profile of Ihovbor

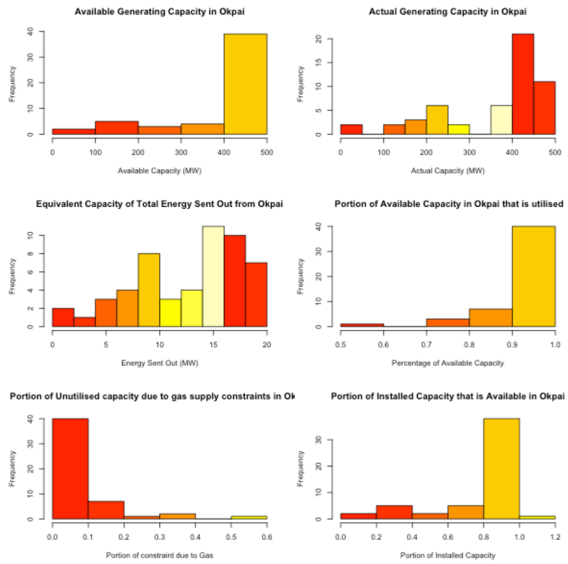

Figure 47: Generation Profile of Okpai

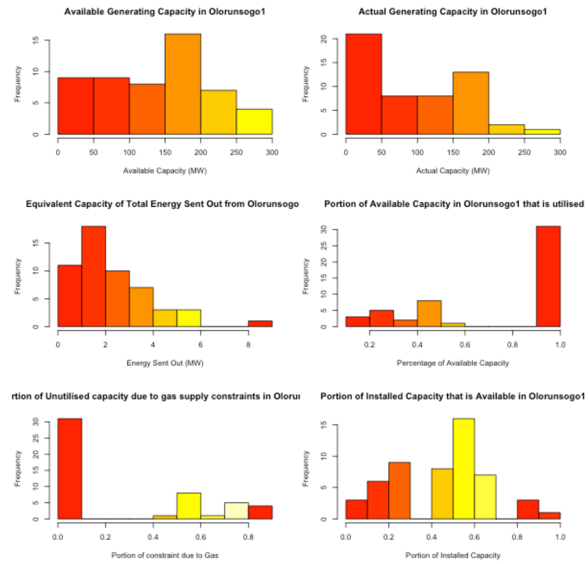

Figure 46: Generation Profile of Olorunsogo1

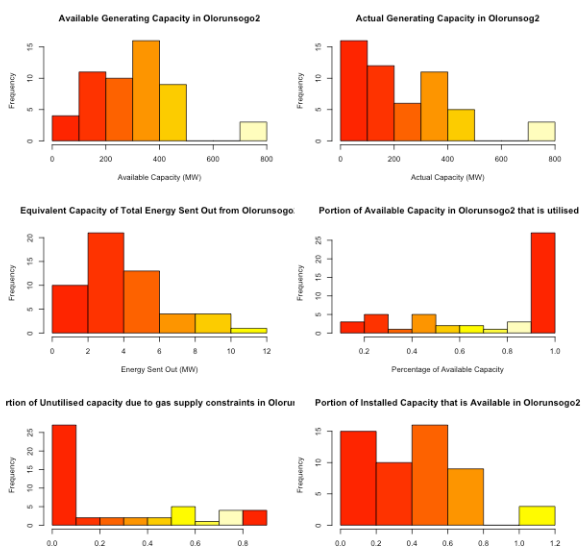

Figure 49: Generation Profile of Olorunsogo2

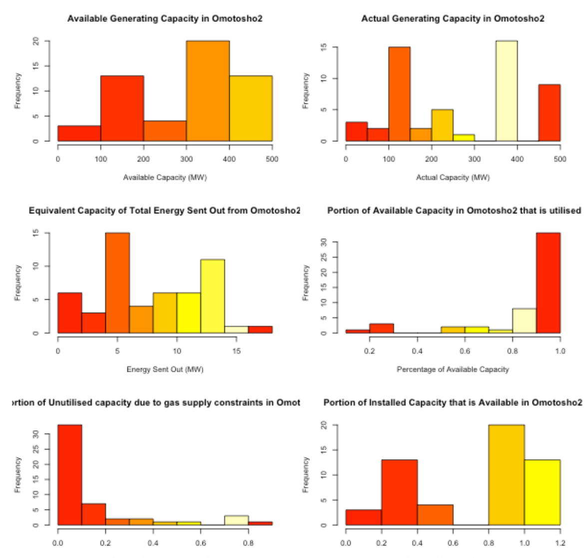

Figure 48: Generation Profile of Omotosho2

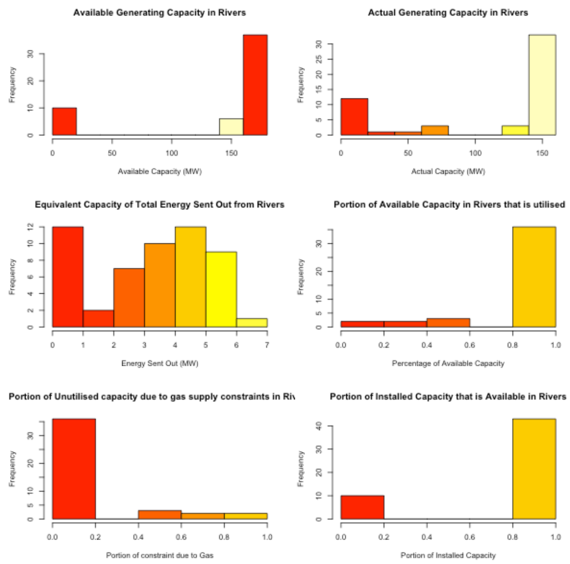

