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The Impact of Climate Change and Variability on Africa's Renewable Energy Development :A Hybrid Uncertainty Approach

Yohannes Daniel Gebretsadik
University of Colorado at Boulder, yohannes_dg@yahoo.com

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THE IMPACT OF CLIMATE CHANGE AND VARIABILITY ON AFRICA'S RENEWABLE ENERGY DEVELOPMENT

A HYBRID UNCERTAINTY APPROACH

by

Yohannes D. Gebretsadik

B.Sc, Addis Ababa University, 2003

M.Sc, Addis Ababa University, 2007

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This thesis entitled:
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written by Yohannes D. Gebretsadik
has been approved for the Department of Civil, Environmental and Architectural Engineering

Paul Chinowsky

Edith Zagona

Balaji Rajagopalan

Kenneth Strezpek

Channing Arndt

Date ___________

The final copy of this thesis has been examined by the signatories, and we

Find that both the content and the form meet acceptable presentation standards

Of scholarly work in the above mentioned discipline.

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The Impact of Climate Change and Variability on Africa's Renewable Energy Development: A Hybrid Uncertainty Approach

Thesis directed by Professor Paul Chinowsky

This dissertation presents advanced methods that could be used to assess various impact of climate change to hydropower and reliability assessment of wind resource using alternative reservoir operation that maximizes the firm generation of integrated wind and hydropower. The first component of this study introduces a hybrid approach of risk based climate change impact assessment. This method combines uncertainties in historical climate variability with uncertainties in climate predictions to conduct more comprehensive climate change impact assessment on hydropower. Results from this study, illustrated in Zambezi and Congo River basins, indicate that the single basecase approach of delta-change technique substantially underestimates the potential impact of climate change. Particularly, assessments for water resource systems in areas with high natural hydroclimatic variability the combined effect natural variability and climate change is more pronounced.

The second component utilizes the concept of Empirical Orthogonal Functions (EOFs) analysis technique to access the join spatio-temporal patterns of interannual variability hydropower generation between different power pools in Africa. EOF analysis of annual streamflow and hydropower generation was carried out followed by investigation of the resulting dominant spatial patterns to identify locations of existing and future potential hydropower sites which indicate a homogeneous or a heterogeneous pattern of variability. Results indicated a distinct out-of-phase pattern of variability between Southern and West African Power pools. Furthermore, the method was extended to conducted potential impact of climate change induced change in inter-annual variability.

The third component presents a reliability assessment method of wind-hydropower integration. A water resources model combined with a single node power grid system model accompanied by a genetic algorithm solver is implemented to determine optimum operation strategy for each storage reservoir aiming at maximizing the 90^{th} percentile power generation over the entire simulation period. This model is tested on the hydropower system in the Zambezi basin to demonstrate how storage reservoirs could be used to offset wind power intermittence in South Africa. Results show an increased level of wind penetration, a reduced level of coal power utilization and less cycling requirement in power system as a result of better regulation that is achieved through the combined operation.

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Many thanks to collogue and friends Chas Fant (simply the most polite person I know), Niko Strzepek and Andrzej Strzepek. They made my time more enjoyable and interesting. I am deeply indebted to them for making me feel “home away from home”. Thank you for providing with the moral support and friendship that I needed.

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Chapter 1

Introduction

1. Overview

Despite the high level of uncertainty involved, scientific evidences are generally indicating a global rise in temperature and change in temporal and spatial pattern of precipitation as a result of human induced change in climate. It is becoming one of the urgent global issues and a topic of several studies and dialogues. Particularly in developing countries, the impact is expected to be more prominent and is believed to soon be a fundamental threat to sustainable development and the fight against poverty (World Bank, 2011), (IPCC, 2007). Some of the major impacts, as outlined in Reports by the Intergovernmental Panel on Climate Change (IPCC), include decline in agricultural productivity, increased water stress, rising sea levels, risks to human health, threats to ecosystems and biodiversity (IPCC, 2007). Due to the complexity of the problem, level of uncertainty and multi-disciplinary nature, there is a growing need to have more advanced analytical tools and methods that would allow us to conduct a robust evaluation of impacts, vulnerability and adaptation to climate change to better understand and address the issues.

There is a circular connection between renewable resource development and climate change which is interlinked by mitigation, impact and vulnerability. In addition to providing a sustainable energy service, the important role that renewable energy sources play in mitigating climate change is one of the key message pointed out by the latest study report by the United Nations' Intergovernmental Panel on Climate Change (IPCC) (Moomaw et al., 2011). Greenhouse gas emissions associated with the provision of energy services are the major cause of climate change. Accordingly, shifting away from fossil fuels to renewable energy resources with low environmental impacts and low greenhouse gas (GHG) emissions are crucial means of reducing these GHG emission. According to International Energy Agency report (IEA, 2011), renewable energy resources account only about 12.9% of global primary energy supply. However, deployment of renewable energy has shown to be increasing rapidly in recent years. For example in year 2009, half of the new electric sources added globally is from renewable sources.

Similarly, regional power integration and cooperation by power pools has long been realized as one of the most effective ways of and ensuring reliability in supply of energy. Strengthening connections within an electrical power system and introducing additional interconnections to other systems not only increases power system reliability but also be an adaptation mechanism through improving resilience of overall system to climatic fluctuation.

On impact side, studies have shown that some renewable resources such as hydropower are highly sensitive to climate change and variability (Harrison & Whittington 2002, Atsushi IIMi 2007, Schaefli et al. 2007, Cherry et al. 2010, Brown et al. 2010, Jia et al. 2012) . Change in climate variables could affect the hydroclimatic behavior of a basin and consequently generating capacity of hydropower generation units. Furthermore, in addition to the magnitude climate change induced shifts in inter-annual variability and seasonality of the flow is one of the potential impacts pointed out by the IPCC Special report on renewable resource, hydropower (Kumar et al., 2011). Changes in variability could affect the system of interconnected hydropower units by disrupting the in-sync and out-sync pattern of generation. Consequently, climate change has become threatening to both a single generating unit as well for interconnected unites power generations as a system.

One of the major technical challenges that comes with the use of the renewable energy supplies, such wind and solar, is whether such supplies can provide reliable sources of electric power for different time scales given the intermittent nature of these resources. Furthermore as the penetration of these intermittent resources increase it will have a major implications on many aspects of power systems planning, operation and control, as well as on the corresponding regulation (J.Perez-Arriagaa & Batllea, 2012).

In summary, while use of renewable resources is a key means for reducing greenhouse gas emissions they are however susceptible to climate change and variability. Therefore assessing the impacts of and vulnerability of renewable resources to climate change and subsequently working out mitigation and adaptation strategies requires good analytic framework and in-depth assessment. The main focus of the three studies presented in this dissertation is on implementing different methods and analytical tools that could be used in impact-mitigation assessment of Climate Change and targets specific aspects of the connection between climate change and renewable resources. On the impact aspect different methods to assess climate change impact on hydropower generation to a single as well as to an interconnected system of power pools have been addressed and the mitigation side implication of increased penetration on power system and optimized strategy of operation to maximize reliability have been visited.

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2. Problem Statement and research questions

The present research puts forward distinct hypothesis and research questions corresponding to each component of the study. There are various type of uncertainties in climate impact studies. For example, structural uncertainty between using different models, downscaling and future greenhouse gas emissions scenarios are some of them. Recently, risk-based impact assessments, where the associated risk is expressed as probabilistic distributions as opposed to discrete future scenarios, are becoming more popular due to their ability to preserve the combination of different levels of risk involved. One of the uncertainties in climate change impact assessment to water resources is the natural variability of the system which has often been given low emphasis by impact modelers. This main research question in the first part of this study is, what is the significance of taking into consideration the combined effect of uncertainties in climate change and uncertainties in natural climate variability by looking at them together through hybrid scenario formulation? It hypothesizes, scenarios formulated through the combination of synthetic time series ensembles of historical variables to represent natural variability and predicted anomalies by GCMs, could provide a robust and more comprehensive risk-based assessment.

In addition to total magnitude of energy production, climate change could also affect the variability of runoff causing monthly, seasonal and decadal shifts in hydropower generation consequently this might have significant effect on reliability of Hydropower for a single hydropower as well as for an interconnected grid system of hydropower plants. Hypothesis - H3: The different power pools in Africa might be affected by climate change differently and thus the variability in generating capacity of hydropower might be going in different direction causing the systems to go in-sync or out-of-sync. If the latter, then connecting the power pools will rectify the effect of climate change if not then additional consideration might need to be taken to eliminate the amplified impact of climate change as a result of the interconnection.

The last section proposes an hour integrated water resources and power system model and using that model investigate if it is possible to come up with globally optimized model based on foreseen wind generation data. And based on improved reliability what is the implication to South Africa energy resource.

3. Significance and contribution

Each of the three research components have their respective key methodological as well as knowledge contributions. This research study will demonstrate application of the proposed comprehensive hybrid uncertainty scenario formulation technique. This method is an improvement over the traditional single-based line approaches of scenario generation which uses the direct application of climate shocks on selected window of historical variables. It will prove a better perspective of the uncertainties in the climate variables and will enable to capture and model these uncertainties. The integrated modeling approach presented together with selection of scenario for a compressive analysis, can be used as an alternative approach where in depth assessment is required in the subsequent other impact assessment similar studies.

The study will also present techniques to assess impact of climate change on interconnected hydropower systems. Result of that assessment will help understand the behavior of interconnected systems to changing climate and will allow filling the knowledge gap that there is in terms of understanding how climate change might drive variability of hydropower generation and ,consequently, to what degree that it might affect the reliability. Little emphasis has been given so far by climate change impact studies for with regards to change in variability and shift in timing of runoff, therefore, the outcome of this research might give new insights to the ways climate change affects the hydropower power sector.

This study develops a reliability assessment method of wind resource using optimum reservoir target power operations that maximizes the firm generation of integrated wind and hydropower. A combination of linear programming hourly water resources model and Genetic Algorithm solvers are combined to determine optimum operation strategy for multipurpose storage reservoirs that yield maximum firm generation over one year of the simulation period. The proposed frame work optimizes resource utilization both at a time step level as well as over the entire period of simulation. The method will have clear benefit over models that implement short-term optimization approach since both water allocation as well as the power grid system model is based on optimum operation policy for each time step and the operation targets identified are over the entire time period. The model allocates a target for each reservoir with an operation rule combination that gives the best possible hourly allocation of power output given physical and policy constraints. This study will also look at the implication wind/hydro integration on coal energy generation. The possible improvement in penetration of wind that could be achieved as a result of more regulated wind energy has both economic as well as environmental advantages

Finally, the quantitative results and outcomes of this research will be very useful input to further similar studies and can support renewable resources development Africa. Climate change impact figures on Grand Inga and hydropower and current variability parent between the different power pools southern Africa region could assist in the planning and implementations of the interconnection projects. There is little information available regarding the how climate change is will affect the already existing and planned interconnected systems of hydropower, this study might serve as a primarily basis for future reference or research activities which might aim to expand on the findings.

Chapter 2

A hybrid approach to incorporating climate change and variability into climate scenario for impact assessments.

Abstract

Traditional delta-change approach of scenario generation for impact assessment of climate change to hydrology and water resources strongly depends on the selected base-case observed historical climate conditions that the climate shocks are to be super imposed. This method disregards the combined effect of climate change and the inherent hydroclimatological variability in the system. This Chapter demonstrates a hybrid approach in which uncertainties in historical climate variability are combined with uncertainties in climate predictions to conduct more comprehensive climate change impact assessment to hydropower in Zambezi and Congo River basins. Synthetic ensembles of basecase scenarios of the relevant climate variables were generated using frequency domain simulation to represent the uncertainty in natural variability. These were combined with large sets of uncertainties in future climate anomalies, hybrid frequency distributions (HFD) which are based on the full set of the IPCC AR4 Global Circulation Models (GCMs). Biophysical modeling of water resource systems in both basins was conducted to study the impact of these scenarios. Results from this study indicate that the use of single base-case approach of delta-change technique could substantially underestimate the potential impact of climate change to hydropower. Particularly, assessments for water resource systems in areas with high natural hydroclimatic variability, careful consideration should be given to the inherent natural variability as the combined effect is more pronounced.

1. Introduction

Hydropower resource is highly sensitive to climate change since water resource is directly linked to climate variables. Changes in temperature and precipitation as a result of climate change will affect the availability of surface water resource both spatially and temporarily. Consequently, changes in river flow volume, in variability or its magnitude have the potential to affect hydropower generation directly, which in turn has significant developmental implications (Kumar et al. 2011). Studies have shown major potential loss in hydropower generation as a result of changing climate (Harrison & Whittington 2002, Atsushi IIMi 2007, Schaefli et al. 2007, Cherry et al. 2010, Brown et al. 2010, Jia et al. 2012).

While General Circulation Models (GCMs) are commonly accepted as being the most appropriate tools to obtain future scenarios, raw GCM outputs are inadequate to be directly used for conducting climate change impact assessment at regional scales (IPCC 1996). Despite the considerable effort made by climate modelers, the spatial resolution of GCM output variables is still too coarse and unreliable to model hydro-climatological processes at sub-grid box scale. One of the simplest and most widely used approach to deal with this drawback is to use the 'delta-change' method. Anomalies of climate variables, e.g. precipitation and temperature, are computed either as ratio or absolute changes relative to a selected base-case from the raw GCM output. The computed anomalies are then superimposed over observed historical sequence to produces future climate states. The idea behind this is the assumption that GCMs are more reliable for modeling the relative changes than the absolute values (Lauren E. Hay et al. 2002)

One of the limitations of the delta-change approach is that the selected historical sequence is taken from a window of observed past series, which is but a single realization of many possible climatic futures. Thus, most extreme events and natural variability might not be adequately captured in the selected window of observed historical climate. Additionally, the different scales of natural variability of the climate variable also introduces temporal uncertainties in the prediction of future hydropower generating capacity. Impact assessment practice based on a single historical time series therefore disregards these uncertainties and its combined effect with future climate changes.

This section presents the significance of taking into consideration the combined effect of uncertainties in human induced climate change and uncertainties in natural climate variability by looking at them together in impact assessment. Comparing the individual risks is also significant in terms of understanding the possible risk of climate change relative to the variability that already exists in the system for future water resources planning and management. This alternative Hybrid uncertainty approach is shown in which scenarios are generated by the combination GCM output and synthetic generation of Climate variables. The GCM outputs used are from Hybrid Frequency Distributions (HFD) results by Schlosser et al. (2011) which encompasses a wider range of uncertainties of GCM results namely a) structural uncertainty of using different models, b) Downscaling and c) Possible future emissions scenarios corresponding to different policies of adaption.

The main objective in the Hybrid uncertainty approach is to integrate the uncertainties involved in the natural variability of the hydrologic system and thus enabling to conduct a more comprehensive assessment of hydropower vulnerability to climate change. The method is demonstrated by making basin wide impact assessment on existing and planned hydropower schemes at Inga site in Democratic Republic of Congo (DRC) and the Hydropower system in Zambezi river basins.

Little has been reported in the literature on the impact of climate change on the Congo River Basin (Mukheibir 2007) and even less on the Grand Inga systems. This section in addition to the methodological contribution will provide valuable additional information on the risk of climate change to the Grand Inga project.

2. Hydropower systems in Congo and Zambezi river basins

Democratic Republic of Congo (DRC) holds nearly 42% of Africa's technically exploitable hydropower potential. Annual energy potential is estimated to be 774 TWh. When this is expressed as firm power capacity, the potential is equivalent to 100 GW of power. The majority of this power potential is concentrated at the Inga site while the rest is distributed all over the country. Inga hydropower existing facilities and identified large projects in DRC consist of Inga 1&2 with total installed capacity of 1,745 MW, Inga 3 generating capacity of 4,320 MW and Grand Inga, the world's largest hydropower scheme, with a total of 39,000 MW of power generated from 52 turbines (Tshombe et al. 2007). This study mainly looks at the combined generating capacity of these four major hydropower schemes. Other small power plants were not considered in water resource systems modeling for current analysis since their generating capacity is very small in comparison to the Inga dams.

In the long-term, the Grand Inga hydropower potential could be developed to integrate the power system interconnections of the sub-regions in Africa and become the major contributor of SAPP grid. As of today, feasible identified power highways include (i) the DRC-Congo-RCA-

Sudan-Egypt interconnection (ii) the DRC – Congo – Gabon - Cameroon-Nigeria interconnection (iii) the DRC-Angola-Namibia-RSA.

Zambezi is the fourth-longest river in Africa after Nile, Congo and Niger, and the largest river with an average discharge of about 3,200 m3/sec. The drainage basin of about 1.4 Million km^2 represents about 4.5% of the total continent by area. Climate and runoff is highly variable across the basin, and from year to year. The Basin has an estimated hydropower potential of 14,250 MW of which 30% is developed so far. Currently the largest plant is in Mozambique (Cahora Bassa) with a capacity of 2075 MW. In Malawi, three hydropower plants (Nkula, Tedzani and Wovwe) are operational with a combined capacity of 220 MW, of which 98% is in the Shire River. Zambia has six plants (Victoria Falls, Kariba North Bank, Kafue Gorge, Mulungushi, Lusemfwa and Lusiwasi) with a combined capacity of 1,658 MW. Zimbabwe has Kariba South Bank with a capacity of 666 MW.

The Southern African Power Pool (SAPP), currently plays the coordination role for centralized energy market in the region integrating the power pool across countries and provide reliable and economical electricity through cooperation and planning and operation of systems to minimize costs and maintain reliability.

3. Methods

3.1. Formulating uncertainties

The procedure of incorporating natural variability in the analysis involves employing an ensemble of scenarios of climate variables that are formulated by stochastic hydrologic methods of a weather generator. Weather generators are statistical methods that base on observed historical records of climate variable to generate long-term series of synthetic climatic data by preserving statistical properties of the observed data. The variance across an ensemble at a time step represents the temporal variability of the hydrologic variables.

The variance across projected GCM anomalies of hybrid frequency distributions (HFD) (Schlosser et al. 2011) are combined results of uncertainties in structural (across all the climate models) , downscaling and possible future carbon emission . These are combined with natural variability to form different ensembles of scenarios which are discussed in 0 below.

3.2. Time series generation of climate variables - Uncertainty in natural variability

There are different variation of both parametric and non-parametric methods that have been developed and used in the past for single as well as multivariate time series. One of the key difference between these methods is the capability of which they are able to reproduce the different statistical property of the historical data. While the parametric models such as autoregressive moving average models (ARMA),(Thomas & Fiering 1962, Yevjevich 1973, Box & Jenkins 1976, Salas & Obeysekera 1992) are able to capture the mean, variance and skewness ; a widely used nonparametric bootstrap models such as , K-nearest neighbor (K-NN) (Lall & Sharma 1996, Rajagopalan & Lall 1999, T.Adri Buishhand 2001, Yates et al. 2003, Grantz et al. 2005, Apipattanavis et al. 2007) have effectively reproduced the probability distribution function (PDF) of the original historical data . These statistical methods have been applied to climate impact studies for downscaling in studies (Gangopadhyay et al. 2005, Eum et al. 2010) or climate sensitivity analysis by simulate possible climate scenarios (Yates et al. 2003)

The traditional models just discussed however fall short when it comes to capturing the spectral property of the original time series. Low frequency signals that could potentially be driven by large scale climate phenomena, such as El Nino–Southern Oscillation (ENSO), the Pacific

Decadal Oscillation (PDO) etc., are lost in the reconstructed ensembles of synthetic time series. Figure 1 shows Wavelet decomposition of precipitation for Congo and Zambezi Basins we can observe a 3- 8 years of signal in Congo catchment at the beginning of the century roughly up until end of the 1970s and 5-8 years of signal in Zambezi basin. These signals are the potentially major source of inter-annual variability in the hydrologic series, (Amarasekera et al. 1996, Nicholson & Kim 1997, Ghil et al. 2002, Gaughan & Waylen 2012), thus it is essential to consider a model that would carry these long term frequencies into the simulated ensembles to have a better representation of uncertainties in the natural variability. Furthermore, in climate impact studies we are often interested in the impact close to the end our analysis time span where the effect of climate change are will be starting to emerge (in this particular study out indicator is the average over 2045-2050) taking historic series does not guarantee an active dry/wet epoch to show at this particular time window, consequently underestimating the effect of natural variability.

Frequency domain simulation of time series has provided a means that would allow to capture the spectral property of time series and have found a growing application in water resource and climate studies as an alternative approach to time domain stochastic simulation methods particularly where the low frequency signals are significant drivers of climate variable.

