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Optimized reservoir operation model of regional wind and hydro power integration

Case study: Zambezi Basin and South Africa

Yohannes Gebretsadik,[1] Chas Fant,[1] and Kenneth Strzepek[2]

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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 hydro power. 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 hydro power 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 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 hydro power 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 results also indicated a reduced level of coal power utilization and less cycling requirement. This will have a positive outcome in terms of contributing to South Africa's goal towards reducing greenhouse gas emissions and the efforts to build green energy supply and resilience to the impacts of climate change.

Keywords: wind, hydro power, optimized operation, Zambezi, Congo
JEL classification: C63, Q25, Q54

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[1]University of Colorado, Center for Climate and Civil Systems; [2]Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change; corresponding author: strzepek@mit.edu

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UNU-WIDER, Katajanokanlaituri 6 B, 00160 Helsinki, Finland, wider.unu.edu

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.

Hydro power has been one of the cheapest and environmentally clean option to co-ordinate with intermittent power sources such as wind and solar power. Hydro power stations with a storage reservoir are highly dispatchable. Power generation can be scheduled in less than an hour time step with continuous start-ups and shut-downs 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.

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 co-ordination in order to increase the over economic and environmental advantage of these intermittent energy sources. Castronuovo and Lopes (2004) present 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 illustrate 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 co-ordination; it employs a time series wind speed model to represent the stochastic nature of wind power. Bélanger and Gagnon (2002) also show wind and hydro combined simulation on an hourly time strep for six years of actual data of patterns of electricity demand. Clement (2012) employed the RiverWare[2] modeling system to evaluate hydro power and wind integration for different levels of wind penetration based on physical characteristics of the hydro power 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 and 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 hydro power. A combination of linear programming hourly water resources model and Genetic Algorithm solvers are combined to determine optimum operation strategy for multipurpose storage reservoirs

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

[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.

that yield maximum firm generation over one year of the simulation period. The proposed framework 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 hydro power plants to come up with an integrated operating plan that maximizes overall 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 per cent 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 co-ordination of power trade with Southern African Power Pool (SAPP) countries is the use of storage available in the Zambezi basin to co-ordinate wind resource with hydro power. 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.

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 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 (see Hasche et al. 2011). 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 the Wind Atlas for South Africa (WASA) project to produce a wind power availability time series on an hourly time step for over ten years, 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 per cent penetration by 2040 (Figure 1). The reader is referred to Ummel (2013) for more detailed information regarding the methods employed to produce wind energy data.

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.[5] 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 the daily fluctuations of resource availability, it does not, however, introduce substantial error in the analysis of hydro power generation due to the high storage capacity of the reservoirs. Additionally, inflows to the large reservoirs, especially the ones found far downstream on the

[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.

[5] MIT Joint Program on the Science and Policy of Global Change.

Zambezi River, are fairly regulated and impacts of the hourly fluctuation can sufficiently be ignored without introducing much error in the analysis.

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 and 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 hydro power 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 hydro power 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 hydro power 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 reservoir 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 hydro power 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.

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 per cent 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 the Zambezi basin is to satisfy the demand within the basin countries.
- Other sources of energy for the Zambezi basin are not accounted besides hydro power. The energy demand indicated is for hydro power energy only.

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

In this configuration, both energy from hydro power 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 hydro power 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)

$$T_i^t = \alpha\,{}_i^s T_T^t + (1 - \beta_i^s\,) H_{Cap_i} \tag{1}$$

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.

$$H_{cap} = \sum_{i=1}^{n} H_{Cap_i} \tag{2}$$

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 a power target, which was expressed only by the first part of equation (1). Results indicate that using 100 per cent of the reservoirs' conservation storage to regulate the wind energy fluctuation does not provide an optimal option of operation, expressed 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 both the environmental flow requirement and the irrigation demand; meaning that the reservoir operation will not respond to all of the rapid fluctuating target assigned to compliment the wind power (we refer to this requisite flow as 'non-power release'). Therefore, the baseload component was provided in the target in order to utilize a 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 per cent 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) and (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 hydro power 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.

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

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

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

Seasonal Coefficients α *and* β 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 set-up the objective function of the GA optimization is set to maximize the 90th percentile wind and hydro energy combination or W_2 as illustrated in Figure 3. The decision variables are α *and* β 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 hydro power 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 and 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. The minimum stream flow requirement is specified in the water resources model as a demand with the highest priority. This is given as

$$Q_i^t \geq Q_{min,i}, \forall\, t \in D, \forall\, i \in D \tag{5}$$

And to account for fluctuation restrictions

$$\frac{\Delta Q_i}{\Delta \mathrm{t}} \leq \emptyset_i \tag{6}$$

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 cycle6 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 hydro power 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 cost has been a topic of many renewable energy resource integration studies; Lefton and Besuner (2011), Connolly et al. (2011) and Kumar et al. (2012) present comprehensive analysis of additional costs, and other implications of coal-fired power plants cycling.

[6] 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.

Although including the cost of cycling in the current analysis is beyond the scope of this study, this loss of efficiency and cycling constraints has 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 detailed 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 per cent of the rated capacity,

$$C_2^t \geq 0.35 C_{Cap} \tag{7}$$

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

$$\frac{\Delta C_2}{\Delta t} \leq 32\ per\ cent \tag{8}$$

- 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.