Figure 51: Generation Profile of Rivers

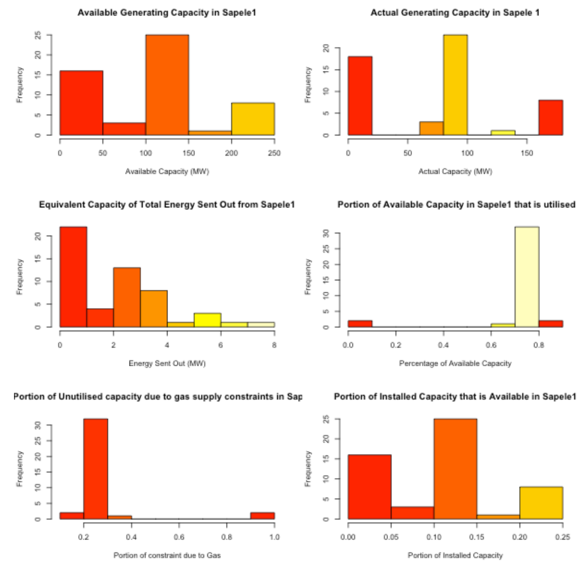

Figure 52: Generation Profile of Sapele1

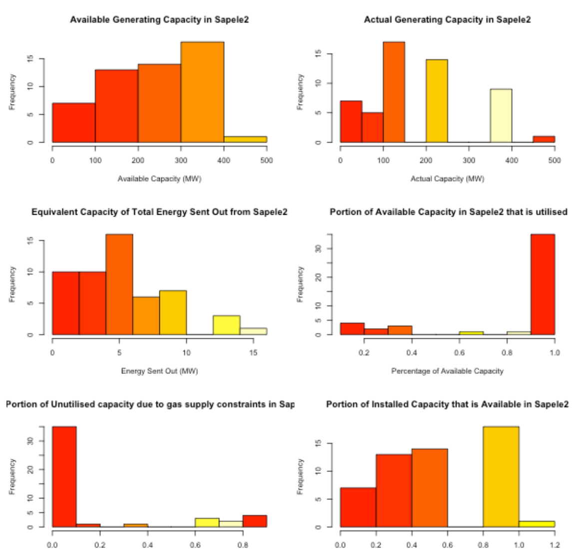

Figure 53: Generation Profile of Sapele2

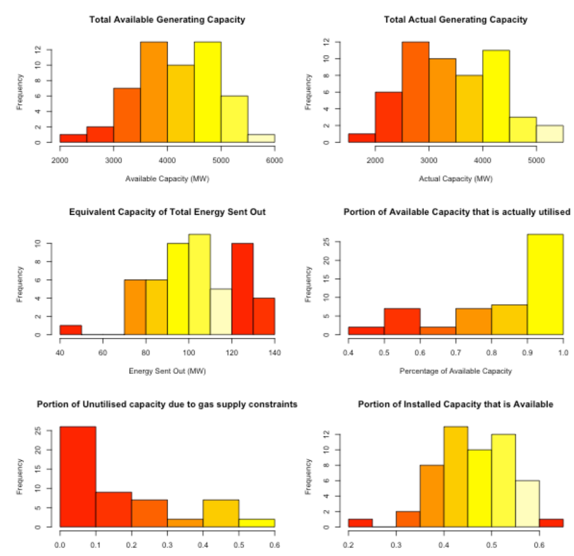

Figure 50: Total Generation Profile

Charts of Budget Allocations and Results of Investment Policies

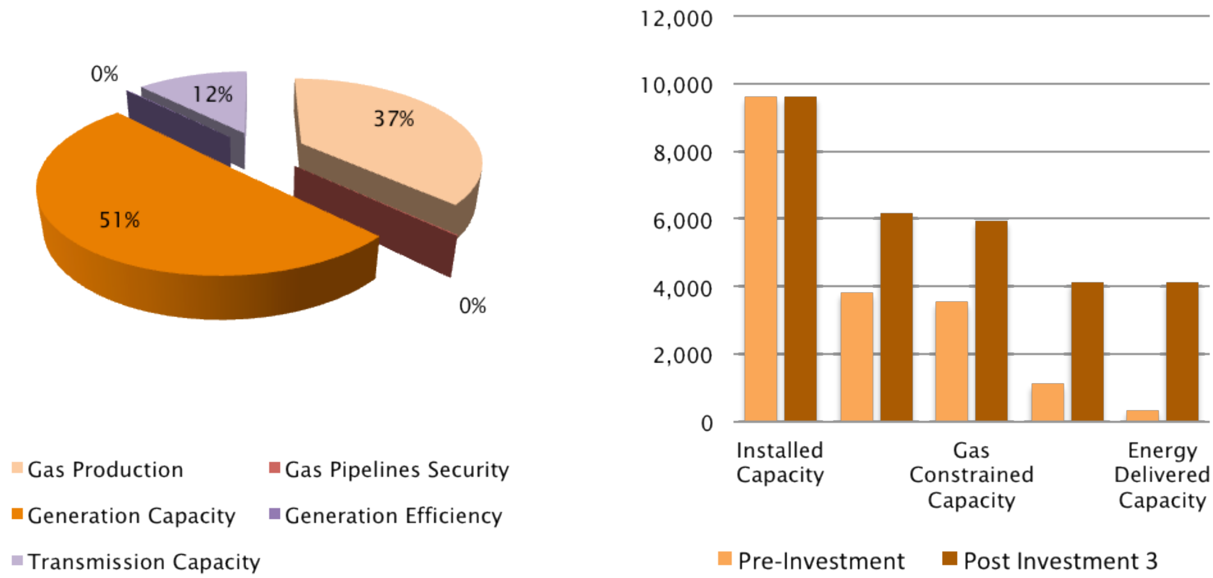