The use of wavelet decomposition followed by an autoregressive model (AR), Wavelet based Auto Regression Modeling (WARM) framework ,as demonstrated by (Kwon et al. 2007), has been shown to capture the spectral property of the historical data in addition to the low order statistical parameters. An improvement on this model coupled with disaggregation is published by (Nowak et al. 2011) and has shown to captures the both local and global spectral property as well as the spatial dependence of variables at multiple locations, simultaneously capturing spectral and distributional properties of the historic data.

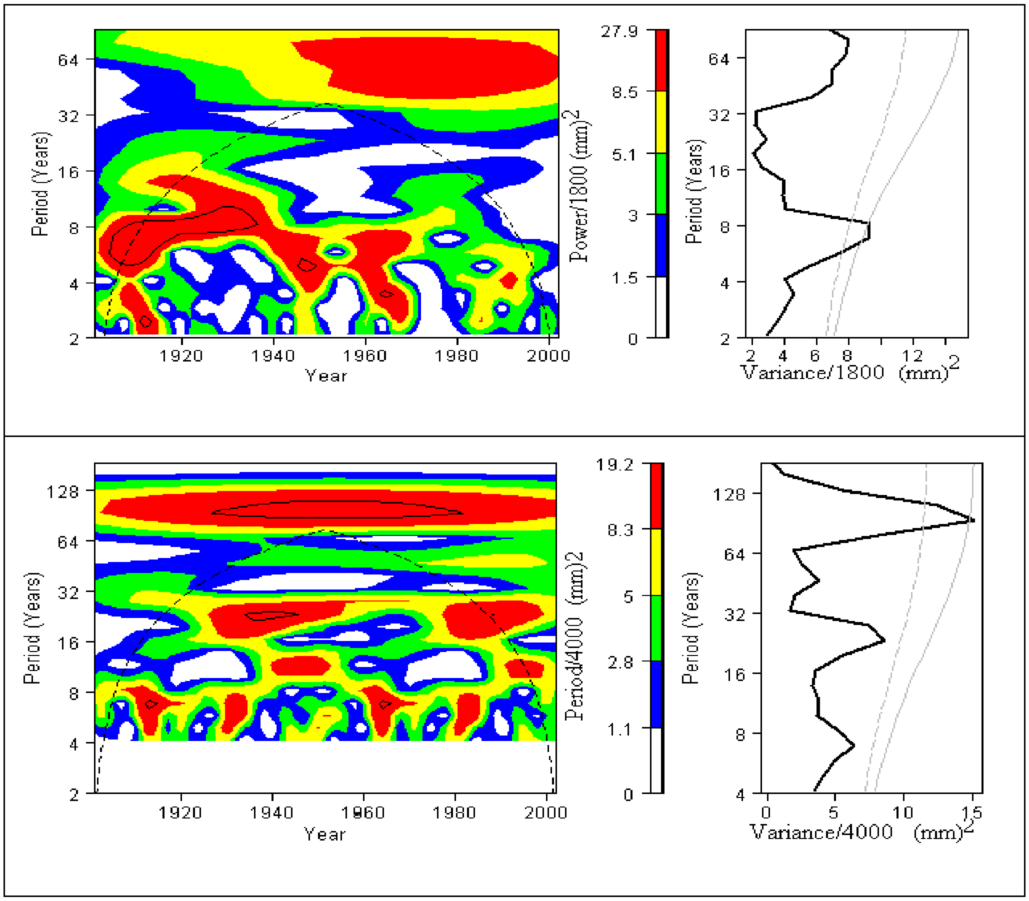

Figure 1 Morlet wavelet transformation of precipitation in northern Congo (top) and Zambezi (bottom) river basins with 95% level of confidence for white noise.

Analogues to time domain simulations, one of the other variations of frequency domain simulation is the use of bootstrap techniques. The surrogate method of Theiler et al., first introduced by (Theiler et al. 1992) , is a widely applied technique in literature. Its basic idea is to first compute Fourier transformation coefficients of the observed time series data followed by bootstrapping the phase coefficients, and then back-transforming them to obtain a surrogate sample in the time domain. Since the randomized components in the reconstruction is the phase, the magnitude of values obtained in time domain are all members of the original time series. More details are presented in (Theiler et al. 1992).

This method was used in this analysis to produced surrogate times series. Simulation was conducted on a 102 years observed precipitation and temperature datasets on annual time step but the monthly structure was later reinstated to get monthly time series ensamples.

Another important aspects that needs careful consideration in this kind of analysis is the correlation between the precipitation and temperature time series. Since these two variables cannot be assumed to be independent it is necessary to maintain their temporal correlation. This was carried out by simulating the temperature and precipitation variables together. The general concept to implement this combined simulation is by preserving precipitation indexes where values are picked during simulation. The corresponding annual temperature is simultaneously picked using this indexes, this will assure pairs of temperature and precipitation to stay together in the simulated ensemble as well. The time series simulation will primarily maintains the spectral property in the precipitation series, however due to the dependence between precipitation and temperature, the spectral property in the temperature will also be indirectly preserved. Furthermore, in larger scale, if there is a dependence between these two variables it is more likely that the drivers of interannual variably could be common to both climate variables, such as regional of global scale climate phenomena, and as a result it is not surprising if the frequencies of temperature are also automatically preserved even though primarily the simulation targets at preserving the spectral property of precipitation. Results are illustrated in Figure 3.

Additionally, since there is also a spatial and temporal correlation of observed data between the catchment divisions, application of the surrogate simulation was conducted simultaneously for all the catchments to preserve this correlation.

To do that, the surrogate method is accompanied by space aggregation-disaggregation technique. Four steps are engaged to carry this out (1) Fit a space aggregation of the climate variables to an index basin. This index basin is a hypothetical sub-basin constructed as the sum of each climate variables of the identified 26 sub-basins (2) generating 500 year ensembles of precipitation and temperature based on the past 100 years of record using surrogate bootstrapping technique.(4) Disaggregating the ensembles into the original sub-basins. An example of similar application of this method in combination with a time domain model, k^{th} nearest neighbor (K-nn), is illustrated by (Tarboton et al. 1998, Clark et al. 2004, Prairie et al. 2007, Bracken et al. 2010) . More application are also found in (Santos & Salas 1992) and (Tarboton et al. 1998).

A Spectrum plot and probability density functions of simulated ensemble of scenarios and original data is shown in the Figure 3 and Figure 3. It can easily be inferred that simulated time-series have managed to capture both the spectral as well as the distribution statistic of the original time series for both temperature and precipitation. Forty years of data was selected from the simulated enables to be used for future (2011- 2050) scenarios of base-case precipitation and Temperature scenarios which shall be discussed in the coming sections.

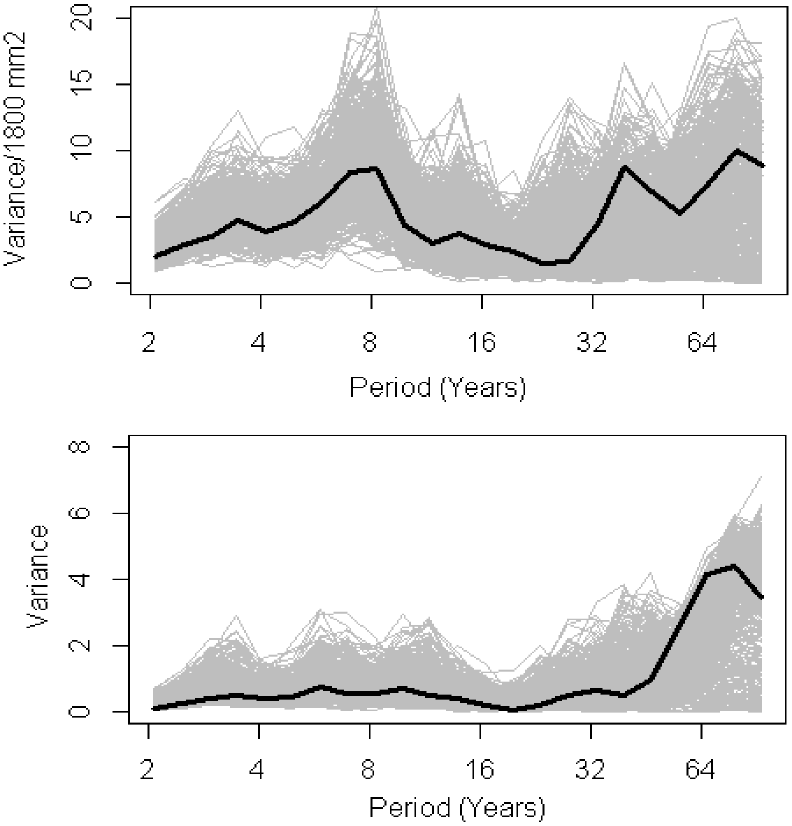

Figure 2: Spectrum plot of simulated synthetic time series data for precipitation (Top) and Temperature (Bottom).

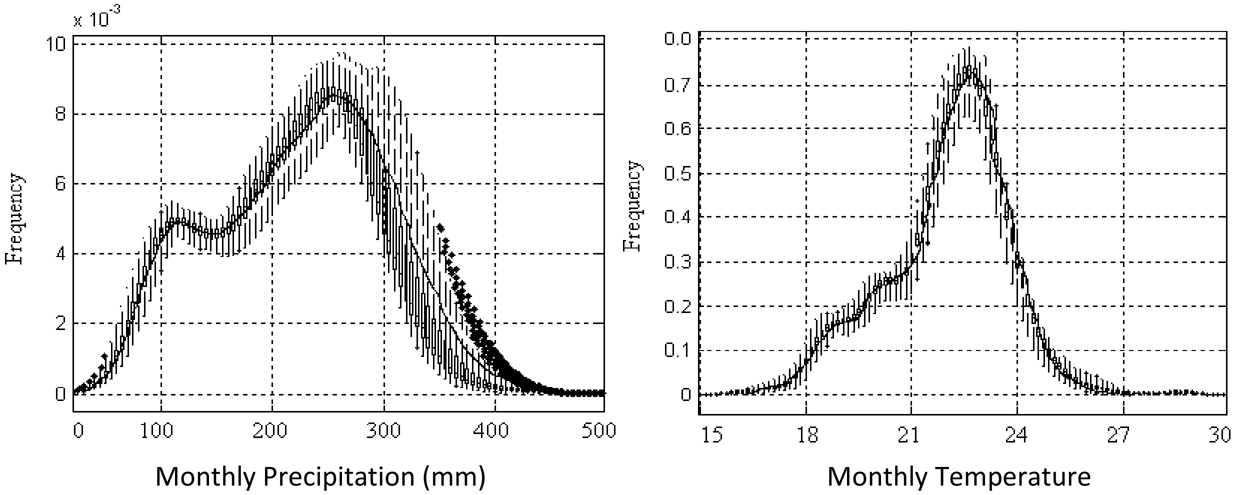

Figure 3: Probability density function of average monthly precipitation (left) and temperature (right) for Congo basin

3.3. Hybrid Frequency distribution (HFD) – Uncertainty in Climate Change

Many previous approach of climate change impact assessment exercises have often been limited to selected number of future climate scenarios obtained by combination of IPCC SRES (Special Report on Emissions Scenarios - SRES) and GCM outputs. Schlosser et al. (2011) introduced "hybrid frequency distributions" (HFD) ,regionally downscaled model scenarios, numerical hybridization of 400 members of policy ensembles from the IGSM[1] results of (Sokolov et al. 2005) and (Webster et al. 2011); for each 17 IPCC AR4 climate model results producing a meta-ensemble of climate change projections containing 6,800 distinct members for different possible adaptation.

These HFDs datasets are the latest available characterization of possible future climate outcomes which combines uncertainties in Structural difference of climate models, in downscaling and possible emission scenarios as represented by the different policy of adaption.

Climate change scenarios in temperature and precipitation are taken from this dataset to represent the uncertainties in future case of climate variables. These dataset are generated for different policy of adaption however two of them are selected and used in this assessment 1) unconstrained emission(UCE) scenarios where no policy action is taken to limit greenhouse gas emissions 2) 'level one stabilization' (L1S) where restraints are imposed on global emissions to limit greenhouse gas concentration at 560 ppm CO2 equivalent, as defined in (Webster et al. 2011). From this large dataset about 400 of them are selected by quadrature thinning technique

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[1] The MIT Integrated Global System Model (IGSM) framework is a global integrated assessment modeling framework that uses emission predictions and economic outputs from the MIT Emission Prediction and Policy Analysis (EPPA) model and earth system modeling predictions from the IGSM to drive a land system component, a crop model (CliCrop) and a Water Resource System (WRS) model.

discussed in 3.5. The distribution for average temperature and precipitation for the years 2041 – 2050 is indicated in Figure 4.

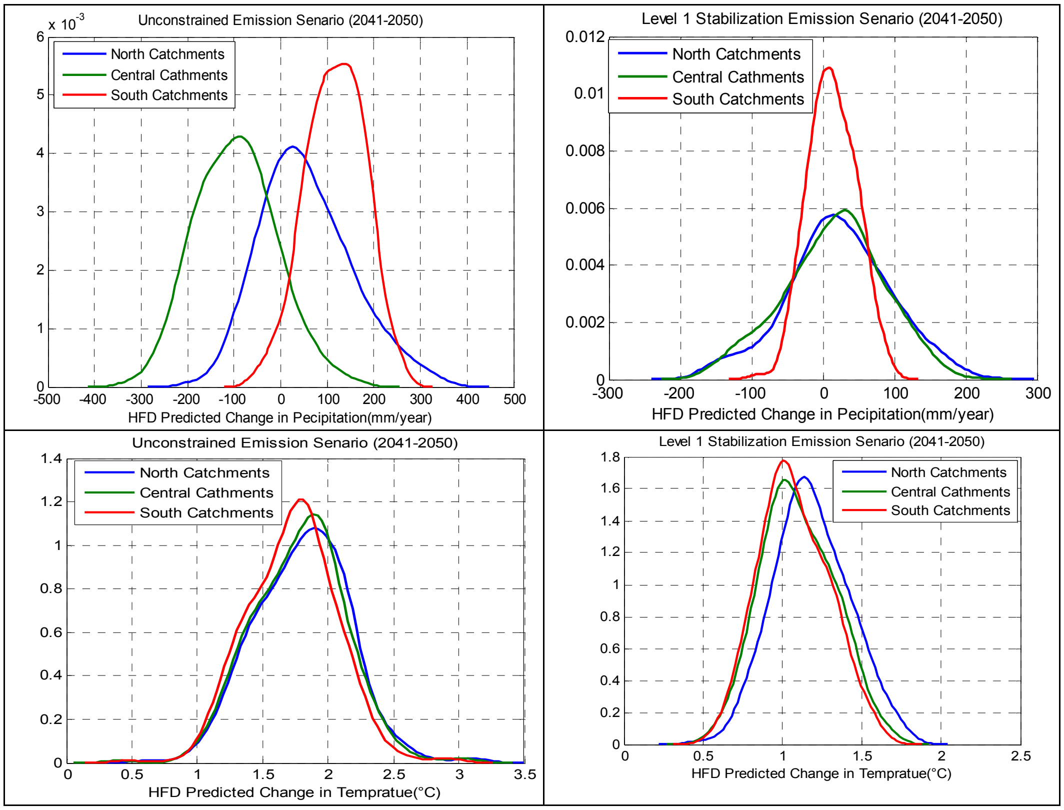

Figure 4: distribution of average temperature and precipitation for 2041-2050 corresponding to L1s and UCE emission scenarios for Congo Basin. Source: Generate by Author

We can observe to Figure 4 for the 2040s that for unconstrained emission scenario changes in precipitations are different spatially. The mode change of precipitation is negative for central catchments while for northern and southern catchments it is close to zero and positive respectively. The temperature however remains positive with average value of 1.25 degrees rise for all the catchments. Similarly, for level one stabilization scenarios, the temperature rise reaches 1.75 degrees.

3.4. Filtering

Although, the HFD scenarios have relatively less noise as compared to IPSS AR4 outputs it was still necessary to filter some noise from the data to utilize the information effectively. A simple moving average technique with a 6 month window was employed to reduce the level of noise and separate the dominant signal from climate projections.

3.5. Quadrature thinning technique

Combinations of future base-case uncertainty ensembles together with the HFD GCM outputs will create huge number of scenarios which might be not practical to process. Following the techniques presented in (Arndt et al. 2006) later expanded to the application on HFD Climate Variables, (Arndt et al. 2012) demonstrated application of Gaussian Quadrature Sampling to systematically select sample of representative scenarios from the ensembles of possible HFD scenarios mentioned above designed to represent the full distribution of likely climate in Zambezi Basin.

A simplified version of filtering technique is devised based on Arndt et al. Gaussian Quadrature Sampling to systematically select sample of representative scenarios from the ensembles of possible HFD scenarios mentioned above designed to represent the full distribution of likely climate in Congo Basin. The idea behind this technique is identifying the dominant aspect of the distribution of future climate variables through 12 summary variables chosen appropriate to the particular analysis. This is then followed by using the summary variables and selecting a set and assigning a weight from the parent distribution where the moments of the distribution of the sample is equal to the moments of the parent distribution out to order three for the summary variables. Therefore, the scenarios will be reduced to manageable number without losing much information.

The selection of the 12 variables is based on a computed 3 indicators. Climate Moisture Index (CMI) (eq. 1) and indicator of overall hydroclimatic conditions and water availability and it computed average for the years 2030-2039 and 2040-2050; standard deviation of precipitation which is an important representative of seasonal variability, and maximum temperature. These four variables will be computed for each of the three regions identified in Congo River basin making a total of 12 summary variable

$$.CMI = \begin{cases} \left(\frac{P}{PET} - 1\right) \; if \; PET > P \\ \left(1 - \frac{P}{PET}\right) \; if \; PET < P \end{cases} \qquad \dots. (1)$$

3.6. Scenario ensembles

Five sets of scenario ensembles are generated. The first set contains "Natural variability" scenarios, in which historical climate variables are systematically resembled using surrogate sampling technique discussed above to produce an ensemble of 500 synthetic climatic scenarios. This provides the first set of uncertainty in natural variability of the hydrologic system. This set also represents possible combinations of future precipitation and temperature to be used as future base-cases when producing the hybrid scenarios.

The second and third sets of ensembles are based on Climate Change uncertainties imposed over single historical time series, which we will hereafter simply refer to as "HFD scenarios". HFD scenarios corresponding to the two levels of policy adaption, i.e. unconstrained Emission and

Level one stabilization represent uncertainty in Climate Change (both structural and emission) Out the 6800 raw HFD scenarios quadrature thinning technique was applied to select 400 members to formulate the HFD scenarios used in our models for each of these two policy of adaptions.

The remaining two sets of scenarios are generated based on the combination HFD Climate change shocks with different historical base-case i.e. Combination Natural variability scenarios and HFDs and following a thinning procedure to bring down to manageable number of scenarios providing a total of 500 members for each set of ensembles, we will refer to them as "Hybrid scenarios". When 400 HFD scenarios and the 500 member synthetic climatic scenarios are combined it produces total of 200,000 unique members. This was thinned down again to 500 members providing the third set of ensembles.

3.7. Biophysical models

3.7.1 Data and Models

The biophysical model set consists of three models ; (1) Hydrologic model to translate precipitation and temperature to runoff and stream flow (2) a crop model to estimate crop water irrigation requirement and (3) A water resource modeling tool for computing monthly hydropower generation. The dataset used in this study for temperature and precipitation is obtained from Climatic Research Unit (CRU)[2]. Historical monthly data set for global land areas from 1901 to 2002, gridded at two different resolutions (2.5° latitude by 3.75° longitude and 5° latitude/longitude) has been constructed and is available for use in scientific research (Hulme 1992, 1994, Hulme et al. 1998, Mitchell et al. 2004). For the crop modeling, daily climate data was

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[2] gu23wld0098.dat' (Version 1.0) constructed and supplied by Dr Mike Hulme at the Climatic Research Unit, University of East Anglia, Norwich, UK. This work has been supported by the UK Department of the Environment, Transport and the Regions (Contract EPG 1/1/48)."

required and therefore daily precipitation at spatial scale of 1-degree by 1-degree was obtained from the Land Surface Hydrology Research Group at Princeton University (Sheffield et al. 2006). This dataset was adjusted to match the CRU monthly dataset.