Figure 54: Budget Allocation and Results of IP3 in SR2

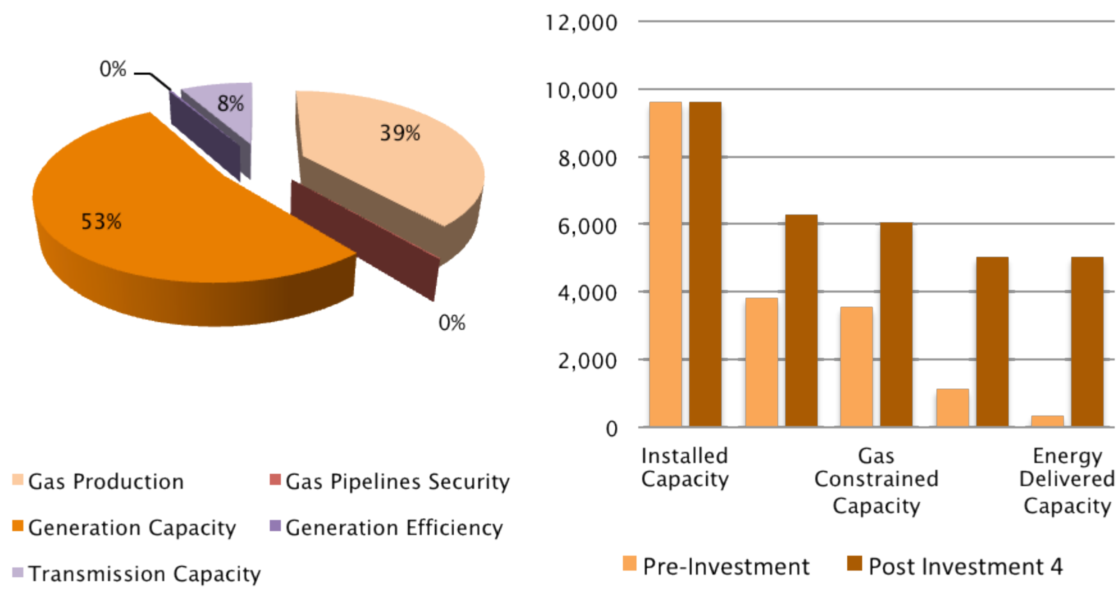

Figure 55: Budget Allocation and Results of IP4 in SR2

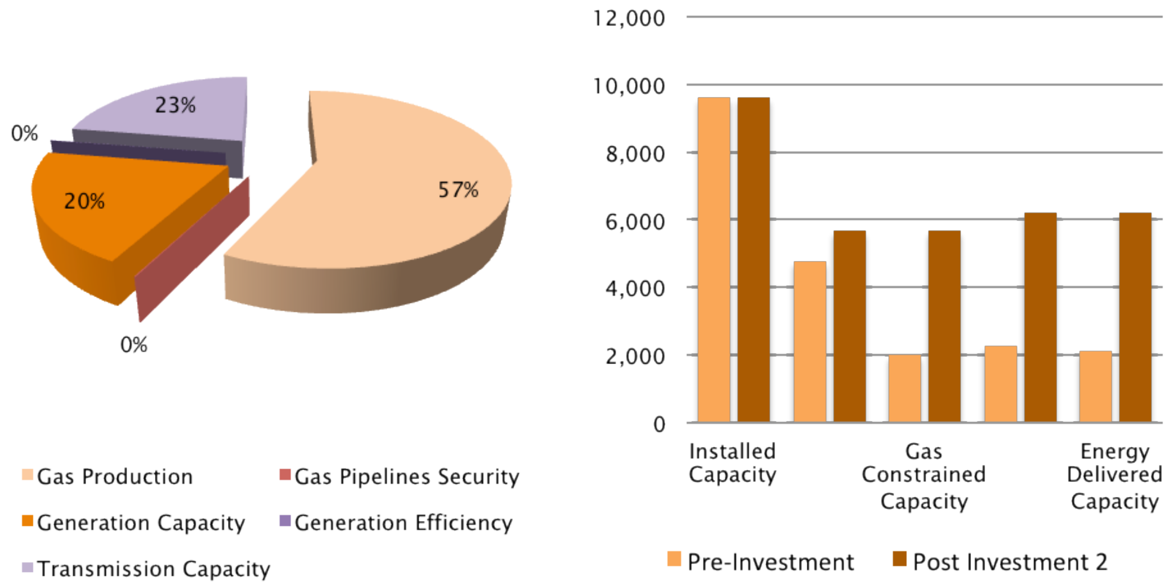

Figure 56: Budget Allocation and Results of IP2 in SR3

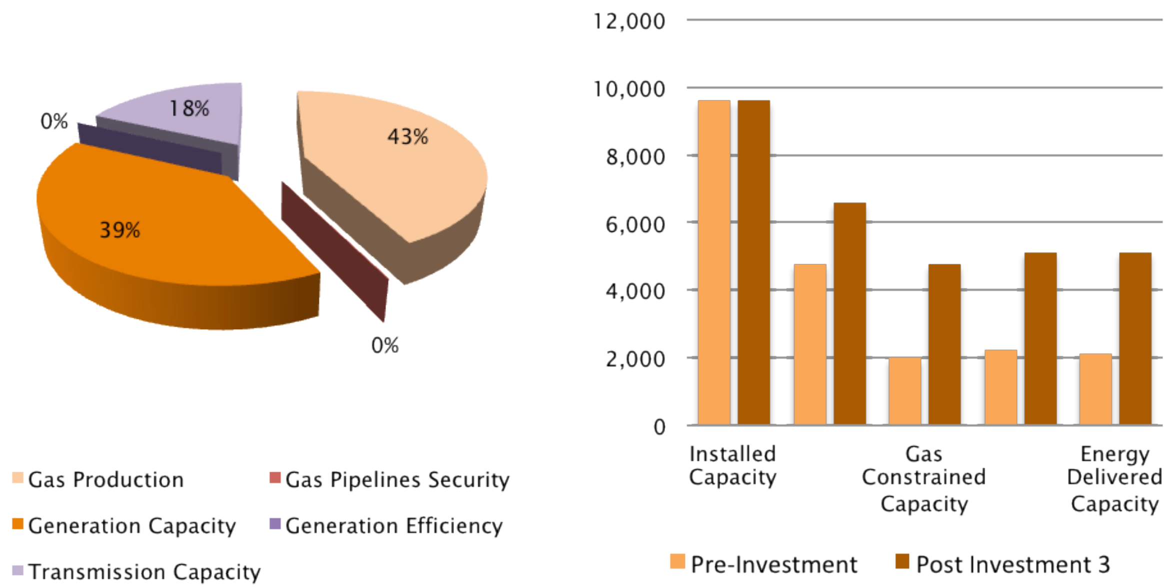

Figure 57: Budget Allocation and Results of IP3 in SR3

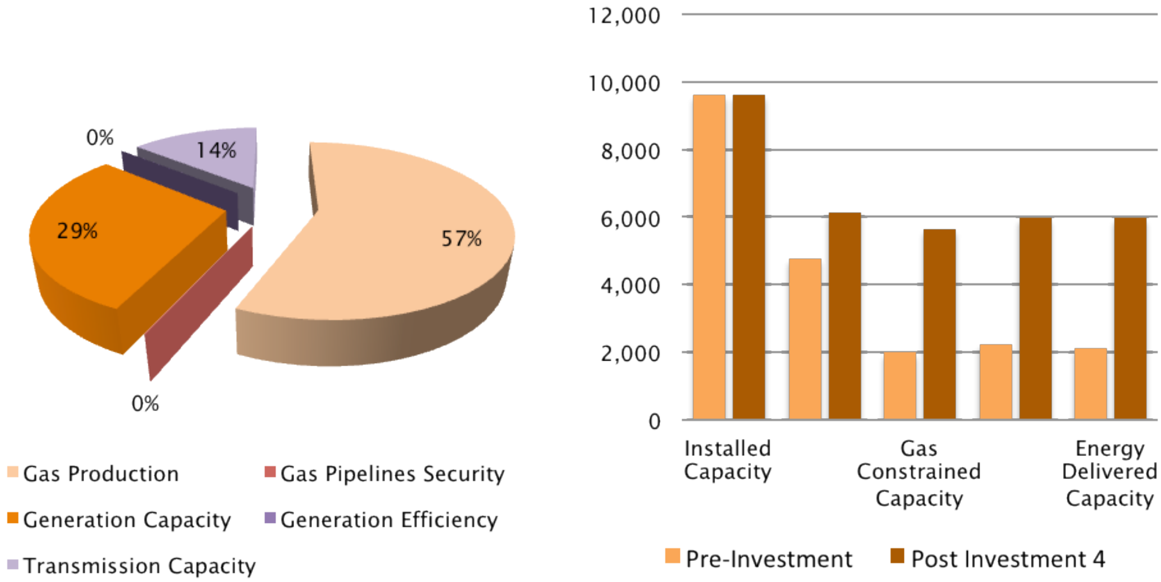

Figure 58: Budget Allocation and Results IP4 in SR3

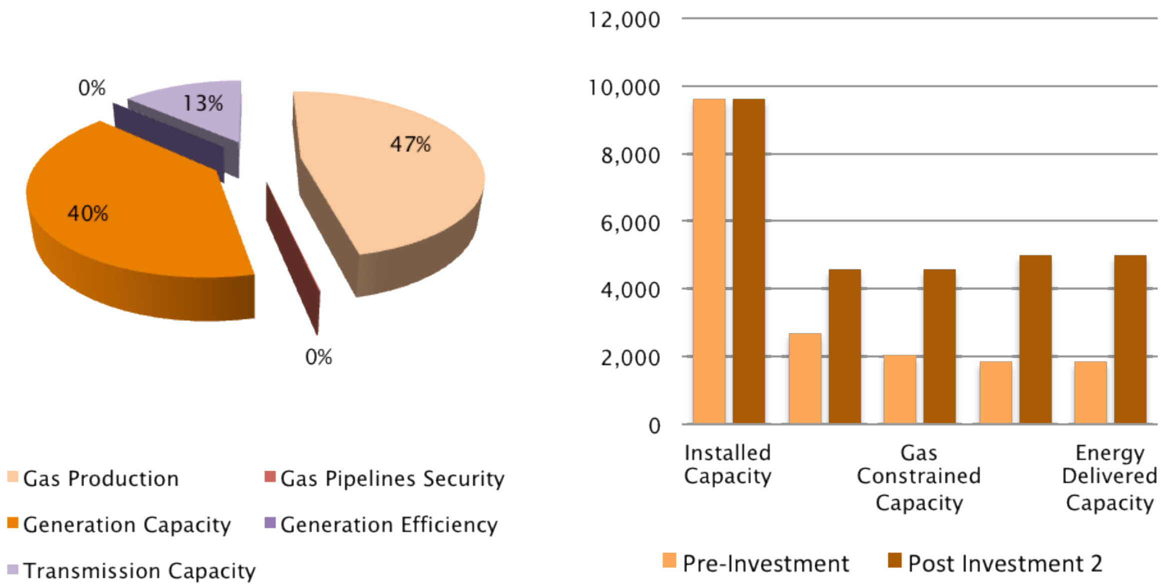

Figure 59: Budget Allocation and Results of IP2 in SR4

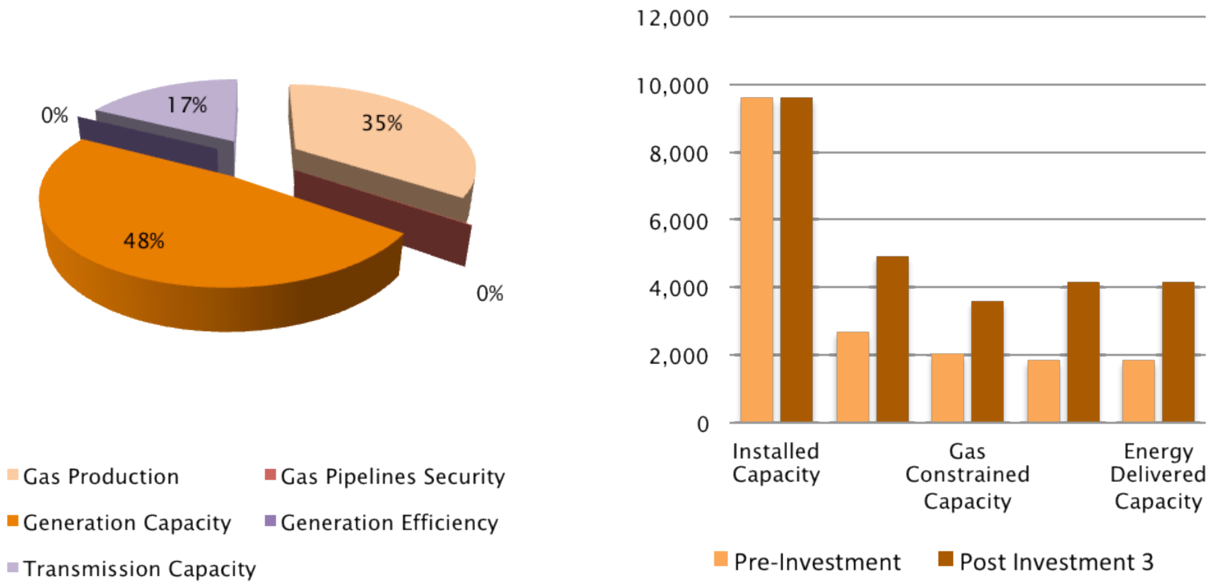

Figure 60: Budget Allocation and Results of IP3 in SR4

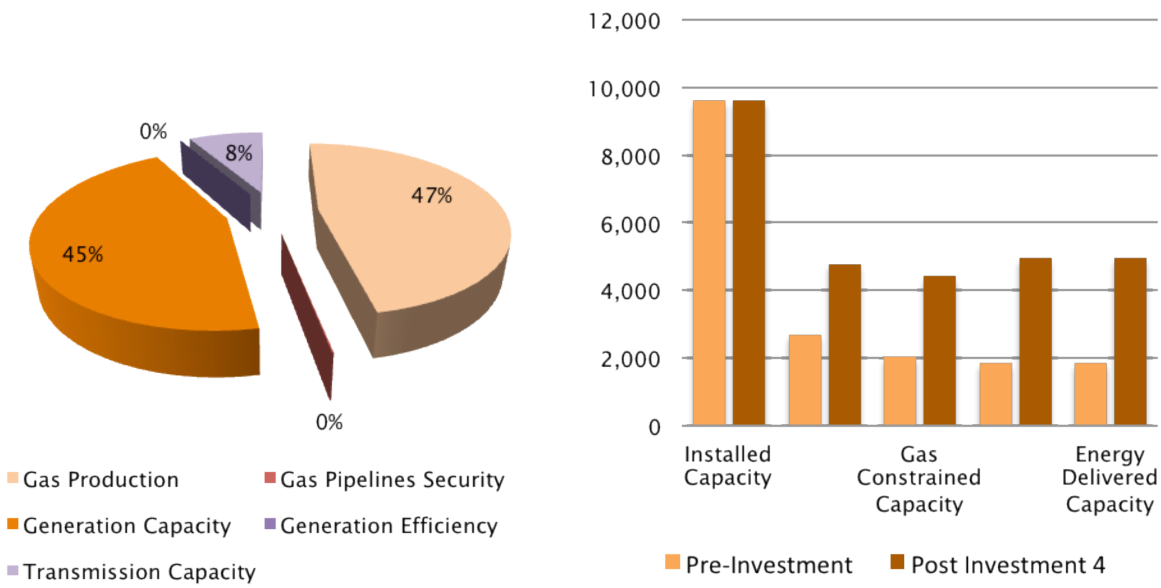

Figure 61: Budget Allocation and Results of IP4 in SR4

Tables of IP Performance in Each Scenario

Scenario 1						
	Reclaimed Generation	Gas Supply	Operating Turbines	Transmission Capacity	Actual Energy Delivered (MW)	
Pre-Investment	44%	83%	59%	54%	Pre-Investment	2265
Investment 1	88%	41%	29%	27%	Investment 1	2265
Investment2	62%	100%	100%	100%	Investment2	5997
Investment3	67%	89%	75%	75%	Investment3	4835
Investment 4	65%	97%	92%	92%	Investment 4	5786

Figure 62: IP Performance Results in SR1

Scenario 2						
	Reclaimed Generation Capacity	Gas Supply	Operating Turbines	Transmission Capacity	Actual Energy Delivered (MW)	
Pre-Investment	40%	93%	29%	9%	Pre-Investment	341
Investment 1	88%	42%	13%	13%	Investment 1	1113
Investment2	59%	100%	103%	103%	Investment2	5816
Investment3	64%	96%	67%	67%	Investment3	4121
Investment 4	65%	96%	80%	80%	Investment 4	5021