3.7.2 Hydrologic and Crop Model

Climate Runoff Model (CLIRUN-II), a two-layer one-dimensional rainfall-runoff model, was used to simulate the hydrologic response of Congo and Zambezi River Basins for the different projected climate scenarios of precipitation and temperature discussed in 0. CLIRUN-II is one of the latest models in a family of hydrologic models developed specifically for the analysis of impact of climate change on runoff (Strzepek, et al, 2008) which has a built-in Modified Hargreaves model (Droogers & Allen 2002) to compute Potential evapotranspiration. Reader is referred to (Strzepek et al. 2011), (Arndt et al. 2012), (Fant et al. 2012) and (Gebretsadik et al. 2012) for further reference on some previous application of CLIRUN-II on climate impact studies. The modeling procedure involves calibration of model parameters for historical observed runoff data and using the calibrated parameters to generate the corresponding runoffs for each ensemble of scenario.

The upstream of Inga Hydropower catchment of Congo River was delineated in to 26 smaller sub-basins and Zambezi Basin was divided into 29 hydrologically significant sub-basins to capture the spatial variability of the hydrologic systems but optimize the biophysical modeling effort. Each sub-basin was calibrated based on Historical precipitation data obtained from CRU and observed stream flow data at different location. The catchment division for Congo and the corresponding precipitation pattern for the different zones is illustrated in Figure 5.

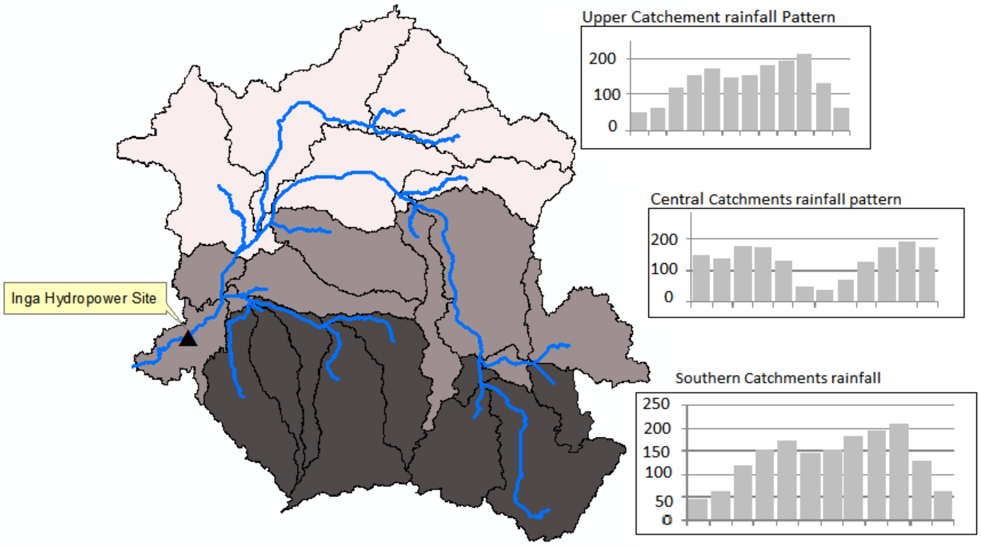

Figure 5: Catchment division and rainfall pattern of the Congo River basin.

In Zambezi basin there is about 260,000 ha of irrigated land. In addition to change in stream flow, changing climate will also affect crop water requirement and thus irrigation demand, which is one of the essential input to the water resource model. Therefore, it was necessary to incorporate a crop model to estimate the irrigation demand for Zambezi basin. CliCrop , first introduced by (Fant 2009) to simulate the impact of the baseline and climate change scenarios on rain-fed and irrigated crop yields and on irrigation water demand. (Fant et al. 2012) demonstrates the application of CliCrop model in the context of climate change general assessment modeling. In this study CliCrop was used to estimate changes in crop water requirement and thus producing the corresponding irrigation water demand to be used in the water resource management model.

3.7.3 Hydropower Generation model

Water Evaluation and Planning (WEAP) system developed by the Stockholm Environment Institute (SEI). WEAP is a demand- priority and preference-driven water resources planning model and it is used for simulation of Hydropower generated from runoff. The Grand Inga dam was represented with runoff river hydropower scheme with no significant storage. WEAP computes

Hydropower generation from the flow passing through the turbine with maximum turbine capacity and desired annual generation specified as an input. For every combination of scenarios ensembles identified hydropower computation was carried out through automating multiple runs.

Irrigation abstractions are not considered For Congo Basin at the current state of this study since no significant amount of withdrawal exists upstream of the reservoirs. Industrial and municipal withdrawals are also very small as compared to the total available water and thus for simplification of modeling and considering to reduce the computation time to run all the simulations Industrial and municipal abstractions are ignored in the WEAP modeling. For Zambezi the Irrigation demands computed from CliCrop were used as abstraction at different nodes.

4. Results and discussion

4.1. Runoff

Looking at impact on the runoff at Inga hydropower site average for the period of 2045-2050, results show that the mode change of runoff for the HFD ensemble is only about -1% (reduced runoff). However, there is a significant variance indicating a higher uncertainty, extreme values roughly ranging between -10% to +18%. The distribution, estimated using a kernel density approximation, is shown in Figure 6. The result for HFD scenarios are obtained by running the HFD climate shocks superimposed on a single historical base-case and computing the percentage of change in runoff by taking the ratios on the selected one historical base-case. The above outcomes in mode of runoff change are in accordance with results reported by (Mukheibir 2007) in which only a slight reduction in runoff as a result of climate change is reported for Congo river basin. For the Hybrid scenarios , that also include the natural variability into consideration, the first notable improvement over the HFD scenarios is a more spread in the tails of the density plots indicating a higher variance, we see that the extreme values now reaching -20% to +30%. . The magnitude of mode change of runoff has also changed slightly to +1% (increased runoff). For Hybrid scenarios the percent change is computed in reference to the corresponding base-case used from natural variability ensembles. Here multiple base-cases are used but since we are comparing the percentage change, the effect of the magnitudes of the base-case are filtered out and thus this impacts we find are just of the climate changes.

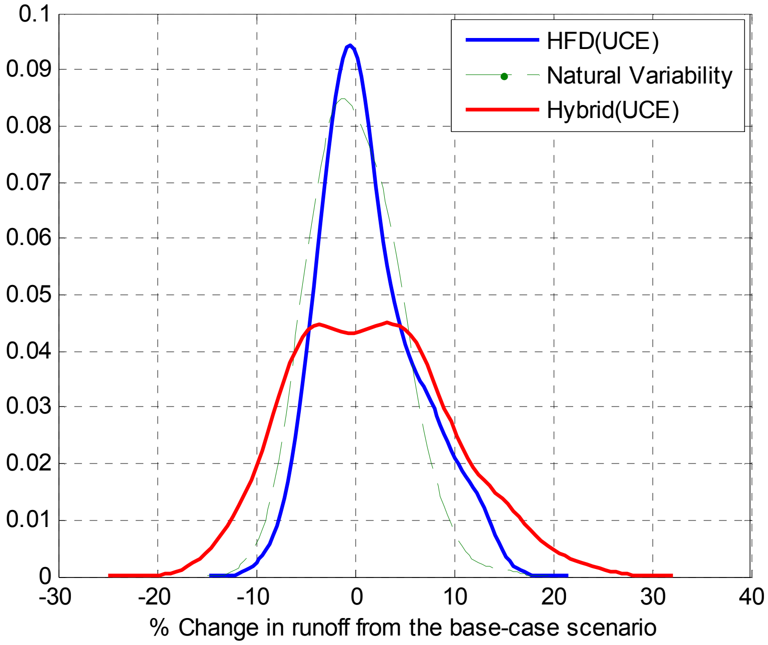

Figure 6: Congo Basin, Frequency distribution of Percentage change in Runoff 2045-2050 over the base-case for HFD and Hybrid scenarios under Unconstrained Emission scenario. Source: Generate by Author

The main reason for mode runoff in Congo basin being less vulnerable to changes in the climate variables is that the catchments area is characterized by high precipitation rate, the changes in precipitation predicted by HFD scenarios are small as compared to the total precipitation and thus the overall impact will be less severe. Additionally, the different parts of catchments are affected differently, increased precipitation in southern and decreased central catchments; this effect could cancel each other keeping the overall Congo River catchment relatively more resilient to the changes predicated by HFD scenarios. However, this will have less effect on the tails of the distributions and the uncertainty is still high since the variance is also a significant indicator.

For Zambezi basin unconstrained emission for HFD scenarios will result in 9% reduction of runoff and indicating overall drought in the basin. Hybrid Scenarios have shown to have a more pronounced effect as compared to the HFD scenarios Figure 7. The mode runoff changed to 16% indicating a higher climate risk. We can also observe a more spread in the tails of the density function the maximum change in percentage roughly going up to -60% from -40% on the negative side of the tail while the positive tail remains relatively unchanged.

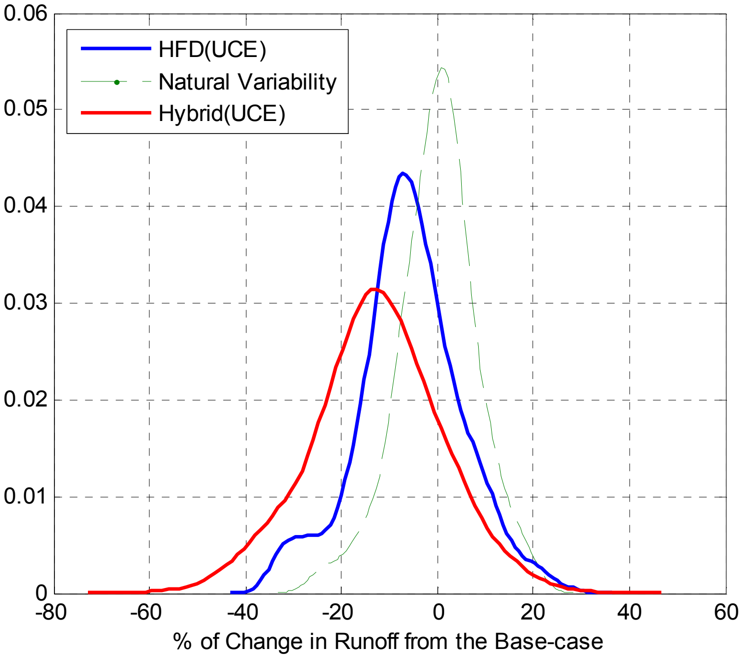

Figure 7: Zambezi Basin, Frequency distribution of Percentage change in Runoff 2045-2050 over the base-case for HFD and Hybrid scenarios under Unconstrained Emission scenario. Source: Generate by Author

From the two plots in we can notice that the Hybrid uncertainty approach seem to deviate from the HFD scenarios more in Zambezi basin than in Congo basin. One of the potential reasons for this is the range of natural variability. There is more variability, both inter and intra annual, in Zambezi than Congo basin. As can be refereed from the Figure 6 and Figure 7 , the mean annual runoff is shown to vary by only 10 % for Congo basin while for Zambezi it shows up to 30% of variability average for the period of 2045-2050. Furthermore the relative changes of precipitating for Zambezi basin is higher than Congo and the combination of higher variance and higher relative change would contribute to the as to why the Hybrid scenarios are showing more deviation in Zambezi than Congo.

4.2. Hydropower

Distribution of total hydropower generation for Congo in both the unconstrained emissions and Level one stabilization is roughly even in both the negative and positive side of the density function tails and the mode value is almost zero. Here the total Hydropower includes Inga I, II, expansion on Inga III and the future planned Grand Inga dam. There is an indication in a slight increase of generation in L1s emission scenarios, + 0.5% increase in the mode. The distribution of percentage of change in Hydropower generation from the base-cases for the time period of 2045-2050 is presented in Figure 8. We can further notice that for Inga Hydropower schemes, the uncertainties in hydropower generation by the end of 2050s as a result of the natural variability of precipitation and temperature are found to be more or less equivalent to the expected changes in Natural variability.

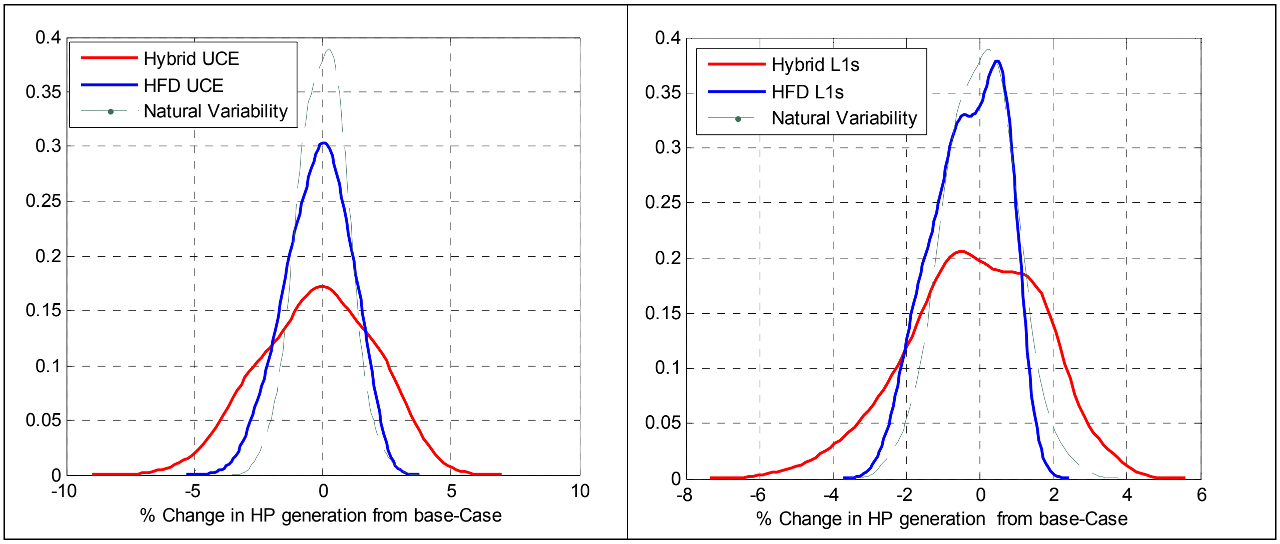

Figure 8: (Right) Comparison of HP generation average for the period of 2045-2050s for unconstrained emission between Hybrid, Climate change and Natural variability scenarios, total Congo Hydropower. (Left) Comparison of HP generation average for the 2045-2050s for Level one stabilization emission scenario between Hybrid, L1s Climate change and Natural variability scenarios, total Congo Hydropower. Source: Generate by Author

For Hybrid uncertainties, although the mode change is almost zero there is still a considerable spread in the tail of the density functions indicating a potential loss or gain of generating capacity ranging from -8% to 6% in UC E and to -6% to 5% in level one stabilization emission. Figure 9 compares the percent of change of hydropower generation between Hybrid UCE and L1s scenarios. Although there is a slight change in the distribution the improvement on the impact by restricting the emission level is not as significant as it is in Zambezi basin.

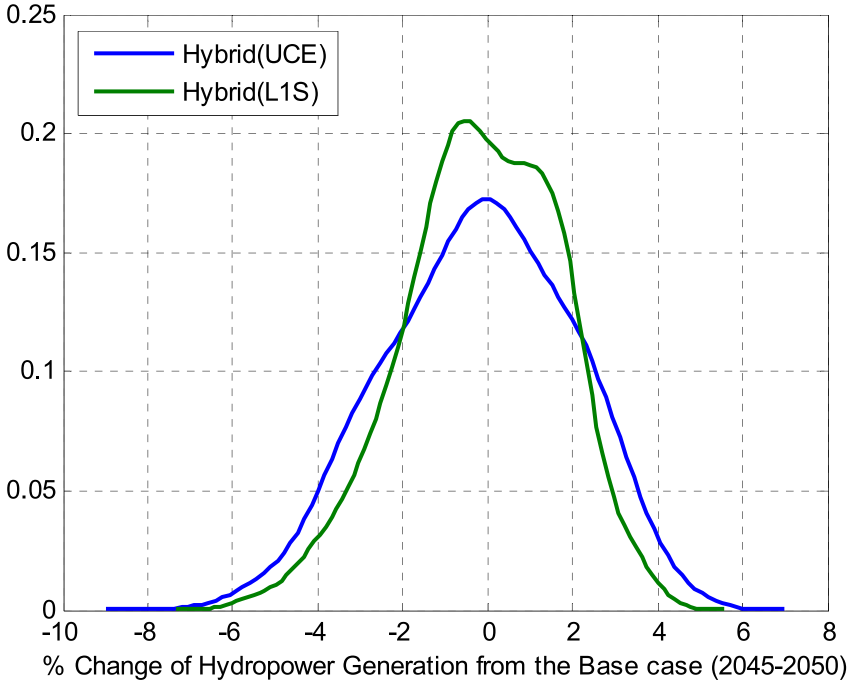

Figure 9: Comparison of HP generation average for the 2045-2050 between unconstrained emission and Level 1 stabilization emission scenarios for Hybrid uncertainties. Source: Generate by Author

Result of total hydropower generation for Zambezi basin is shown in Figure 10. There will be a general loss of hydropower generation in the basin. The Hybrid scenarios have estimated the mode to reduce by -10%. This result is an improvement over the HFD scenarios which show about 5% reduced generating capacity. The variance is also improved by 50%, extreme values ranging roughly from -30% to +10% while for HFD scenarios these figures were -15% to 8%.

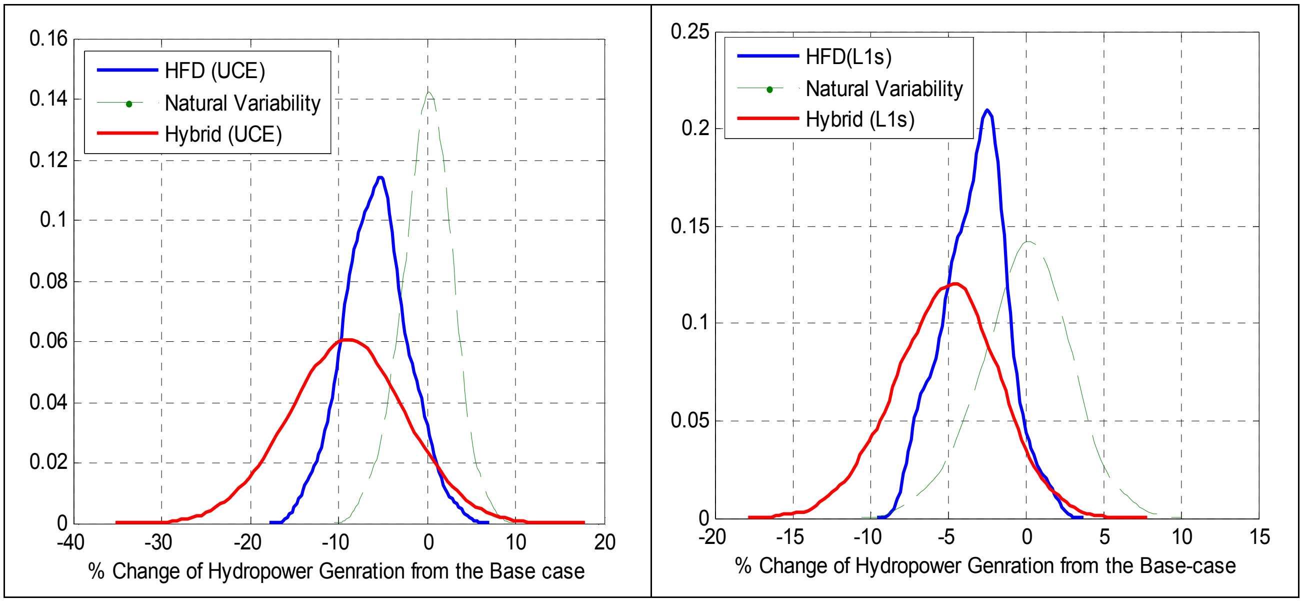

Figure 10: (Right) Comparison of HP generation average for the period of 2045-2050s for unconstrained emission between Hybrid, Climate change and natural variability scenarios, Zambezi. (Left) Comparison of HP generation average for the 2045-2050s for Level one stabilization emission scenario between Hybrid, L1s Climate change and Natural variability scenarios, Zambezi.

Between the two Emission scenarios, unlike the Inga hydropower schemes, we can see a 5% improvement in mode on the Level one stabilization scenarios, Figure 11. Indicating considerable gain in the mitigation policy of restricting the emission level. Furthermore, the spared in the tails of the density function has also shown improvement by nearly 50% indicating a reduced uncertainty in the level of impact for Hydropower in Zambezi basin.

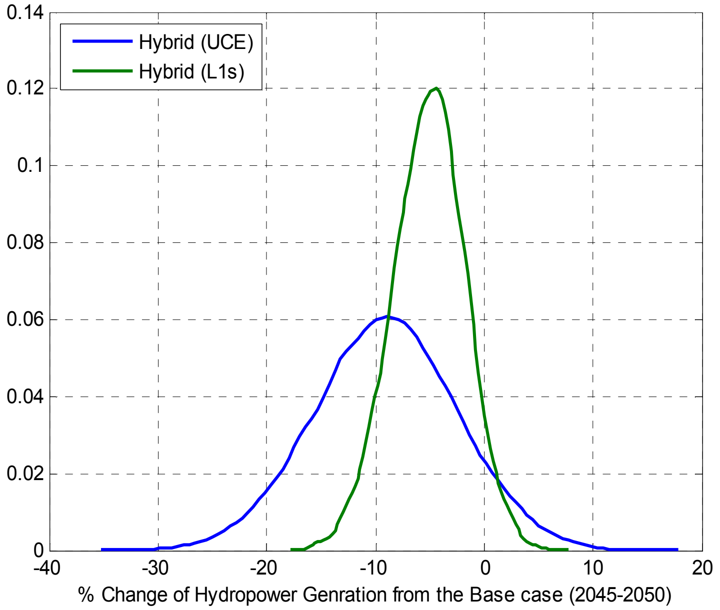

Figure 11: Comparison of HP generation average for the 2045-2050 between unconstrained emission and Level 1 stabilization emission scenarios for Hybrid uncertainties, total in Zambezi basin. Source: Generate by Author

5. Conclusion

This section has demonstrated the application of hybrid uncertainty approach to basin-wide climate change assessment. Results have indicated improvement over the traditional delta-change approach in both the mode and range of uncertainties. The findings support the initial claim that the traditional 'single base-line' approach underestimates the uncertainties involved predicting future impact on hydropower and water resources management in general. Particularly, in the areas with high natural hydroclimatic variability it is more important to consider the variability in the impact assessment exercise in order to be able to accurately explain the inherent uncertainty of climate change impact on basin-wide hydropower generation and careful consideration should be given to the natural variability as the combined effect is more pronounced.

It is also worth noting that alike to the case of runoffs, results from hybrid uncertainty approach seem to diverge from the HFD scenarios more in the Zambezi basin than in the Congo. In addition to the previously discussed two reasons, the combination of higher natural variability and smaller ratio of change in climate variables over the total magnitude, this more pronounced divergence of the hybrid uncertainty scenarios is that fact that the water resource system is complex and more non-linear in Zambezi than in Congo due to the storage in the reservoirs and irrigation abstraction in Zambezi water resource system. All the hydropower units in Congo are modeled as a runoff river and thus relatively less complicated than Zambezi.

The integrated modeling approach presented here to produce hybrid uncertainty scenarios by making use of synthetic ensembles and quadrature selection approach can be used as an alternative methodology of scenarios generation where more rigorous assessment may be required in the subsequent climate change impact studies.

Chapter 3

Joint variability assessment of hydropower between African power pools and the potential impact of climate change induced shift in variability

Abstract

This chapter utilizes the concept of Empirical Orthogonal Functions (EOFs) analysis technique to access the join spatio-temporal patterns of interannual variability of hydro-climatic variables relevant to hydropower generation between African power pools. EOF analysis of annual streamflow data, simulated for major sub-basins based on monthly time step hydrologic model, was conducted followed by investigation of the resulting dominant spatial patterns to identify locations of existing and future potential hydropower sites which indicate a homogeneous or a heterogeneous pattern of variability. Results indicated a distinct out-of-phase pattern of variability between Southern and West African Power pools. Congo River basin also shows minimum correlation with all the other power pools indicating the synergetic benefit that could be obtained if the long term plan of connecting Grand Inga hydropower to the other power pools is realized. Possible impact of climate change induced shift in variability was also investigated for hydropower locations in Zambezi and Congo River basins based on 100 years of simulated hydropower generation data. Results show climate change induced change in variability will have little impact with regards to changing in-phase and out-phase pattern of generation.

1. Introduction

Regional power integration and cooperation through power pools has long been realized as one of the most effective ways of ensuring reliability in supply of energy. Particularly in Africa, where spatial distribution of power potential and demand is highly uneven, the need for regional grid interconnection has been recognized as the best strategy to increase access to electricity and satisfy the ever increasing energy demand which is essential to support the rapidly growing economic activity in many African countries (Tshombe et al. 2007). Southern Africa power pool (SAPP) is one of the successful examples of an operational regional interconnection in Africa currently playing a significant role in power exchange and trade among SADC countries.

Hydropower and fossil fuels are currently the two major sources of electricity in Africa. However, hydropower remains the most common and preferred source particularly for Sub-Saharan Africa due to is it relatively cheap and clean energy, accounting about 51% of the total supply. Recent figures indicate a total installed capacity of 20.3 GW with a hydro production capability of about 76 TWh/year (Water for Agriculture and Energy in Africa 2008) while the total potential of continent is estimated around100,000 MW . Majority of the potential is concentrated at central and eastern Africa with a large portion in Democratic Republic of Congo, Ethiopia and Cameroon total generating capacity estimated at 774 TWh, 260 TWh and 115 TWh per year respectively.

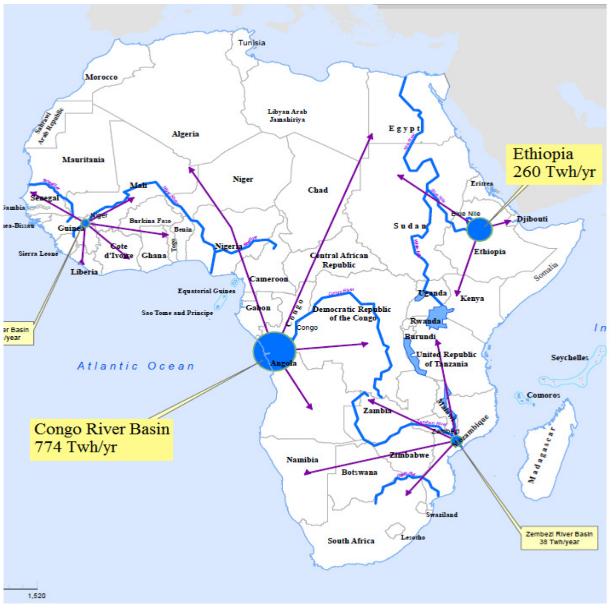

Figure 1 Estimated Hydropower Potential in Africa and opportunities for possible regional interconnections. [Source: Atlas of African Transport & Energy Infrastructure (2003)]

In addition to creating a means for exchange and trade of energy between the different utilities involved in a power pool, one of the main technical advantages of interconnection is realized in the increased power system reliability that is obtained through reserve sharing. In the case of hydropower driven power pools this is achieved by hydro complementarity, a drought in one river basin may be offset by production from other basins. Interconnected system of hydropower units take maximum advantage when their water availability (and thus generating capacity) is out-of-sync .i.e. opposite timing of shortage and surplus so that the shortage in one or more of the components can be offset by the surplus in another basin making the overall system more resilient to annual fluctuation in resource availability. This synergistic integration makes hydropower interconnection more effective and attractive for investment. Due to this reason, different scales of variability of hydropower generation is particularly more important to a system of interconnected units than to a single hydropower. It is therefore highly relevant to find a technique that measures complementarity of hydro-climatic variables related to hydropower generation which can be an input to for both regional interconnection as well as for national energy sector development planning and management.

The first part of this chapter applies the concept of Empirical Orthogonal Functions (EOFs) analysis to assess the joint correlation of hydro-climatic variables relevant to hydropower generation between power pools to identify a possible spatio-temporal pattern of common variability between them. Identifying regions of homogeneous or heterogeneous pattern of variability can be an essential input to decision making during the planning or management of interconnections.

Climate change induced shifts in inter-annual variability and seasonality of the flow is one of the potential impacts pointed out by the IPCC Special report on renewable resource, hydropower (Kumar et al. 2011), Changes in variability could affect the system in two possible ways; by either driving the generating units to be in-sync reducing the total efficiency of the grid system resulting in poor load factor or make them be out-of-sync, to which case could add more reliability to the system.

This potential change in variability and its impact has been overlooked by many climate change impact studies. Most assessments focus on how the change in magnitude of climate variables such as precipitation and temperature will change the hydroclimatic characteristic of a catchment and thus stream flow, and subsequently looking at how the hydropower generation will be impacted in comparison with the no-change scenario.

Changes in variability (both short and longer time scale) and timing of stream flow can lead to reduced hydropower production (Kumar et al. 2011) even with no change in average runoff. Possible cause of change invariability and shift in runoff timing can be caused by temporal difference in temperature and precipitation changes and shift as a result of different spatial impact of climate change (Cherry et al. 2010) or could be attributed to change in large scale regional or global climate phenomena, e.g. ENSO. (Ghil et al. 2002).

The second part of this chapter applies similar joint correlation technique to investigate change in reliability of interconnected system of hydropower under changing climate. Examining closely in more detail to look at impact in Southern Africa Power Pool (SAPP) which includes, the existing hydropower systems in Zambezi river basin, existing Inga 1& 2 in Congo River basin and the future potential member of the system Grand Inga Hydropower. Initially by looking at the existing interannual variation of hydropower generation at each location and finding the spatio-temporal correlation of interconnected systems of existing and future planned hydropower plants. Secondly, looking at how climate change induced changes in the variability could affect their spatio-temporal pattern of variability for the different scenarios under investigation.

This paper is organized as follows. The Section 2 provides general overview of Hydropower and existing power pools in Africa .Section 3 outlines the data source and methodology. Section 4 presents characterization of existing joint spatio-temporal relation between the different power pools. Section 5 discusses results of joint variability under changing climate for Congo and Zambezi hydropower. Section 6 give conclusion and remarks.

2. Hydropower and Power Pools in Africa

There are primarily five major power pools in in Africa. (I) the Eastern Africa Power Pool (EAPP) (II) the Central Africa Power Pool (CAPP) (III) the West Africa Power Pool (IV) ,The Southern Africa Power Pool (SAPP) and (V) the Comité Maghrébin de l'Electricité (COMELEC)[1].

- *East African power pool*

East Africa has the second largest potential but with only about 20% of its capacity developed. The Eastern Africa Power Pool (EAPP), established in 2005, is a specialized agency of the COMESA with 9 member countries which aims at facilitating power supply to the countries of the Eastern Africa Region. The current Members countries are Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Libya, Rwanda, Sudan and Tanzania. Potential Member Countries are Uganda, Djibouti, and Eritrea. According to figures from 2011, EAPP total installed capacity is estimated about 26,374 MW. Out of the total hydropower is about 24% (6,725 MW) (Infrastructure Consortium for Africa (ICA) 2011)

- *West Africa power pool*

The West African Power Pool (WAPP) is a cooperation of the national electricity companies in Western Africa under the backings of the Economic Community of West African States (ECOWAS). The total generating capacity of the region is estimated at 9,912 MW, in which 35% of that is from Hydropower. Nigeria and Ghana are the two major hydropower generators in the region

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[1] Also referred to as Northern Africa Power Pool

- *The South Africa power pool and the Grand Inga*

The Southern African Power Pool (SAPP) is a cooperation of twelve state-owned power utilities in Southern African Development Community (SADC) countries established in 1995 and have been playing the main role in creating a plat form for centralized power trade in the countries. At present its members are the utilities and ministries involved in energy usage in Angola, Botswana, Democratic Republic of the Congo, Lesotho, Mozambique, Malawi, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe.

Total current available generating capacity estimated as of 2013 is reported to be 52,102 MW (SADC Regional Infrastructure Investment Conference 2013) in which about 18% of that comes from Hydropower, Table 1 . The three largest existing hydropower sites existing within SAPP are at Inga, DRC (1775 MW), Hydro Cahora Bassa, Mozambique (2075 MW) and Kariba, Zambia–Zimbabwe (1470 MW).

Table 1: Existing Power Generating Capacity (MW) in SAPP , [Source: (IRENA International Renewable Energy Agency 2013)]

	Country	Oil	Coal	Gas	Nuclear	Hydro	Total
1	Angola	89		174		474	737
2	Botswana		132				132
3	DRC					2,333	2,333
4	Lesotho					73	73
5	Malawi	36				278	314
6	Mozambique	64				2,122	2,186
7	Namibia	29	115			240	384
8	South Africa	2,424	36,360		1,616	665	41,065
9	Swaziland					62	62
10	Tanzania	79		640		561	1,280
11	Zambia	10				1,752	1,762
12	Zimbabwe		1,026			750	1,776
	Total	**2,731**	**37,633**	**814**	**1,616**	**9,310**	**52,104**

The prime focus of future potential supplier of energy in this region is in Democratic Republic of Congo (DRC), the Grand Inga site. This hydropower project has an estimated capacity of 40,000 MW with the potential to boost the generating capacity of the region significantly that could even possibly be shared between the different power pools in Africa, (Tshombe et al. 2007). There are also other significant sites on the Zambezi river which include, but not limited to, Batoka Gorge(1600 MW), Devil's Gorge (1240 MW) , Mepanda Uncua (1780 MW), (Economic Consulting Associates Limited 2009).

- *Interconnection options between power pools*

In the long-term, the Grand Inga hydropower potential could be developed to integrate the power system interconnections of the sub-regions in Africa and become the major contributor of affordable clean energy. As of today, feasible identified power highways include (i) Northern Highway the DRC -Congo-RCA-Sudan-Egypt interconnection (ii) Western Highway the DRC – Congo – Gabon - Cameroon-Nigeria interconnection (iii) Southern Highway the DRC-Angola-Namibia-Republic of South Africa . These electricity highways would potentially supply the five African power pools: SAPP, WAPP, PEAC, EAPP and COMELEC (World Energy Council 2011)

3. Data and methods

3.1. Hydro-Climatic Datasets

The dataset used in this study for temperature and precipitation is obtained from Climatic Research Unit (CRU)[2]. Historical monthly data set for global land areas from 1901 to 2006, gridded at two different resolutions (2.5° latitude by 3.75° longitude and 5° latitude/longitude) has

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[2] gu23wld0098.dat' (Version 1.0) constructed and supplied by Dr Mike Hulme at the Climatic Research Unit, University of East Anglia, Norwich, UK. This work has been supported by the UK Department of the Environment, Transport and the Regions (Contract EPG 1/1/48)."

been constructed and is made available for use in scientific research (Mitchell et al. 2004), (Hulme et al. 1998), (Hulme 1994) and (Hulme 1992). For the crop modeling , which was necessary to determine irrigation water demand in Zambezi basin , daily climate data was required and therefore daily precipitation at spatial scale of 1-degree by 1-degree was used from the Land Surface Hydrology Research Group at Princeton University (Sheffield et al. 2006). This dataset was adjusted to match the CRU monthly dataset. The University of New Hampshire, in collaboration with the Global Runoff Data Center (UNH-GRDC)[3] global half-degree, monthly runoff fields were also used as the observed runoff to calibrate the hydrologic model.

3.2. Biophysical models

This study follows up on the models and methods used in the chapter 2 of this publication. Climate Runoff Model (CLIRUN-II), Water system modeling tool (WEAP) and a crop model (CliCrop) results were adopted for Zambezi and Congo basins. Reader is refereed to (Strzepek, et al, 2008) ,(Fant 2009) and (Yates et al. 2005) for further description of these models. In general, the analysis consists of modeling runoff and major crop water demands where it was required such as irrigation demand in Zambezi basin. Surface water inflows from runoff model and crop water requirement from the crop model were used as input to an aggregated basin model in WEAP (Yates et al. 2005)

The scope of analysis illustrated in chapter 2 was is limited to Congo and Zambezi basins it was therefore necessary to include additional biophysical analysis to model Africa wide runoff

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[3] Fekete, B., T. Maurer, and C. J. Vörösmarty. 2011. ISLSCP II UNH/GRDC Composite Monthly Runoff. In Hall, Forrest G., G. Collatz, B. Meeson, S. Los, E. Brown de Colstoun, and D. Landis (eds.). ISLSCP Initiative II Collection. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.

to estimate 100 years of monthly runoff for each USGS Level 2 classifications basins (Verdin 2002).

For Congo basin the major hydropower plants, mainly the four Inga dams and for Zambezi a total of 17 the major planned and existing projects were included in the water resources model which are summarized in the Table 2.

Table 2 List of hydropower plants considered in water resources systems modeling in Zambezi and Congo Basins. Data source: (World Energy Council 2011) & (The World Bank 2010)

Name	*Basin*	*Capacity (MW)*	*Name*	*Basin*	*Capacity (MW)*
Inga 1	Congo	351	Victoria Falls	Zambezi	108
Inga 2	Congo	1424	Iztezhi Tezhi	Zambezi	120
Inga 3	Congo	4320	Batoka Gorge*	Zambezi	1600
Grand Inga*	Congo	40,000	Kafue Gorge L*	Zambezi	600
Cahora Bassa	Zambezi	2075	Kholombizo*	Zambezi	240
Kafue Gorge U	Zambezi	990	Lower Fufu*	Zambezi	100
Kapichira	Zambezi	64	Mphanda Nkuwa*	Zambezi	2000
Lake Kariba	Zambezi	1470	Rumakali*	Zambezi	256
Nkhula Falls	Zambezi	124	Songwe I,2,3*	Zambezi	340

(*) planned hydropower plants

3.3. Climate Change scenarios

Schlosser et al. (2011) introduced “hybrid frequency distributions” (HFD) ,regionally downscaled model scenarios, numerical hybridization of 400 members of policy ensembles from the IGSM results of (Sokolov et al. 2005) ,(Webster et al. 2011); for each 17 IPCC AR4 climate model results producing a meta-ensemble of climate change projections containing 6,800 distinct members for different possible adaptation.

These HFDs datasets are the latest available characterization of possible future climate outcomes which combines uncertainties in Structural difference of climate models, in downscaling and possible emission scenarios as represented by the different policy of adaption.

Climate change scenarios in temperature and Precipitation are taken from this dataset to represent the uncertainties in future case of climate variables. These dataset are generated for different policy of adaption however two of them are selected and used in this assessment 1) unconstrained emission (UCE) scenarios where no policy action is taken to limit greenhouse gas emissions 2) 'level one stabilization' (L1S) where restraints are imposed on global emissions to limit greenhouse gas concentration at 560 ppm CO2 equivalent, as defined in (Webster et al. 2011). From this large dataset about 400 of them are selected by quadrature thinning technique discussed in 3.5

3.4. Empirical Orthogonal Functions

Empirical Orthogonal Function (EOF) Analysis, also referred to as Principal Component Analysis (PCA), is an analytical tool that uses orthogonal linear transformation to convert a number of possibly correlated variables in into a set of linearly uncorrelated variables, called principal components, that capture as much of the variability in the data as possible at each succeeding component. This powerful technique can also be used to characterize patterns of similar variability by identifying how the variations are correlated across different variables. Reader is referred to (Preisendorfer 1988) for further detailed mathematical formulation EOF analysis. (Bjornsson & Venegas 1997) and (Storch & Zwiers 1999) also discuss in detail particular application of this method to climatic time series data analysis . (Kim & Wu 1999) provides a comparative analysis of the different variation of EOF analysis techniques in identifying independent patterns from a dataset for Climatic time series.

EOF analysis technique has been employed in understanding the principal modes of climatic variability of atmospheric variables in a number of studies e.g. (Janowiak 1988) , (Antunes et al. 1990) , (Mann et al. 2000), (Kahya et al. 2008), (Bordi et al. 2004) , (Badr et al. 2013) . It provides a measure of temporal correlation between spatially distinct time series climate variables and gives indication on how the time series variables under consideration are evolving in time together (Bjornsson & Venegas 1997).

In the present chapter , the application of EOF analysis to look at joint spatio-temporal variability bases at exploiting two basic concepts (1) examination of the resulting dominant spatial patterns, or the EOFs, to identify those hydropower locations which indicate a homogeneous or a heterogeneous variability. In the first step, characterization of existing variability without adding climate change scenarios, the resulting EOFs can directly be used as indicators to assess whether these spatial variables under investigation have homogeneous or heterogeneity pattern by simply looking at the signs and magnitudes of the Eigen values. (2) When looking at how this joint variability are changing under scenarios of climate change we apply the transformation on two parts of the resulting time series data on each one of the corresponding HFD climate change scenarios. We divide the series into two, before and after 2030. For the first half of the data the resulting spatial pattern should more or less give us the same EOF as in the existing pattern since the impact of climate shocks are minimal of non-existent . We then compare this result with the EOF pattern obtained on the second half of the data where detectable effects of climate change are expected to emerge. Looking at the expansion coefficients or the EOF time series that is obtained through should also reveal if there are any changes in terms of percentage share of variance captured by subsequent dominant principal axis.