Figure 63: IP Performance Results in SR2

Scenario 3						
	Reclaimed Generation Capacity	Gas Supply	Operating Turbines	Transmission Capacity	Actual Energy Delivered (MW)	
Pre-Investment	50%	42%	47%	44%	Pre-Investment	2119
Investment 1	87%	24%	27%	25%	Investment 1	2119
Investment2	59%	100%	109%	109%	Investment2	6200
Investment3	69%	72%	78%	78%	Investment3	5111
Investment 4	64%	92%	97%	97%	Investment 4	5959

Figure 64: IP Performance Results in SR3

Scenario 4						
	Reclaimed Generation Capacity	Gas Supply	Operating Turbines	Transmission Capacity	Actual Energy Delivered (MW)	
Pre-Investment	28%	75%	68%	68%	Pre-Investment	1837
Investment 1	73%	22%	26%	26%	Investment 1	1837
Investment2	47%	100%	109%	109%	Investment2	4988
Investment3	51%	73%	84%	84%	Investment3	4136
Investment 4	50%	92%	104%	104%	Investment 4	4946

Figure 65: IP Performance Results in SR4

Budget Allocations for Each Investment Plan in Each Scenario

Investment 2							
Scenario 1							
Investments into the system							
Budget to Fix the System			$				7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output		
Gas Production	$ 45,000.00	/MWh	$ 2,730,258,000.00	39.00%	$	5,056.03	MW
Gas Pipelines Security	$ 1,000,000.00	/%	$ 9,717,826.00	0.14%	$	9.72	%
Generation Capacity	$ 1,500,000.00	/MW	$ 2,692,750,000.00	38.47%	$	1,795.17	MW
Generation Efficiency	$ 15,000.00	/MW	$ 14,821,365.00	0.21%	$	988.09	MW
Transmission Capacity	$ 500,000.00	/MW	$ 1,552,452,809.00	22.18%	$	3,104.91	MW
			$ 7,000,000,000.00	100%			
Scenario 2							
Investments into the system							
Budget to Fix the System			$				7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output		
Gas Production	$ 45,000.00	/MWh	$ 2,464,644,000.00	35.21%	$	4,564.16	MW
Gas Pipelines Security	$ 1,000,000.00	/%	$ 8,430,863.00	0.12%	$	8.43	%
Generation Capacity	$ 1,500,000.00	/MW	$ 2,995,616,650.00	42.79%	$	1,997.08	MW
Generation Efficiency	$ 15,000.00	/MW	$ 36,309,499.00	0.52%	$	2,420.63	MW
Transmission Capacity	$ 500,000.00	/MW	$ 1,494,998,988.00	21.36%	$	2,990.00	MW
			$ 7,000,000,000.00				
Scenario 3							
Investments into the system							
Budget to Fix the System			$				7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output		
Gas Production	$ 45,000.00	/MWh	$ 4,017,239,999.93	57.39%	$	7,439.33	MW
Gas Pipelines Security	$ 1,000,000.00	/%	$ 7,463,337.19	0.11%	$	7.46	%
Generation Capacity	$ 1,500,000.00	/MW	$ 1,403,800,000.00	20.05%	$	935.87	MW
Generation Efficiency	$ 15,000.00	/MW	$ 3,457,687.50	0.05%	$	230.51	MW
Transmission Capacity	$ 500,000.00	/MW	$ 1,568,038,975.38	22.40%	$	3,136.08	MW
			$ 7,000,000,000.00				
Scenario 4							
Investments into the system							
Budget to Fix the System			$				7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output		
Gas Production	$ 45,000.00	/MWh	$ 3,255,582,478.00	47%	$	6,028.86	MW
Gas Pipelines Security	$ 1,000,000.00	/%	$ 8,056,003.83	0%	$	8.06	%
Generation Capacity	$ 1,500,000.00	/MW	$ 2,799,192,330.00	40%	$	1,866.13	MW
Generation Efficiency	$ 15,000.00	/MW	$ 2,047,718.75	0%	$	136.51	MW
Transmission Capacity	$ 500,000.00	/MW	$ 935,121,469.42	13%	$	1,870.24	MW
			$ 7,000,000,000.00				

Figure 66: Budget Allocations for IP2

Investment 3

Scenario 1

Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	**Unit Cost ($)**		**Budget Allocation**		**Additional Capacity/Output**	
Gas Production	$ 45,000.00	/MWh	$2,440,206,000.00	34.86%	$ 4,518.90	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 9,787,629.31	0.14%	$ 9.79	%
Generation Capacity	$1,500,000.00	/MW	$3,304,125,000.00	47.20%	$ 2,202.75	MW
Generation Efficiency	$ 15,000.00	/MW	$ 1,417,305.00	0.02%	$ 94.49	MW
Transmission Capacity	$ 500,000.00	/MW	$1,244,464,065.69	17.78%	$ 2,488.93	MW
			$7,000,000,000.00	100%		