The data matrices are formulated such that the rows represent the time and columns represent the spatial variables. In the case of Africa wide assessment, the spatial variables are basin runoff and precipitation. For Zambezi and Congo Basins analysis the spatial variables are power generation results obtained from the water resources systems model at each hydropower plant, equation (1).

$$F_i = \begin{bmatrix} x_1^1 & x_1^2 & \dots & x_1^p \\ x_2^1 & \ddots & & \\ \vdots & & \ddots & \\ x_n^1 & & & \end{bmatrix} \qquad \dots\ (1)$$

where $\mathrm{x}_\mathrm{t}^\mathrm{j}$ represents, power geberation of hydropower plant j at time step t

EOF computation is carried out using singular value decomposition (SVD) method on the correlation matrix Z of the data matrix F to factorize it into three matrices given in equation (2)

$$Z = U * D * V^t \qquad \dots(2)$$

Where U and V are orthonormal and D is diagonal matrices known as known as the singular values of Z. Then, the loading patterns and EOF time series are given as equations (3) and (4) respectively.

$$EOFs = V \qquad \dots\ (3)$$

$$ECs = U * D \qquad \dots.(4)$$

Although there are a number of studies carried out to look at variability patterns of precipitation using EOF and some on stream flow, little work has been reported in literatures on application of this method to look at joint variability of hydropower to assess their generating modes of variability. Example of these type of analysis applied on Africa wide studies are (Badr et al. 2013) and (Janowiak 1988). These two studies presented assessment of the inter-annual variability of precipitation over Africa at annual and seasonal scaled using EOF. Results were then used to regionalize areas of homogenies precipitation variability patterns. Other similar studies conducted on inter-annual variability streamflow is (Lins 1985), which looked at interannual modes of streamflow variation at 106 locations across the United States and (Kahya et al. 2008) , which identified zones having similar streamflow variability. In current analysis we are extending this concept to look at variability in hydropower generation in Congo and Zambezi river Basins and explain any disparities on the climate change scenarios vis–à–vis historical conditions.

4. Characterization of Historical joint variability

As mentioned before, mapping of selected dominant modes of EOFs could easily reveal if the time series variables under investigation are varying together or behaving oppositely. We looked at precipitation and runoff as an indicator of power generation for Africa. Result of EOF analysis is highly sensitive to the relative scaling of the original variables specially if there is significant difference in variance. For example, the variance both of precipitation as well runoff for Congo basin is much higher in magnitude than other parts of Africa. To avoid the dominance of a set of variables, therefore, it was necessary to use correlation matrix by scaling the original time series data by the standard deviation for the computation EOFs as suggested by many authors (Bjornsson & Venegas 1997) , (Hannachi 2004) and (Storch & Zwiers 1999). Furthermore, dry parts of Africa such as Sahara, Nubian, Somalian, Namib and Parts of Kalahari desert were masked out of the analysis.

4.1. Variability annual precipitation pattern

EOF analysis of annual precipitation in Africa across the identified 90 USGS level 2 basin classification for 100 years of CRU monthly precipitation dataset is carried out to explore the modes of variability and investigate if there is different pattern of variability between the major basins of Africa. About 50% of the total variance can be explain in the first 5 PCs.

Figure 2 shows the first 4 modes which hold about 45% of the variance. Result indicate that the first variability mode, that shows precipitation varying in same way in all regions , explains a large fraction of the variance (20%) although there is a slight variation between the eastern and western part of Africa they more or less vary together in the same way. the northern African catchments are dry basins with no significant amount of precipitation .The second EOF, which explains 10 % of variance shows opposite variation between central west coast and rest of the continent. The third and the fourth EOFs which account 13% of the variability together show clear opposite behaviors between central and southern regions more obviously between lower Congo and Zambezi versus west coast basins.

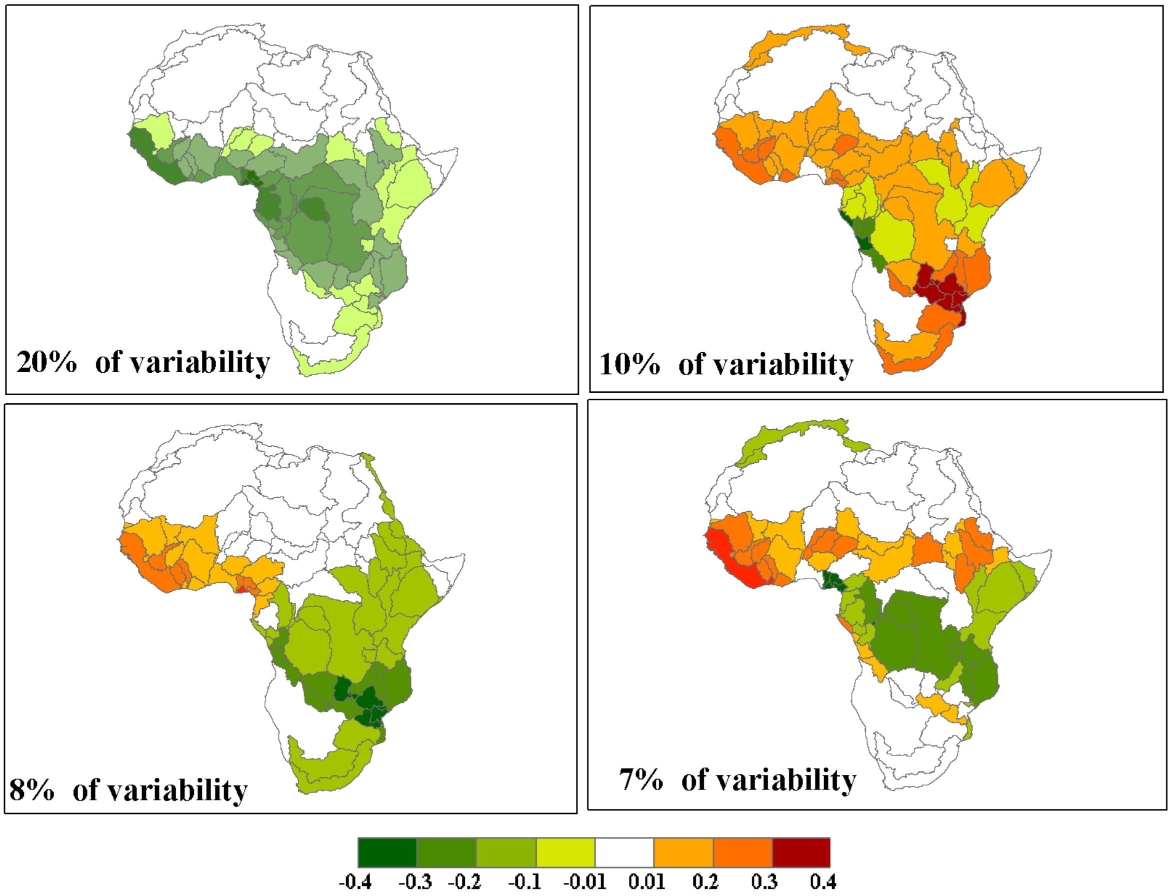

Figure 2: The first four EOFs of the monthly precipitation for Level 2 basins

The results obtained are more or less in accordance with the results reported in some previous studies e.g. (Badr et al. 2013). (Badr et al. 2013) uses Hierarchical Clustering Analysis (HCA) to further identify regions of homogeneous variability at different levels. The results Based on the 4 regions level indicates that, Northern Parts of Congo Basin, Central-West Coast Basins , South Sudan and the Ethiopian part of the Nile basins are classified in the same region, where as Zambezi and West African Basins Share the same pattern of variability.

Even though the above analysis gives a general picture of the hydrologic property of the catchment with regards to precipitation, it is not however, a strong indicator to hydropower generation since accumulated streamflow at basin outlet is different from the basin average precipitation in most of the cases therefore it is necessary to expand the result and analysis further on streamflow.

4.2. Joint variability in annual runoff pattern

Hydropower generation is a function of the discharge through turbines, the available net head under which the turbines operate, and the efficiency of the turbine-generator group. Monthly hydropower generation for dams with storage reservoir the net head is equally important as the discharge but annual generations are more or less linearly correlated with annual streamflow. In the present study since we are mainly interested in the inter-annual variability thus the authors believe that taking annual discharge as a general measure of hydropower generation is a reasonable assumption for preliminary assessment. Furthermore, monthly discrepancies of power gaps can be accommodated by storage and alternative reservoir management plan and change in operation. It will be beyond the scope of this study and the assumptions made to look at monthly level since detail information regarding reservoir operations are required. Therefore, this section bases at using annual streamflow as a coarse indicator of hydropower generation for Africa wide preliminary assessment.

We make EOF Analysis of runoff for Africa based on calibrated runoff data obtained from CLIRUN on 100 years of monthly dataset. The two dominant spatial patterns are presented in Figure 3. In the first EOF, which accounts for 21% of the total variance, we see a distinctive out-of- phase pattern of variability between the Western and Southern Africa power pools. From interconnection point of this is highly desirable and it indicates a potential benefit that can be exploited through interconnecting these two systems. Similar strong out-phase pattern of variability is also observed between Eastern and Southern Power pools. Another feature that we can detect from the results is that the Congo River basin, particularly the lower part where all the Inga dams including Grand Inga is located, is not correlated either of the North as well as the Southern Power Pools. This is a positive result with respect to the long term plan of connecting Inga to the three power pools.

Due to the reason that the Congo River basin lies on both side of the equator it holds the inter-annual variability characteristic of basins on both above and below the equator. As illustrated in chapter 2 of this study this characteristic is also reflected on the monthly time series. The upper and lower part of Congo catchments have different seasonal pattern of flow when this two flows are combined they provides an all year stable flow at the location of Inga dams which makes Inga dams very suitable for runoff hydropower generation. This central location of Congo basin is also what is making the interannual variability pattern be out-of-phase with both with the Eastern, Western and Southern part of Africa.

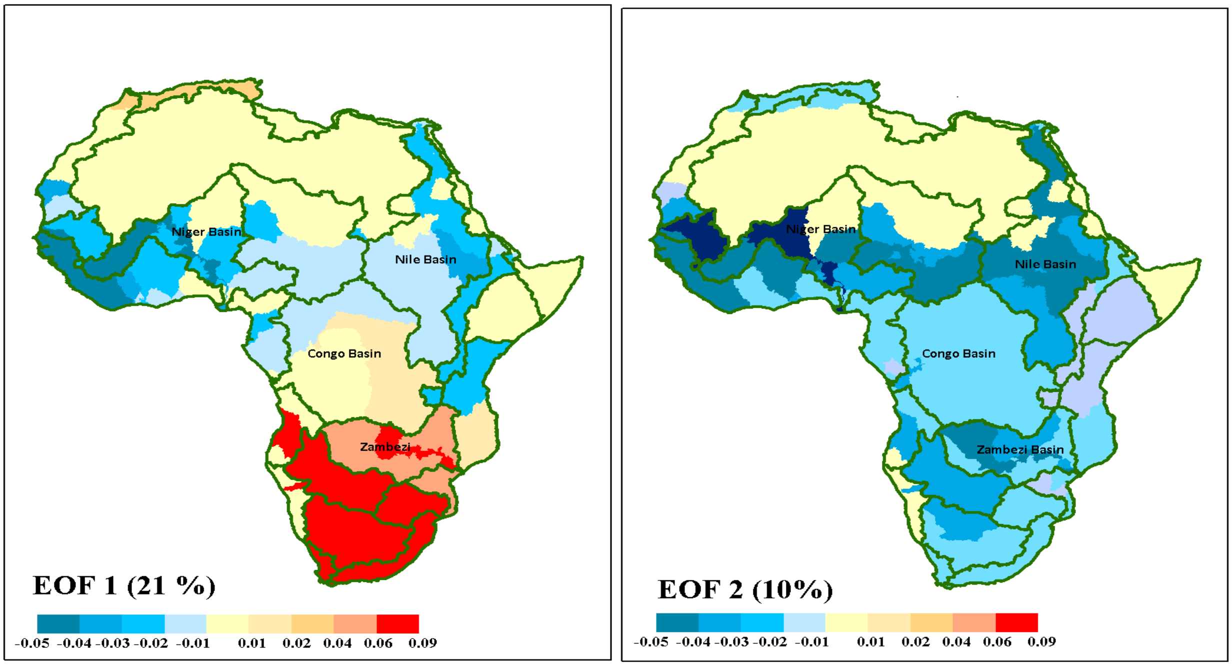

Figure 3: The first two EOFs of the Annual stream flow for Level 2 basins

In smaller scale also, we can further identify other interconnection opportunities from inter-annual variability perspective. For example interconnecting Kenya's hydroelectric generations to either Ethiopian Rift valley or Tanzania and Zambia systems would result in a more resilient supply of energy to annual fluctuations than that to hydropower plants in Southern Ethiopia catchment, which it is in-phase with as shown in Figure 3.

4.3. Correlation with SST pattern

Precipitation pattern in southern part of African is dominantly modulated by Sea Surface Temperature (SST) from the Atlantic and Indian Oceans (Mason and Jury , 1997). Gaughan & Waylen (2012) has shown that ENSO phase has a stronger influence in certain part of Zambezi catchment. However, no significant correlation pattern was observed between EOF time series of the dominant PCs of the accumulated runoff can and PCs of SST as can be observed in Figure 4.

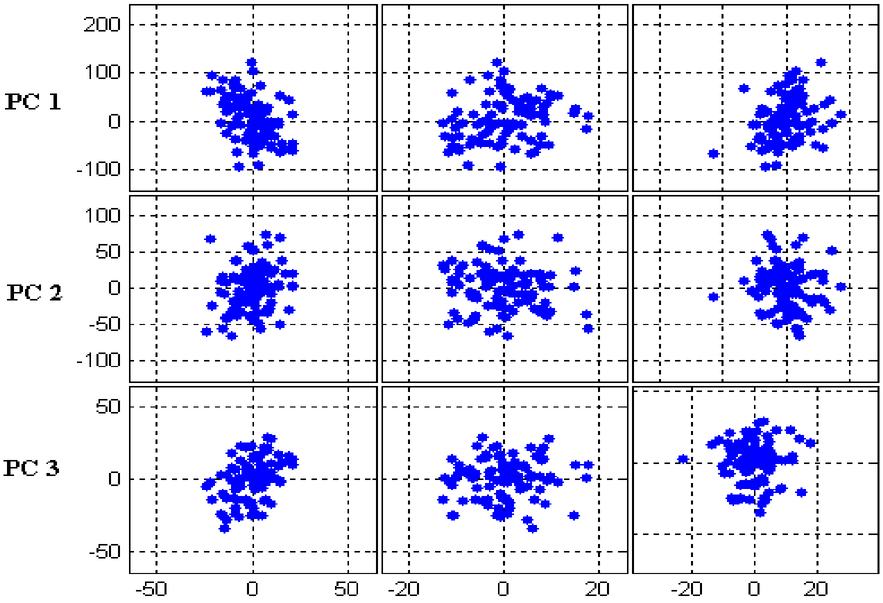

Figure 4 Correlation plot between Annual SST PCs and Dominant PCs of runoff annual accumulated

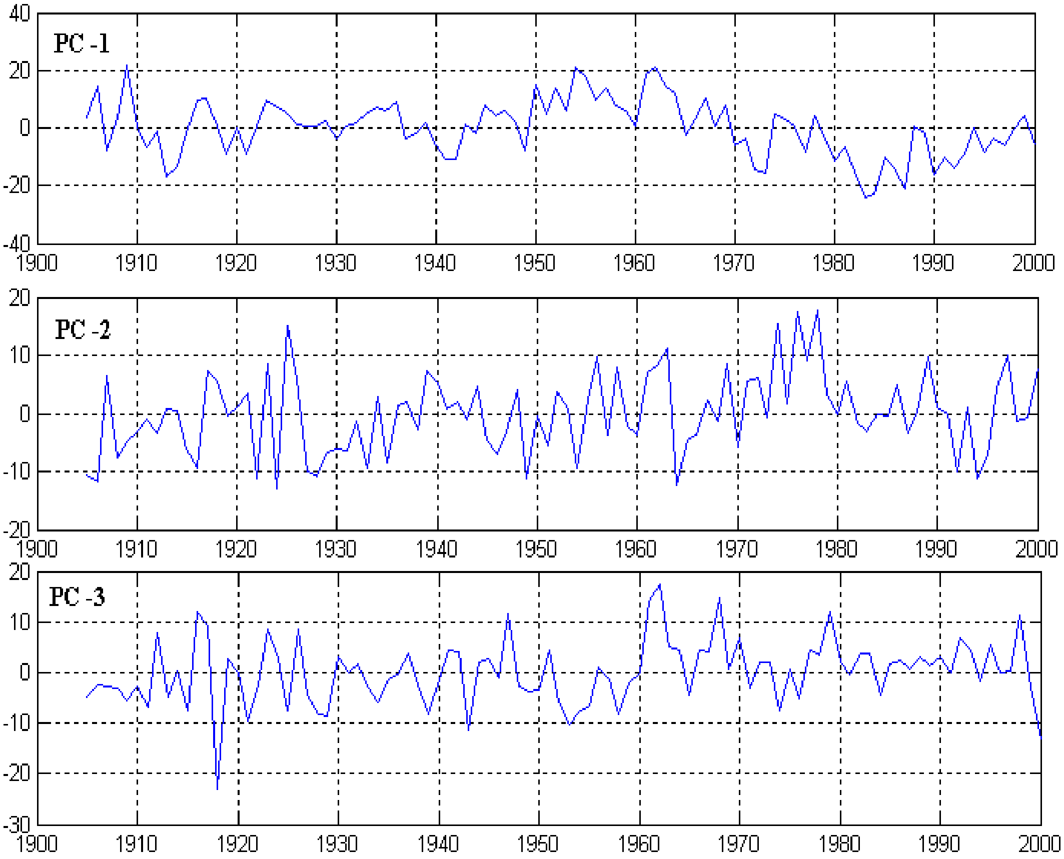

Figure 5: Annual-mean PCs of the fire three leading eigenvectors of the 1903–2000 Southern and Central Africa runoff.

4.4. Variability Hydropower generating pattern for Congo and Zambezi river basins

More detail analysis was conducted for Congo and Zambezi River basin based on actual power generation. Hydropower modeling was carried out to simulate power generation for 100 years of streamflow data available on monthly level for existing as well for planned Inga Hydropower schemes in Congo. Based on detailed generating capacity followed by EOF analysis on the hydropower plants is to assess the joint correlation of variability of annual generation between the power plants. Here our spatial variables are annual generation pattern of Energy at each Hydropower unit a total of 4 hydropower units in Congo and 17 in Zambezi.

Again since the variance of HP generation has much larger orders magnitude at Grand Inga dam then all the others combined thus the EOF analysis was conducted on scaled and detrend residuals. The results indicate that the first two EOF capture 75% of the variance, 45% and 30 % for first and second EOFs respectively,

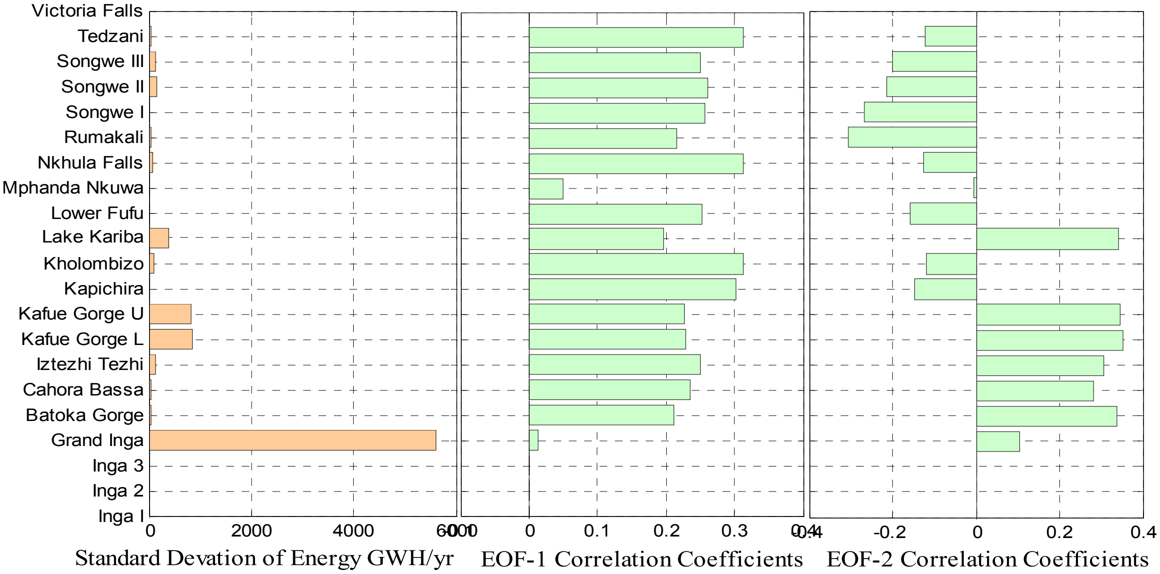

Figure 6 Dominant EOFs of generating pattern between Congo and Zambezi basin.

As can be referred from Figure 6, EOF 1 shows common pattern of variability for all Zambezi hydropower for 45% of the variability which is accordance with the result obtained in the runoff analysis. For EOF 2, however, we can observe that not all hydropower dams have similar pattern of variability almost 50% of the dams are out of phase with the remaining. It is important to iterate that the standard deviation of hydropower generation of Grand Inga is more than five times greater than any of the existing or future planned hydropower projects in Zambezi therefore pattern of variability between Inga vs. Zambezi hydropower might in actual case be more important to the overall system than pattern of variability among the dams in Zambezi.

5. Joint variability under climate change for Congo and Zambezi hydropower

We carried out similar approach to conducted EOF analysis for each one of the HFD climate change scenarios. There are a total of 320 unique scenarios (obtained from analysis in Chapter 2) and hydropower simulation followed by EOF analysis on the resulting generating patter was conducted for each one of the scenarios. A subset of the data ,the second half of the time series where the impact of climate is significant, was selected and this was compared with the result obtained from the first half where effect of climate change is not that prominent or no existent.

For the EOF-1 which holds about 45% of the variance, almost no noticeable change was observed between the join correlations. However for EOF-2 slight changes were coming to emerge. The results are presented in Figure 7 below for all the unconstrained emission HFD scenarios. As can be referred from the plot in majority of the cases the join spatio-temporal relationship remains the same for almost 92% of the scenarios. However, about 2 % of scenarios are showing a detectible change from the reference scenario, indicating a chance in which the generation could be in-sync between Cong and Zambezi hydropower generation more prominently for extreme dry and wet scenarios.

For the Level one stabilization scenarios the changes are almost negligible which indicates the small chances of the hydropower plants getting to be in-phase detected in the unconstrained emission cases could be prevented by the restrained emission policy where greenhouse gas concentration is limited at 560 ppm CO2.

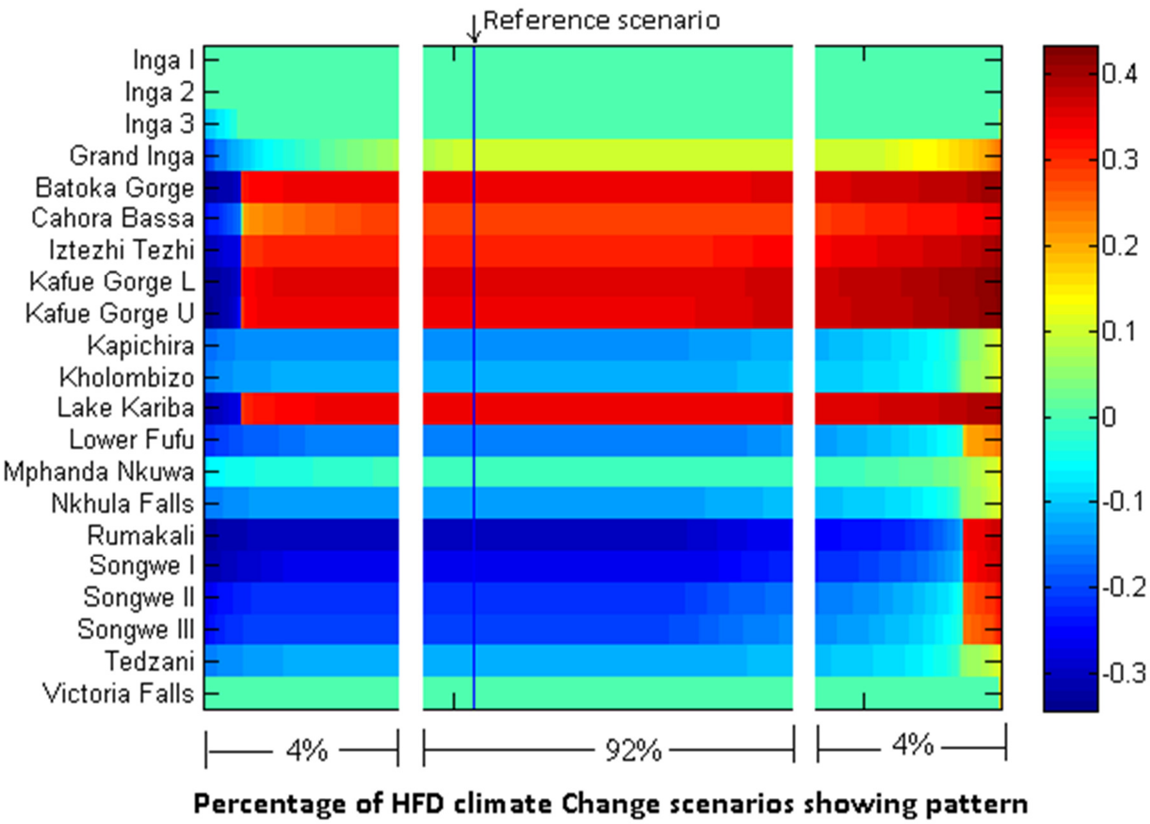

Figure 7: EOF 2 (10%) variability spatial pattern of hydropower generation for the identified climate change scenarios Congo and Zambezi.

To isolate and look at the impact between overall Zambezi and Grand Inga, the correlation coefficient were averaged and one indicator was produced for each basins. Subsequently, the relative change between those two was computed taking the difference between the two averages to get one indicator of how far Zambezi and Congo will be diverging from the base case scenario. This difference is shown as a histogram plot in Figure 8. Majority of the scenarios are showing little or no change but some scenarios still indicate possible change as shown scattered between 0 and 0.2 in the histogram plot.

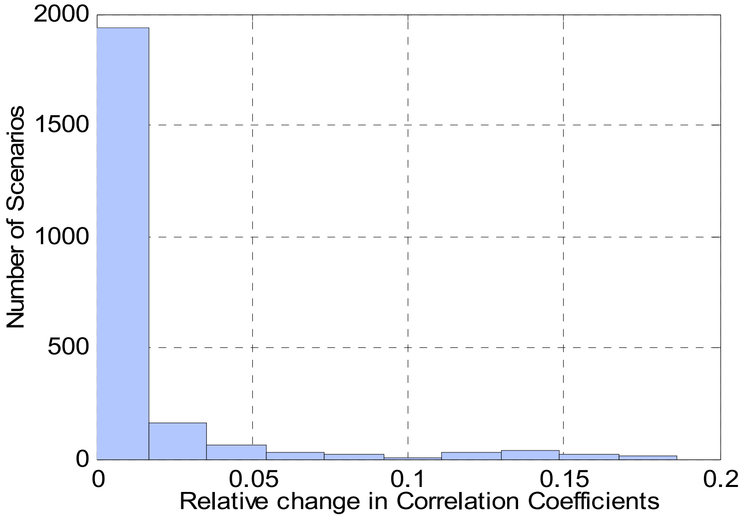

Figure 8: Relative change of correlation coefficients between Zambezi and Congo

6. Conclusion

The method of Empirical Orthogonal Functions (EOFs) analysis in accessing joint spatio-temporal pattern of variability allowed the detection of homogeneous or heterogeneous pattern of variability between different hydropower pools in Africa. The strong out-phase pattern of variability observed between Eastern and Western power pools versus the Southern Africa Power pools reinforce the importance of integrating these power pools in terms of adding resilience to the overall system from inter-annual fluctuation point of view .

Furthermore, the method was applied to investigate if there could be any impacts as a result of climate induced changes of variability but in the time domain this analysis was conducted the impact was found to be very minimal.

It is important to stress here that analysis like this do not consider the actual magnitude of fluctuations into consideration and the conclusion that are drawn are simply based on the pattern of variability. The significance of similar or opposite pattern of variability could highly depend on the magnitude of inter-annual fluctuations and economic values of generated energy at the respective locations.

In general, continental wide power integration between the different pools in Africa would result in a more reliable supply of energy market which is resilient to drought and inter-annual fluctuations. The role that Grand Inga hydropower could play in this regard is considerable not only because of its huge generating potential but also due to its strategic central location which makes its it both feasible and less expensive for building transmission and distribution networks running to the different end of Africa and the fact that it is annual variability is out-of-phase with most part of the continent as findings from this study have demonstrated.

Chapter 4

Optimized reservoir operation model of regional Wind and Hydro power integration Case study: Zambezi Basin and South Africa

Abstract

The present study develops a reliability assessment method of wind resource using optimum reservoir target power operations that maximizes the firm generation of integrated wind and hydropower. A combined water resources model for a system of reservoirs that implements a priority based linear programing algorithm and a single node power grid system model is implemented on an hourly time step. This model was then accompanied by a genetic algorithm solver to determine optimum operation targets for each storage reservoir aiming at maximizing the 90th percentile power generation produced by the integration of wind and hydro over the entire simulation period.

This model is applied on the reservoir storages and hydropower system in the Zambezi river basin to demonstrate how storage reservoirs could be used to offset wind power intermittence in South Africa subjected to different physical and policy constraints. Based on the optimized target operation and hourly annual real data for the year 2010 , the water resources system and power interconnection system were simulated together to assess the maximum firm generation of power as a result of the new wind and hydro combination target for storage hydropower plants.

The result obtained indicates that high regulation of wind and hydro can be achieved as a result of combined operation and showed an increased level of wind penetration in South Africa's power system over the reference scenario. The result also indicated a reduced level of coal power utilization and less cycling requirement. This will have a positive outcome in terms contributing

to South Africa's goal towards reducing greenhouse gas emission and the efforts to build green energy supply and resilience to the impacts of climate change

1. Introduction

Technologies in utilizing wind energy have made considerable progress in the recent years. As a result, efficiency of wind power harvesting as well as forecasting has been improved considerably. Due to its clean and cost-effective renewable supply of energy, wind power has become an attractive investment and the world's fastest growing energy resource. Yet the penetration[1] of this renewable resource remains low in most power grid systems due to the inherent intermittent nature of resource availability. In addition to its variable characteristics it is also often difficult to control or easily adjust the power output. Consequently, wind energy is considered a highly non-dispatchable source of energy. Exploitation of this resource still remains one of the biggest challenges. The use of complementary or other dispatchable energy resource in integration with wind has been one of the effective ways to make the wind power more usable.

Hydropower has been one of the cheapest and environmentally clean option to coordinate with intermittent power sources such as wind and solar power. Hydropower stations with a storage reservoir are highly dispatchable. Power generation can be scheduled in less than an hour time step with continuous startups and shutdowns without a significant damaging effect on the infrastructure service life. Due to this nature they are very suitable to be used as energy storage facilities, "batteries", to store water during high wind periods, and release this water to produce electricity when it is needed.

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[1] Penetration refers to the fraction of energy produced by wind compared with the total available generation capacity.

This integrated operation of wind and hydro has been the topic of some studies and there is a growing interest in developing efficient ways of coordination in order to increase the over economic and environmental advantage of this intermittent energy sources. Castronuovo and Lopes (2004) presents a linear hourly-discretized optimization method to determine optimum daily operational strategy based on availability of a 24-hour forecast for wind power by aiming to maximize the 24-hour operational economic gain of wind and hydro. Jaramillo et al. (2004) also illustrated a model of operation of a wind–hydro-power system, from which a constant supply of firm power can be achieved by the combined operation. The model bases as operating reservoirs to meet a firm demand by filling gaps in wind generation and ignoring the fluctuation of load on the system. A study by Karki et al. (2010) shows a Monte Carlo simulation approach to evaluate reliability of wind and hydro coordination, it employs a time series wind speed model to represent the stochastic nature of wind power. Bélanger & Gagnon (2002) also shows wind and hydro combined simulation using on hourly time strep for 6 years of actual data of patterns of electricity demand. Clement (2012) employed the RiverWare[2] modeling system to evaluate hydropower and wind integration for different levels of wind penetration based on physical characteristics of the hydropower system that accounts for realistic power and non-power policy constraints. It also provided an economic evaluation to investigate the implications of non-power constraints. Other similar relevant studies on wind and pumped storage schemes are Bueno & Carta (2006) and García-gonzález et al. (2004).

This study develops a reliability assessment method of wind resource using optimum reservoir target power operations that maximizes the firm generation of integrated wind and

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[2] RiverWare is a water resources systems model and a decision support tool developed and maintained by The Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado Boulder.

hydropower. A combination of linear programming hourly water resources model and Genetic Algorithm solvers are combined to determine optimum operation strategy for multipurpose storage reservoirs that yield maximum firm generation over one year of the simulation period. The proposed frame work optimizes resource utilization both at a time step level as well as over the entire period of simulation. This proposed model is tested on South Africa's wind resource and Zambezi hydropower plants to come up with an integrated operating plan that maximizes over all regional benefits of firm power availability.

South Africa is looking to aggressively develop wind resource by 2040 to increase penetration of wind up to 20% by bringing the total installed capacity to 23,000 MW. However, with a lack of strong complimentary dispatchable energy sources the penetration goal might be too optimistic. A possible opportunity to explore through the existing coordination of power trade with SAPP countries is the use of storage available in the Zambezi basin to coordinate wind resource with hydropower. A successful integrated operation of wind and Hydro could increase the reliability and usability of wind resource. We test the model presented in this study to see if this can be achieved.

This chapter is laid out as follows. Section 3 presents the main data sources used in the study followed by Section 4 which presents the computational methodology and detail description of and mathematical formulation of each model. Section 4 presents results of simulation of South Africa and Zambezi wind-hydro system. Finally, section 5 provides concluding remarks.

2. Data sources

Temporal resolution and time span of analysis are important parameters especially for studies that explore integration of different energy resources. Multi-year simulation on hourly time step has been recommended by authors (Hasche et al. 2009) to accurately depict the intermittency of wind power as well as to conduct a robust assessment of the long term reliability through capturing the effect of interannual variability of both resource availability and power demand fluctuation. For this study, an hourly time step was used to run models and analysis was conducted over one year of simulation span. The year 2010 was found to be a representative of average year for water resource availability. Accordingly, hourly electricity demand in South Africa for the selected year was obtained from ESKOM[3].

Ummel (2013) made use of hourly wind speed data from the GEOS-5[4] climate model and wind speed distribution data from WASA project to produce a wind power availability time series on an hourly time step for over 10 years of time span corresponding to ESKOM's four power system development plan scenarios (ESKOM 2012). This present study uses the data generated for the default 'Green scenario' which targets an aggressive development of wind resource to bring the total installed capacity to 23,000 MW resulting in a 20.4% penetration by 2040, Figure *1*. Reader is referred to Ummel (2013) for more detail information regarding the methods employed to produce wind energy data.

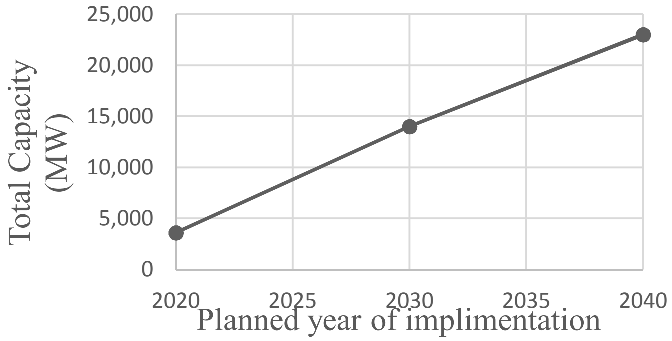

Figure 1 ESKOM plan wind implementation for GREEN scenario (Large Renewable Energy Generation)

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[3] ESKOM is a South African electricity public utility

[4] The Goddard Earth Observing System Model, Version 5 (GEOS-5) is a system of models integrated using the Earth System Modeling Framework developed in the GMAO to support NASA's earth science research in data analysis.

Source : The Strategic 2040 Transmission Network Study, (ESKOM 2012)

For the water resource model, the best stream flow data that was made available for this study was on a monthly time step. Water requirement for irrigation demand was available on daily time step based on outputs obtained from the CliCrop model discussed in Chapter 2 of this study. These datasets were discretized into an hourly time step on an equal interval basis. Although this approach appears to highly ignore the hourly as well as daily fluctuations of resource availability, it doesn't, however, introduce substantial error in the analysis of hydropower generation due to the high storage capacity of the reservoirs. Additionally, inflows to the large reservoirs, especially the ones found far downstream on the Zambezi River, are fairly regulated and impacts of the hourly fluctuation can sufficiently be ignored without introducing much error in the analysis.

Table 1: Summary of information on power capacity and generation. [Source: Calculation of the Emission Factor of the Electricity System of the Southern African Power Pool (GFA INVEST 2012)]

South Africa

Power Source	*Installed Capacity(MW)*	*Remark*
Gas/Diesel Oil	1,680	Existing(2010)
Pumped Hydro	2,000	Existing(2010)
Natural Gas	746	Existing(2010)
Nuclear	1,930	Existing(2010)
Sub-Bituminous Coal	37,755	Existing(2010)
Wind power	23,000	Planned Capacity under “Green” scenario

Energy Balance	*Energy (TWH/year)*	*Remark*
Generation	237	based on 2010 data
Consumption	214	based on 2010 data
export	14	based on 2010 data
imports	12	based on 2010 data
Losses	25	based on 2010 data

Zambezi

Hydropower Capacity	9,605 MW	Including capacity expansion

Environmental flow requirement and policies related to pattern and amount of downstream release for reservoirs were compiled from different sources. Cahora Bassa investment report (SWECO 1983) recommends seasonal environmental releases from the dam. Environmental Impact Assessment reports of feasibility studies for the reservoir projects were also utilized to get downstream release policies and the current practice of accommodating environmental flows from dams, (UTIP 2002). Other studies by Beilfuss & Brown (2010) and Nyatsanza (2012) were also used to update the indicative vales obtained.

3. Conceptual framework and system modeling

In order to simulate a real time operation of hydropower generation, it was essential to implement a river basin model on an hourly time step. In most of the cases reservoirs are multipurpose, operated to provide regulation to fulfil consumptive use of water, flood protection and other environmental requirements. Therefore a priority based reservoir operation model capable of managing different power and non-power constraints is presented in this study. This model is partly based on a demand- priority based optimized water allocation system introduced by Yates et al. (2005), but adopted to a smaller time step with integration of an hourly fluctuating hydropower operation target , river routing component and different policy constraints.

The water resource systems model uses a Linear Programming (LP) approach to optimized water allocation at a time step which aims at maximizing satisfaction of demand based on the priorities assigned for each water use namely ,consumptive water demand, flow requirement in rivers and hydropower generation. Each time step is independent of the other except for storage in the reservoir and decision variables responsible for river routing.

In conjunction with the water resources allocation model, a simplified single node power interconnection model is used to model power exchange between the different electric utilities involved. These two models interact at each time step to determine reservoir target operation and the different policy and physical constraints that must be satisfied.

Initially, these models were operated under a Genetic Algorithm (GA) solver to determine optimum operation targets for each storage reservoirs with the objective function set to maximize the firm power generation produced by the combination of wind and hydro over the entire simulation period. Using the optimized target operation and hourly annual real data for the year 2010 , the water resources system and power interconnection system was simulated together to assess the maximum firm generation of power as a result of the new wind/hydro combination target for storage hydropower plants in the Zambezi.