Scenario 2

Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	**Unit Cost ($)**		**Budget Allocation**		**Additional Capacity/Output**	
Gas Production	$ 45,000.00	/MWh	$2,593,382,400.00	37.05%	$ 57,630.72	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 8,186,715.17	0.12%	$ 8.19	%
Generation Capacity	$1,500,000.00	/MW	$3,526,920,000.00	50.38%	$ 2,351.28	MW
Generation Efficiency	$ 15,000.00	/MW	$ 9,089,801.00	0.13%	$ 605.99	MW
Transmission Capacity	$ 500,000.00	/MW	$ 862,421,083.83	12.32%	$ 1,724.84	MW
			$7,000,000,000.00			

Scenario 3

Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	**Unit Cost ($)**		**Budget Allocation**		**Additional Capacity/Output**	
Gas Production	$ 45,000.00	/MWh	$2,989,936,799.99	42.71%	$ 5,536.92	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 7,567,350.91	0.11%	$ 0.63	%
Generation Capacity	$1,500,000.00	/MW	$2,741,490,000.00	39.16%	$ 152.30	MW
Generation Efficiency	$ 15,000.00	/MW	$ 1,648,374.91	0.02%	$ 9.16	MW
Transmission Capacity	$ 500,000.00	/MW	$1,259,357,474.19	17.99%	$ 209.89	MW
			$7,000,000,000.00			

Scenario 4

Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	**Unit Cost ($)**		**Budget Allocation**		**Additional Capacity/Output**	
Gas Production	$ 45,000.00	/MWh	$2,421,230,401.00	34.59%	$ 4,483.76	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 7,000,000.00	0.10%	$ 7.00	%
Generation Capacity	$1,500,000.00	/MW	$3,355,320,001.00	47.93%	$ 2,236.88	MW
Generation Efficiency	$ 15,000.00	/MW	$ 862,689.00	0.01%	$ 57.51	MW
Transmission Capacity	$ 500,000.00	/MW	$1,215,586,909.00	17.37%	$ 2,431.17	MW
			$7,000,000,000.00			

Figure 67: Budget Allocations for IP3

Investment 4

Scenario 1						
Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output	
Gas Production	$ 45,000.00	/MWh	$2,926,018,800.00	41.80%	$ 5,418.55	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 7,231,118.00	0.10%	$ 7.23	%
Generation Capacity	$1,500,000.00	/MW	$3,208,495,000.00	45.84%	$ 2,139.00	MW
Generation Efficiency	$ 15,000.00	/MW	$ 8,939,415.00	0.13%	$ 595.96	MW
Transmission Capacity	$ 500,000.00	/MW	$ 849,315,667.00	12.13%	$ 1,698.63	MW
			$7,000,000,000.00	100%		

Scenario 2						
Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output	
Gas Production	$ 45,000.00	/MWh	$2,719,080,000.00	38.84%	$ 60,424.00	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 8,176,864.33	0.12%	$ 8.18	%
Generation Capacity	$1,500,000.00	/MW	$3,688,000,000.00	52.69%	$ 2,458.67	MW
Generation Efficiency	$ 15,000.00	/MW	$ 20,854,002.00	0.30%	$ 1,390.27	MW
Transmission Capacity	$ 500,000.00	/MW	$ 563,889,133.67	8.06%	$ 1,127.78	MW
			$7,000,000,000.00			

Scenario 3						
Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output	
Gas Production	$ 45,000.00	/MWh	$3,955,802,399.72	56.51%	$ 7,325.56	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 7,011,106.78	0.10%	$ 0.58	%
Generation Capacity	$1,500,000.00	/MW	$2,060,369,999.00	29.43%	$ 114.46	MW
Generation Efficiency	$ 15,000.00	/MW	$ 692,136.50	0.01%	$ 3.85	MW
Transmission Capacity	$ 500,000.00	/MW	$ 976,124,358.00	13.94%	$ 162.69	MW
			$7,000,000,000.00			

Scenario 4						
Investments into the system						
Budget to Fix the System			$			7,000,000,000.00
Part of System	Unit Cost ($)		Budget Allocation		Additional Capacity/Output	
Gas Production	$ 45,000.00	/MWh	$3,286,116,000.72	46.94%	$ 6,085.40	MW
Gas Pipelines Security	$1,000,000.00	/%	$ 7,441,620.49	0.11%	$ 0.62	%
Generation Capacity	$1,500,000.00	/MW	$3,130,049,999.00	44.71%	$ 173.89	MW
Generation Efficiency	$ 15,000.00	/MW	$ 995,868.75	0.01%	$ 5.53	MW
Transmission Capacity	$ 500,000.00	/MW	$ 575,396,511.04	8.22%	$ 95.90	MW
			$7,000,000,000.00			

Figure 68: Budget Allocations for IP4