3.1. Water allocation model

The water allocation model solves different LP problems that are defined at each time step iteratively. These problems are determined based on the priorities and nature of demand (water demand, power demand and stream flow requirement). The algorithm that implements the methods for the main computational steps is illustrated in Figure 2.

```
for each time step
    for P in each priority grop
        $Max\ Z = \sum_{1}^{number\ of\ P} D_i$ , Maximize summation of demand coverage
        Subjected to
            - Water balance Constrains (Flow routing , Reservoir water balance)
            - Demand Coverage Constrains
            - Reservoir characteristic & operation levels (flood , conservation, min operation)
            - Fluctuations of downstream flow constraints (see section 4.4)
            - Equality Constraints of Solution from Previous priority group iteration

        Set result of decision variables for group P as equality constrains for next iteration
    Next Iteration for Priority grop P

    Set result of decision variables as equality constrains for next iteration

    $Max\ Z = \sum_{i=1}^{number\ of\ reserviors} S_i$ , Maximize reservior storage
    Subjected to
        - Water balance Constrains
        - Equality Constraints of Solution from previous iteration

    $Max\ Z = \sum_{1}^{number\ of\ P} E_i$ , Maximize houlry energy generation
    Subjected to
        - Water balance Constrains
        - Equality Constraints of Solution from Previous priority group iteration
        - Fluctuations of downstream flow constraints (see section 4.4)
        - Coal power generation cycling constraints (see section 4.5)
Next time step
```

Figure 2 Algorithm of linear programming based water resource allocation model

3.2. Power interconnection model

For power grid interconnection, a simplified single node interconnection model is implemented that assumes no transmission or distribution constraints. Other assumption are listed below:

- Losses in transmission and distribution are assumed to be directly proportional to the amount of power, and 8% of the annual energy is added to the electric consumption data when computing the electric power demand to account for these losses.
- The model also lumps together the existing power exchange between the other SAPP members and South Africa into Zambezi's power demand.
- The current target of power generation in Zambezi basin is to satisfy demand within the basin countries.
- Other sources of energy for Zambezi basin are not accounted besides hydropower. The energy demand indicated is for hydropower energy only.

Schematic diagram of this model of interconnection is illustrated in Figure *3*.

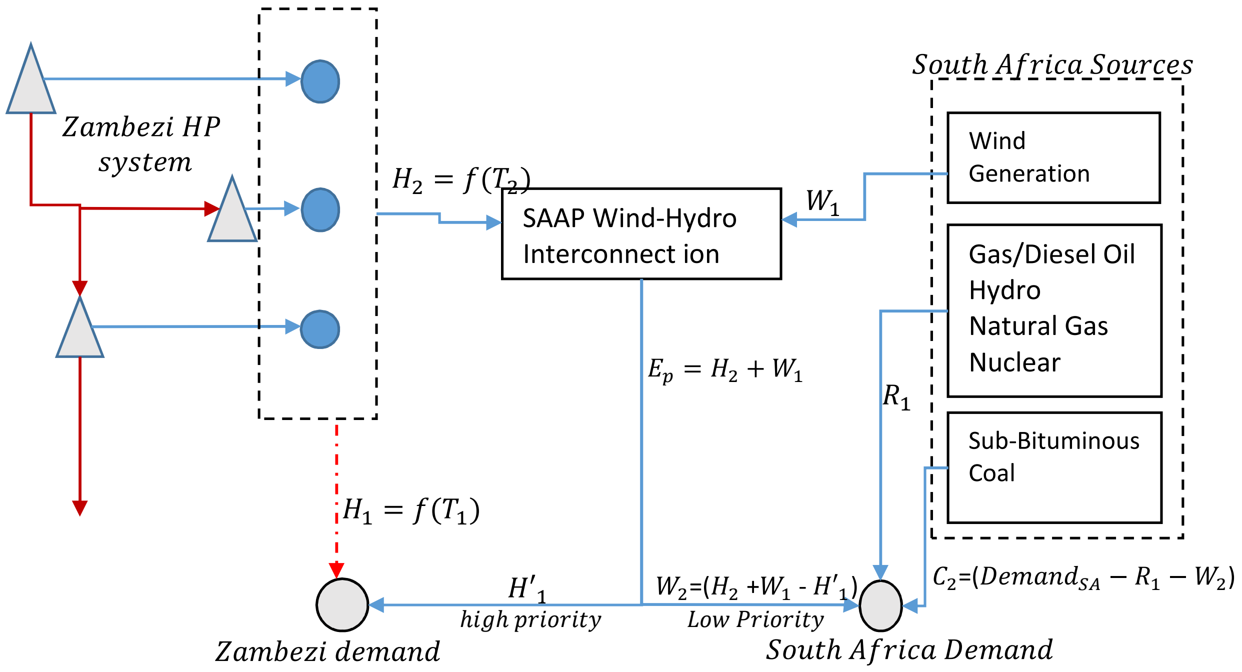

Figure 3 Schematic representation of power interconnection model for Zambezi and South Africa wind-Hydro integration

Where

W_1, Wind generation for South Africa under 'Green'scenario
H_1 , Total Hydropower generation from Zambezi basin in the present operation
H_2 , Hydropower generation from Zambezi basin in the modeified wind/hydro operation
T_1 , Current Target power operation of all Hydropower in Zambezi
T_2 , Modified Wind/Hydro Target power operation for all hydropower in Zambezi
E_p, Combination of Wind and Hydropower, Total energy availble in the Pool
H'_1, Total available Energy for Zambezi on wind/hydro operation
W_2, Total available Energy for South Africa Wind/Hydro Combination
C_2 , requred Coal generation to offset generation to meet demand
R_1 , Other source of Energy geenration in South Africa
$Demand_{SA}$, South Africa total power demand
$Demand_{ZA}$, Zambezi hydropower demand

In this configuration, both energy from hydropower plants and wind turbine will go into the pool and are distributed back to the demands of the Zambezi countries and South Africa. H_1 should ideally be equal to the target power T_1, i.e., existing combined generation of energy within the Zambezi is equal to the target in situations where there is no unmet energy demand in the system. However that is not often the case. There may be unmet power demand as a result of annual fluctuations of inflow to the reservoirs. Similarly, H'_1 refers to the energy available to meet the Zambezi country's demand in the new target configuration, which should also ideally be equal to the original power demand in the Zambezi countries. Therefore, the additional total loss or gain to countries in Zambezi as a result of this integration is the difference between H_1 and H'_1. Furthermore, it is also assumed any excess energy produced as a result of this combination will go to meet South Africa's demand. However, higher priority of power allocation is given for Zambezi to fulfil energy requirement in the existing situation. The remainder (W_2) will be made available for South Africa's consumption.

3.3. Determining energy target for reservoir operation

Operation target for hydropower is formulated such that a certain portion of the storage is used as a battery to save water when winds energy is available and the remaining is used to generate a regulated base power generation. The individual power target for each reservoir is formulated as equation (1)

$$T_i^t = \alpha_i^s T_T^t + (1 - \beta_i^s) H_{Cap_i} \qquad \text{... (1)}$$

Where, T_i^t is the total power target generation required from each storage reservoir and T_T^t is the total target required to modulate fluctuations in the wind energy at a time step *t*. H_{Cap_i} is the generating capacity of each reservoirs, excluding spinning and supplemental reserves. Total capacity (H_{cap}) given as summation of individual capacities expressed as equation (2) where n is number of reservoirs.

$$H_{cap} = \sum_{i=1}^{n} H_{Cap_i} \qquad \text{... (2)}$$

The coefficients α_i^s and β_i^s are seasonal multiplication factors for the percent share of total power required to regulate fluctuations in the wind energy and percentage of total installed capacity that should be used to generate baseload for each season s. These two seasonal factors are our decision variables in the GA optimization to determine the required optimum operation for each reservoir.

The second term of the equation refers to the portion of the target required for baseload generation. Incorporation of this baseload component in the target power is also dictated by the preliminary optimization results carried out based on target power which was expressed only by the first part of equation (1). Results indicate that using 100% of the reservoirs conservation storage to regulate the wind energy fluctuation does not provide an optimal option of operation which was reflected in terms of unmet power demand. This is because the streamflow will have some requisite flow determined by the LP component of the water resource model for the purpose of meeting demand requirement of both environmental flow the irrigation demand, the reservoir operation will not respond to all of the rapid fluctuating target assigned to compliment the wind power. (We will refer to this requisite flow as '*non-power release')*.Therefore, the baseload component was provided in the target in order to utilizing portion of non-power release to produce power.

Part of this non-power release is also used to ancillary services requirement, which accounts for 15% of peak demand, is allocated for spinning reserve based on figures obtained from the regional power sector integration study repot (Economic Consulting Associates Limited 2009).

Equation (1) requires the calculation of T_T^t . This is first calculated from the wind generation data given by equations (3) & (4). The main idea here is to set the generation target in the time steps where wind power is not available so that the summation of power generated from hydropower and wind could give a more regulated firm generation pattern. This target is then distributed to each reservoir based on the multiplier α_i^s.

$$T_T = \left(H_{cap} - W_1\right) > B_T \qquad \text{... (3)}$$

$$B_T = \sum_{1}^{n} \left(H_{Cap_i} * \beta_i\right) \qquad \text{... (4)}$$

The definition of α_i^s and β_i^s together with the corresponding two components of equation (1) are illustrated in *Figure 4*.

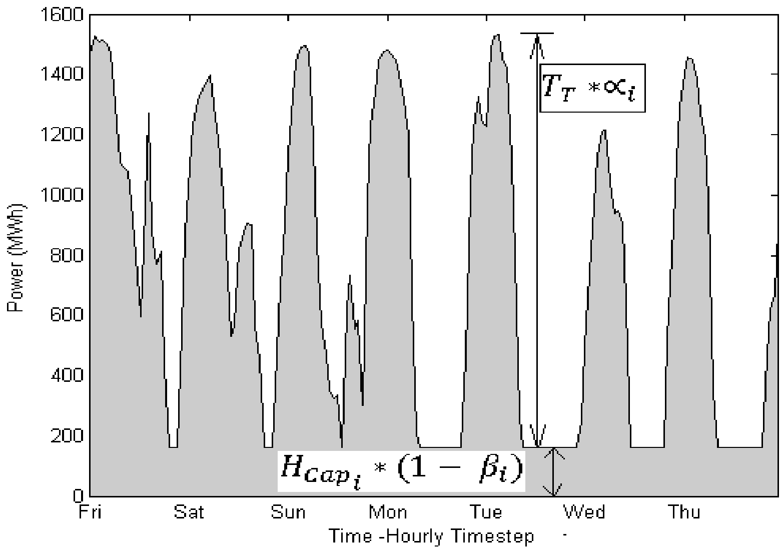

Figure 4 Sample of one week Hydropower Target energy schedule

Seasonal Coefficients $\alpha \, and \, \beta$ are determined by the result of genetic optimization algorithm that aims to maximize the reliability of wind and hydro combinations. Typically the 90th percentile (P90) and 50th percentile (P50) of annual energy production from the power duration curves are used directly into economic models. Therefore in this setup the objective function of the GA optimization is set to maximize the 90^{th} percentile wind and hydro energy combination or W_2 as illustrated in *Figure 3* . The decision variables are $\alpha \, and \, \beta$ on seasonal scale. For each one of the 11 reservoirs and four seasons, a total of 44 decision parameters were identified. The reason behind having different coefficients for each season is mainly because both resource availability as well as demand pattern have high seasonal variations. Once these parameters are determined the water resources and power grid simulation model is executed based on the target generating pattern calculated in equation (1).

3.4. Environmental flow constraints

The importance of accurately representing all the operational constraints in modeling the hydropower generation, especially in studies that assess integration of different energy sources, has been strongly remarked by many authors. Achieving a realistic understanding of the effects of integrating high wind penetrations and hydro system operations depends highly on how well those constraints are accurately represented in the analysis (Hodge et al. 2011),(Acker & Pete 2012), (Clement 2012).

One of the important constraints is stream flow requirement for environmental protection. The restrictions are imposed both in terms of the amount of stream flow required (flow rate) and minimum level of fluctuations that is allowed within a time step at a point or a section of river. Minimum stream flow requirement is specified in the water resources model as a demand with the highest priority. This is given as

$$Q_i^t \geq \; Q_{min,i} \; , \forall \, t \in D \, , \forall \, i \in D \qquad \ldots(5)$$

And to account for fluctuation restrictions

$$\frac{\Delta Q_i}{\Delta \mathrm{t}} \leq \emptyset_i \qquad \ldots(6)$$

Where

Q_i^t : Refers to stream flow at location *i* for time step *t*

$\emptyset_i$: Maximum level of unnatural stream flow fluctuation allowed at location *i*

D : Refers to time domain of our simulation

The water resource model algorithm implements these restrictions as a constraint at each time step when solving the LP problem as it is outlined in Figure 2.

3.5. Power generation cycling constraints

The other main constraint in determining the target for reservoir operation is set by operational restrictions required for the coal power plants generation cycle[5] in South Africa. Since the optimization problem aims at maximizing firm generation of hydro-wind combination, it assumes power generated by coal is cycled to counterbalance the amount of hourly demand fluctuations that cannot be offset by either Wind-hydro or other sources of energy. Coal generating units are often designed for baseload operation and their cycling cost is relatively higher than hydropower or gas-fired units. However at increasing cost and loss of efficiency the generation in coal fired units can still be ramped up and down, when needed, to follow load. This cycling coast has been a topic of many renewable energy resource integration studies ; Lefton & Besuner (2011), Connolly et al. (2011) and Kumar et al. (2012) present comprehensive analysis of additional cost and other implication of coal-fired power plants cycling.

Although including the cost of cycling in current analysis is beyond the scope of this study, this loss of efficiency and cycling constraints have been accounted for in the optimization problem in three constraints given in equations (7), (8) and (9). Loss in efficiency and cost of cycling is a function of the type of the plant and generating capacity, it was not possible to obtain detail information regarding the coal power plants in South Africa. Therefore indicative figures were obtained from Kumar et al. (2012) . Other constrains such as ramp rate and Design efficiency at rated turbine Maximum continuous rating (MCR) were obtained from Eskom.

- Minimum generation is limited at 35% of the rated capacity,

$$C_2^t \geq 0.35 C_{Cap} \qquad \ldots(7)$$

---

[5] Cycling refers to the operation of generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements

- The ramp rate, i.e. rate of change of coal generation shouldn't exceed 32 per hour. This is an average value of all the coal power plants weighted by generating capacity.

$$\frac{\Delta C_2}{\Delta t} \leq 32\% \qquad \ldots(8)$$

- Loss of efficiency as a result of operating below the design capacity is modeled using a penalty coefficient γ, that accounts for the loss of efficiency as a function of the percentage of generation below the rated capacity.

$$C_2(t) = \begin{cases} C'\gamma, & 0.65\, C_{cap} \geq C' \geq 0.35 C_{cap} \\ C', & 1.00\, C_{cap} \geq C' \geq 0.65 C_{cap} \end{cases} \qquad \ldots(9)$$

γ is set as a linear percentage ranging from 0.5 at $C' = 0.35C_{cap}$ to 1.0 at $C' = 0.65\, C_{cap}$, which can be formulated as equation (10)

$$\gamma = \frac{5C'}{3C_{cap}} - \frac{1}{12} \qquad \ldots(10)$$

Here C' refers to the initial estimate of C_2 which is obtained by lifting cycling constraints.

The value range assumed for γ is not based on actual efficiency curve of coal generating plant in South Africa but author's subjective estimate from studies on other countries, (Kumar et al. 2012), (Lefton & Besuner 2011) and (Connolly et al. 2011)

4. Result and discussion

This section presents outputs obtained in the optimization stage which was carried out to determine the reservoir operation targets and simulation result based on the optimal wind/hydro operation.

4.1. Optimization of target generation

Optimization output for selected iterations corresponding to different values of $(1 - \beta\ )$ is shown in *Figure 5* .One of the interesting out comes of this analysis is that in the cases where more than 20% of the generating capacity is allotted for baseload energy generation while maintaining the combined wind-hydro operation, there is added benefit for Zambezi demand in terms of meeting the target. This can be observed in the plot for average values of $(1 - \beta\ ) \geq 0.2$, where the delivered energy for Zambezi (H'_1) is greater than that of the generation with current operation (H_1) which only targets power demand in Zambezi. As mentioned in section 4.2 , the difference between H_1 and H'_1 is the benefit or loss for Zambezi's power demand as a result of the new operation. In this case, clearly a benefit for majority of the cases.

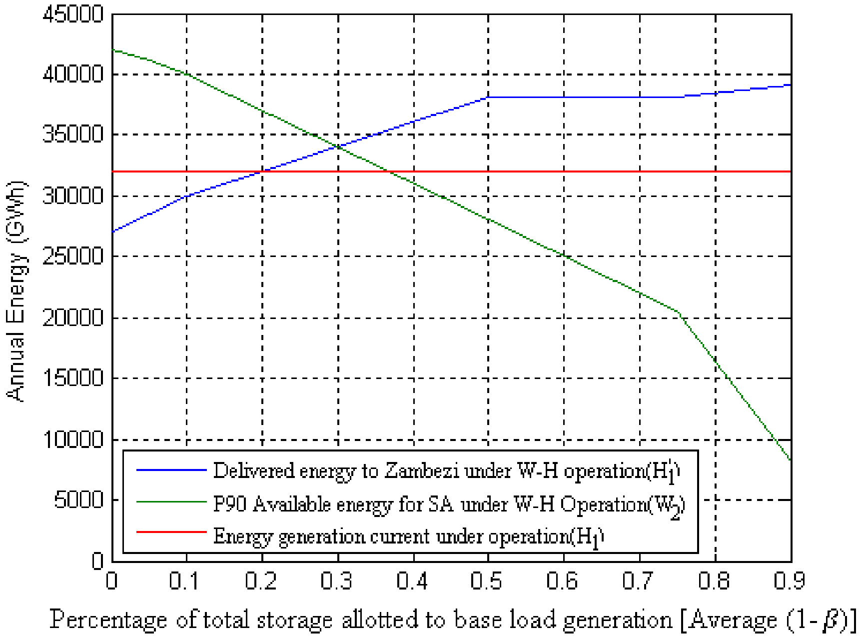

Figure 5 Power system simulation result for different levels fraction of installed capacity used for base load generation

The seasonal multiplier β can serve as an indirect measure of the amount of storage available for wind regulation. As we reduce the allocated storage for wind regulation (or increase$(1-\beta)$), it reflects in reduction of reliability of P90 energy available for South Africa subsequently increasing delivered energy for Zambezi (H'_1). However, as we go more than 50% of the capacity for baseload generation, it will almost remain constant until 75% subsequently followed by a gentle rise in the curve, with the generating capacity reaching up to 39 TWH. There is little benefit added for Zambezi within that range. But on the other hand, if we look at the loss of reliability, P90, there is a steep decline for W_2. Therefore it is not economical to go above 50% range from total regional energy availability perspective.

Furthermore, if we aim at keeping the existing share of Zambezi Energy , which can be achieved by only using 20% of the total generating capacity for base flow generation, there could still be some gain in the increased reliability of energy available for South Africa. Decreasing the based generation to only 10% results in a decrease of 2TW of annual energy for Zambezi but an increase of 4TWH of firm energy available for South Africa. Again, from the regional perspective it is advantageous to reduce the base generation of Zambezi. The result of GA optimization result indicates optimum Wind-Hydro operation can be achieved at keeping 10% of the generating capacity for baseload generation. Total firm energy in the region, P90 of E_p , is given in *Figure 6.*

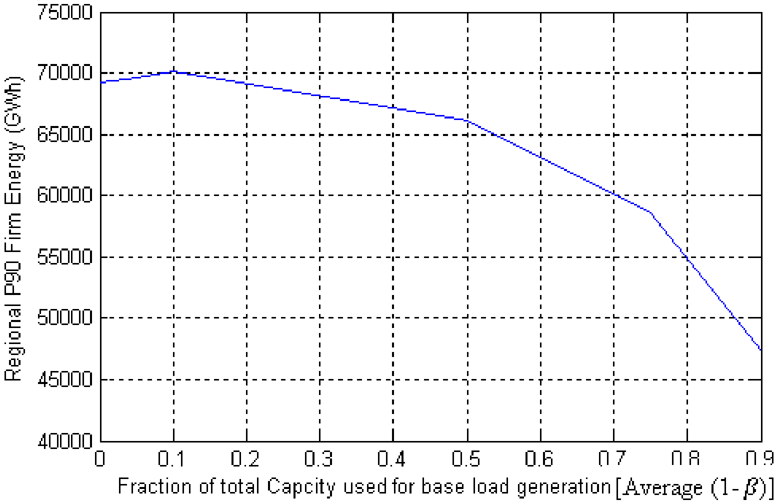

Figure 6 Total firm energy available for combined Wind-Hydropower generation for different level fraction of installed capacity used for base load generation

For the second optimization decision variableα, which accounts for distribution of total target among the reservoirs in Zambezi, the initial feasible solution was obtained by simply distributing the total target (T_T) as a percentage share of generating capacity. However, these values were later refined by the GA results. The optimum value of α is a function of several parameters among which are seasonal inflow pattern, storage capacity and top of conservation storage are some of them. For example, if we look at the initial estimate and optimized values obtained for the Winter season shown in Figure 7, a larger share of the total target was assigned to the Cahora Bassa plant and the opposite to Lake Kariba . One of the potential reasons for this could be that the top level of conservation storage for Cahora Bassa reservoir is the highest in this season but needs to remain low in the subsequent season. Thus the reservoir can yield more water from the storage as opposed to Lake Kariba, which needs to remain at a relatively constant level throughout the seasons. Consequently, making Cahora Bassa more flexible for the purpose of wind power modulation. As a result, a larger share of the target than the initial was assigned by the GA optimization routine.

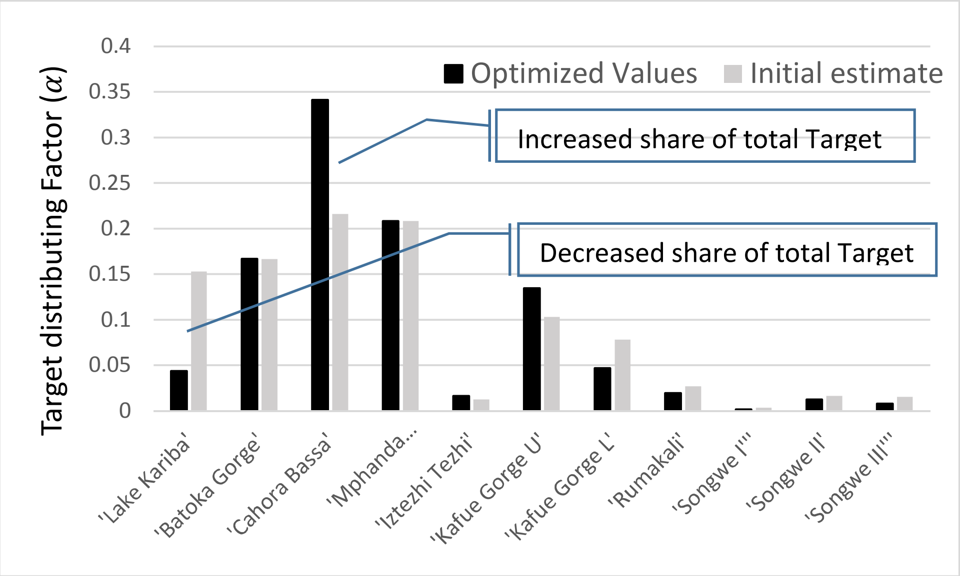

Figure 7 Optimized values for Seasonal Target distributing Factor (α) for winter season

4.2. Simulation result

Using the seasonal coefficient obtained simulation of the water resources and power system model was conducted. Sample hourly output of hydropower generation (H_2), Wind (W_1) and combined Wind/Hydro (E_P) is shown for 14 days of the generation sequence in Figure 8.

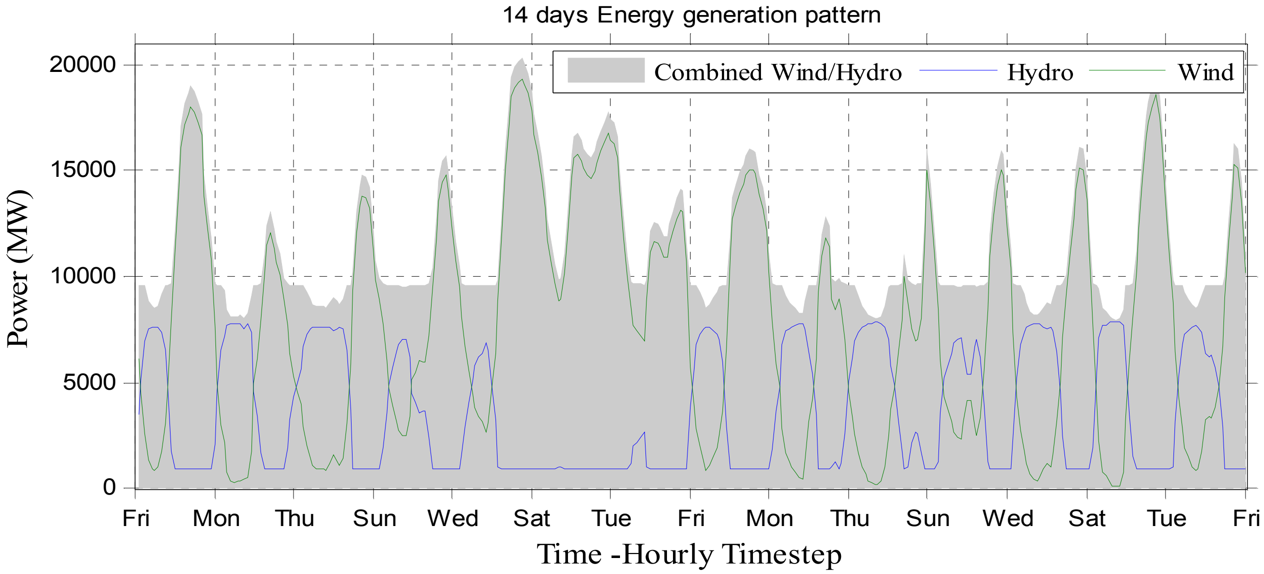

Figure 8: Total Energy generation under the Combined Wind/Hydro Operation scenario

Sample hourly stream flow pattern for 6 month of period for selcted location along Zambezi river is given in figure 9.

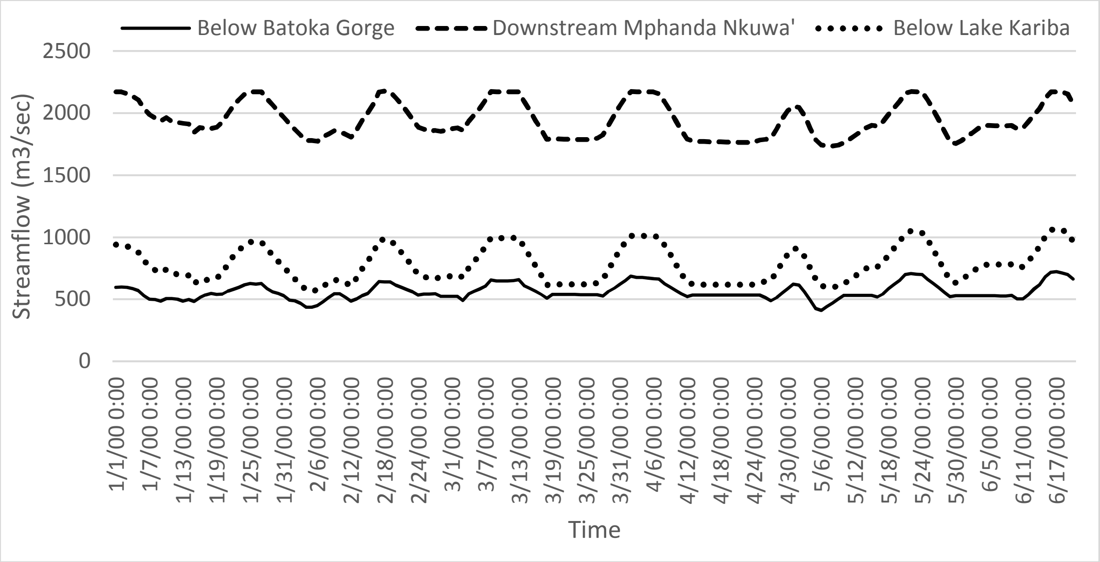

Figure 9: Hourly stream flow at selected Locations along Zambezi River

Duration curve of power generation over the entire simulation period is given in Figure 10. The 90th percentile firm energy is found to be 4530 MW which is 20% of the maximum wind generating capacity. This could bring the penetration of wind power up to 18.69% for the South African power system considering the existing generation from other sources remain the same.

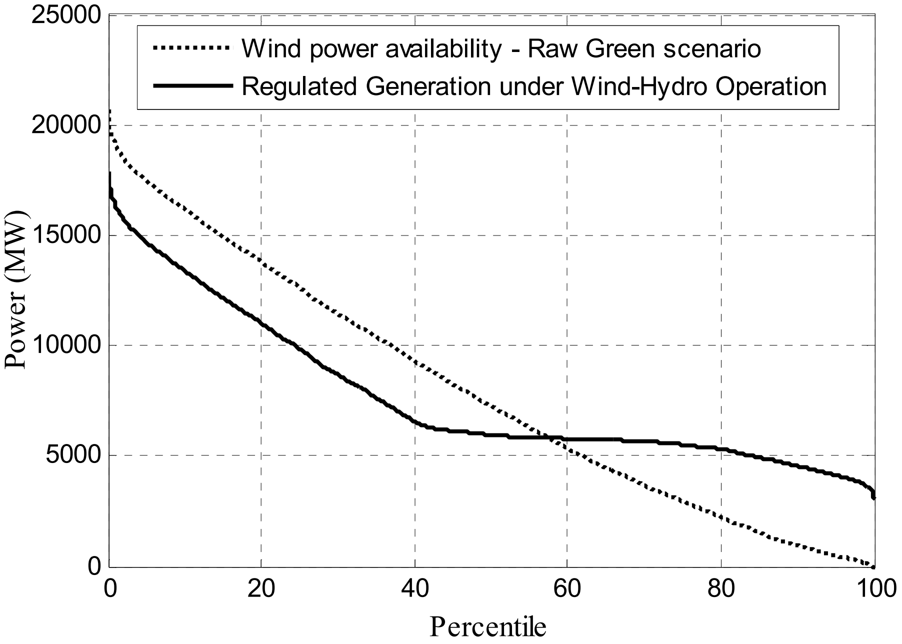

Figure 10 Power duration curve of wind power generation –under Green scenario capacity and regulated wind power availability under the Wind/Hydro operation

With the implementation of the planned reservoir schemes in the Zambezi water resources system, the storage capacity is going to increase. This means more battery for wind regulation, which will increase the reliability of combined wind/hydro energy considerably, accordingly improving the penetration. As pointed out in the regional power sector integration study repot (Economic Consulting Associates Limited 2009) further regional cooperation within the SAPP framework will result in benefits in the area of auxiliary services, such as the sharing of spinning reserves. This will further relax the constraints in operation of the reservoir to offset the wind power availability. This will result in a more reliable supply of energy as well savings.

4.3. Level of wind energy penetration in Wind-Hydro operation

Here we compare two scenarios of wind penetration over the analysis period 2010, 1) The reference case scenario, in which majority of demand fluctuation in excess of all the other energy sources and wind is met by cycling of coal power plant and 2) Wind-hydro operation scenario, with more regulated wind energy made available which results in relatively better wind penetration than the reference case. In the latter scenario, coal power plant will still play the major load following role but since wind-hydro combination will have a regulated energy output the cycling requirement is reduced and thus an increase in the efficiency of coal generation is expected.

4.3.1. The reference case scenario

Since the coal power plants in South Africa are designed for fairly flexible operation with regards to restrictions on cycling requirement, the desired effect of load following and smoothing out wind intermittency can still be achieved but with an incurred cost of more resource usage, wear and tear of coal infrastructures and more carbon emission to the environment. The sources of energy besides wind in both scenarios are coal, nuclear, pumped hydro and gas generators. Energy balance or demand matching is computed using the cycling of the coal plant and is subjected to constraints given in equations (7) (8) and (9). Figure 11 shows the mean diurnal generation profile, by season. In this operation 13% of wind penetration can be achieved.

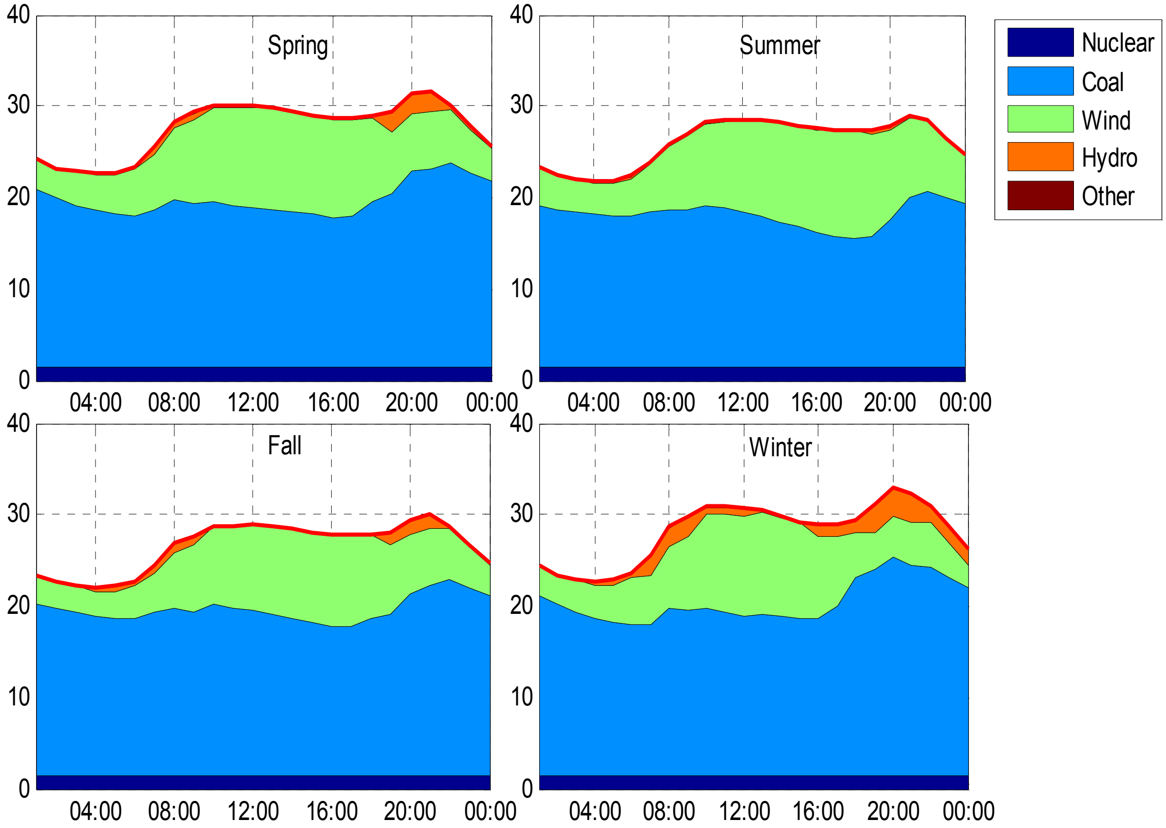

Figure 11 mean diurnal generation profile in the analysis period, reference case for default Green scenario capacity of wind generation by season

4.3.2. Wind/hydro operation scenario

In the operation of wind-hydro, the penetration of wind will significantly increase as a result of less cycling requirement for the coal power plant and thus increased efficiency and the availability of firm energy whenever it is required, which can increase the penetration to 18.7 %. The diurnal profile of energy generation is given shown for each seasons in the Figure 12.

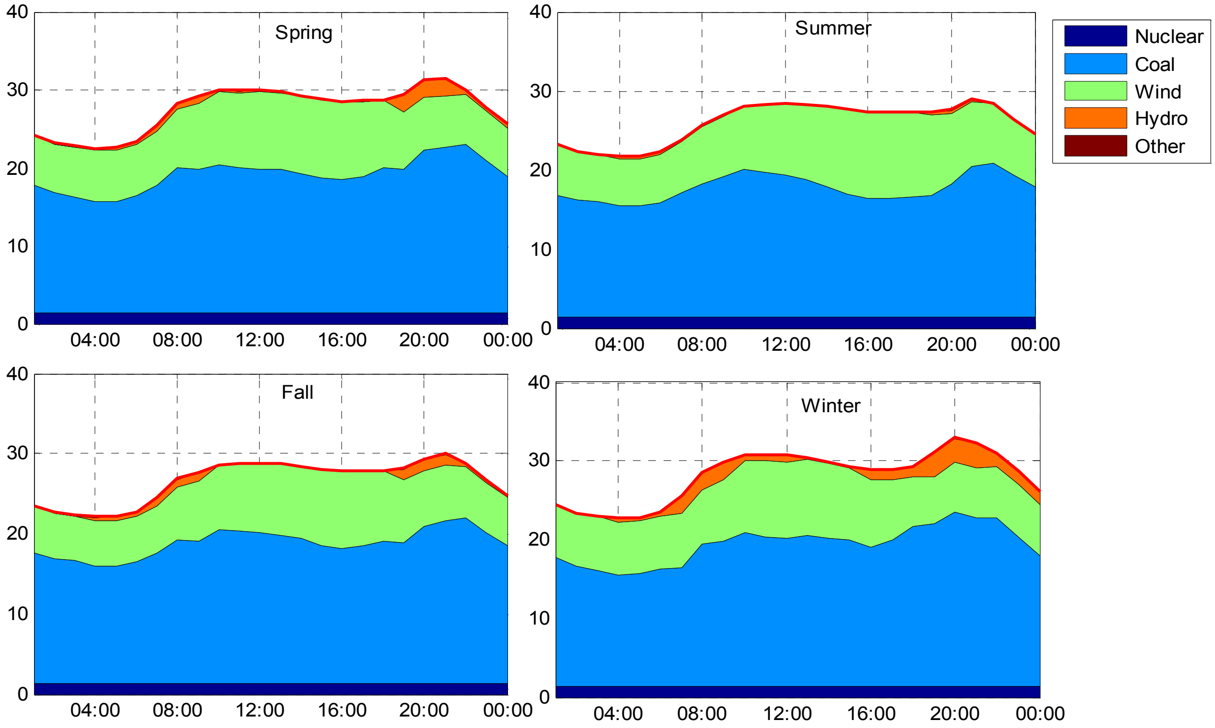

Figure 12: mean diurnal generation profile in the analysis period, wind hydro operation case of wind generation by season

5. Conclusion and remarks

An hourly time step water resources and power grid system model is presented in this paper to assess reliability of combined wind/hydro energy development simulated over one year. Although the analysis conducted is based on observed wind generation and it assumes foreseen wind generation pattern, the techniques employed can directly be applied to short term forecasted wind generation pattern as well. With the recent development of both physical and statistical methods of forecasting wind energy it has been possible to estimate 48–72 hours of generation with a reasonable accuracy sufficient for the power system management or energy trading (Pinson & Kariniotakis 2003). The optimization routine illustrated in this study can be made to look at maximizing the net benefit over 48-72 hours of generation. Furthermore, coefficient obtained based on optimization over observed longer time scale can serve as guiding values in which the annual maximum operation can be obtained, provided that the stochastic properties of wind generation remain consistent.

Approach presented in this paper has several clear benefits over simulation approaches. Both water allocation as well as the power grid system model is based on optimum operation policy for each time step and the operation targets identified are over the entire time period. The model allocates a target for each reservoir with an operation rule combination that gives the best possible hourly allocation of power output.

This study also looked at the implication wind/hydro integration on coal energy generation. The 7% increase in penetration of wind that could be achieved as a result of more regulated wind energy has both economic as well as environmental advantages. Reduced carbon emission due to reduced operation of coal plant will have a substantial contribution to South Africa's goal towards reducing greenhouse gases (mitigation) and the efforts to build resilience to the impacts of climate change

These kind of studies are particularly more relevant to developing counties such as in Africa. For many African counties both the wind as well as hydropower resource have not been well developed yet but many African countries are actively engaged in developing their renewable resource and new wind and hydropower plants are being contracted. This can see as an opportunity where wind and hydro integration can be considered both in the design of this hydropower plants as well as operation such that the synergetic benefit that can be obtained with operating them together can be effectively exploited.

The preliminary values obtained in the analysis are strong indicators of the need for strong cooperation between South Africa and SAPP countries to consider combined operation of wind resource together with hydropower and plan accordingly before embarking on the development of their wind resources.

The analysis time span of this study is limited to one year. Some studies strongly recommend a longer time scale analysis. Hasche et al. (2009) recommends a minimum of 4 years of time span as a good base for stable calculations. Therefore to confidently report the findings on the actual reliability values this study need to be extended into a longer time analysis to capture the effect of interannual variability of both resource availability as well as demand fluctuations. In Addition to that it is also important to look into the future to take power demand growth into consideration and storage capacity expansion in Zambezi. Nevertheless, since the main objective of this study is to introduce the methods and tools, the author believes it is sufficient for the scope of the objective of this study.

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