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

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

$$\gamma = \frac{5C'}{3C_{cap}} - \frac{1}{12} \tag{10}$$

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 the actual efficiency curve of a coal generating plant in South Africa but the authors' subjective estimate from studies on other countries (Kumar et al. 2012; Lefton and Besuner 2011; 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 results based on the optimal wind/hydro operation.

4.1 Optimization of target generation

The 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 per cent of the generating capacity are 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 the majority of the cases.

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 (i.e. increase $(1-\beta\ )$), the model responds by reducing the reliability of P90 energy available for South Africa, subsequently increasing delivered energy for Zambezi (H'_1). However, as we go more than 50 per cent of the capacity for baseload generation, it will almost remain constant until 75 per cent 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 per cent range from a 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 per cent 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 per cent results in a decrease of 2 TW of annual energy for Zambezi but an increase of 4 TWH 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 results indicates an optimum wind-hydro operation can be achieved at keeping 10 per cent of the generating capacity for baseload generation. Total firm energy in the region, P90 of E_P, is given in Figure 6.

For the second optimization decision variable α, which accounts for a 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 the 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, Cahora Bassa is made 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.

4.2 Simulation result

Using the seasonal coefficient obtained simulation of the water resources and power system model was conducted. Sample hourly output of hydro power generation (H2), Wind (W1) and combined Wind/Hydro (EP) is shown for 14 days of the generation sequence in Figure 8.

A sample of hourly stream flow pattern for a 6-month period for a selected location along the Zambezi River is given in Figure 9.

The 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 per cent of the maximum wind generating capacity. This could bring the penetration of wind power up to 18.69 per cent for the South African power system considering the existing generation from other sources remain the same.

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 report (Economic Consulting Associates Limited 2009), further regional co-operation 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 the majority of the demand fluctuation in excess of all the other energy sources and wind is met by cycling of a coal power plant and (2) a 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, a 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.

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 per cent of wind penetration can be achieved.

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 per cent. The diurnal profile of energy generation is shown for each season in Figure 12.

5 Conclusion and remarks

Running on hourly time step, an integrated 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 a foreseen wind generation pattern, the techniques employed can directly be applied to short-term forecasted wind generation patterns 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 and Katiniotakis 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, the 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.

The 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 of wind/hydro integration on coal energy generation. The 7 per cent 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 plants 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 kinds of studies are particularly more relevant to developing countries, such as those in Africa. For many African countries both wind as well as hydro power resources have not been well developed yet but many African countries are actively engaged in developing their renewable resources and new wind and hydro power plants are being contracted. This can be seen as an opportunity, where wind and hydro integration can be considered both in the design of new hydro power plants as well as new cooperative management of existing plants.

Furthermore, the preliminary values obtained in this analysis are strong indicators of the need for more robust collaboration between South Africa and SAPP countries—considering a combined operation of wind resources and hydro power, especially when planning future investments in wind power infrastructure.

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 four years of time span as a good base for stable calculations. Therefore to confidently report the findings on the actual reliability values this study needs 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, power demand growth and storage capacity expansion in Zambezi were not considered in this analysis, both of which are important factors to include in future research. Nevertheless, since the main objective of this study is to introduce the methods and tools, the authors believe it is sufficient for the scope of the objective of this study.

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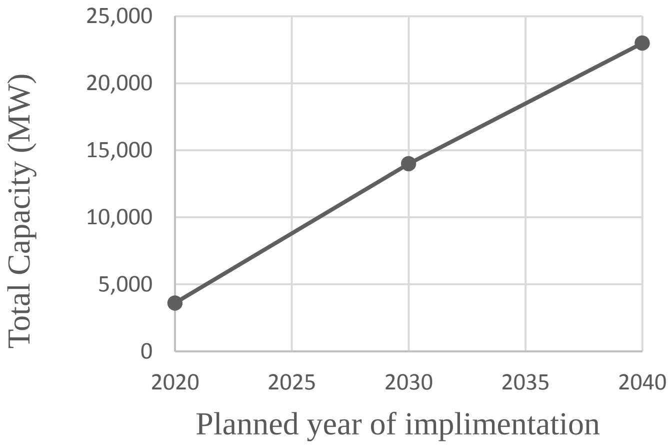
Figure 1*:* ESKOM plan wind implementation for GREEN scenario (large renewable energy generation)



Source : ESKOM (2012).

Figure 2*:* Algorithm of linear programming based water resource allocation model

$For\ each\ time\ step$

$For\ P\ in\ each\ priority\ grop$

$$Max\ Z\ = \sum_{1}^{number\ of\ P} D_i\ ,\text{Maximize summation of demand coverage}$$

Subjected to

- Water balance constrains (flow routing, Reservoir water balance)
- Demand coverage constrains
- Reservoir characteristic and 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

$$Max\ Z\ = \sum_{i=1}^{number\ of\ reserviors} S_i\ ,\text{Maximize reservior storage}$$

Subjected to

- Water balance constrains
- Equality constraints of solution from previous iteration

$$Max\ Z\ = \sum_{1}^{number\ of\ P} E_i\ ,\text{Maximize hourly energy generation}$$

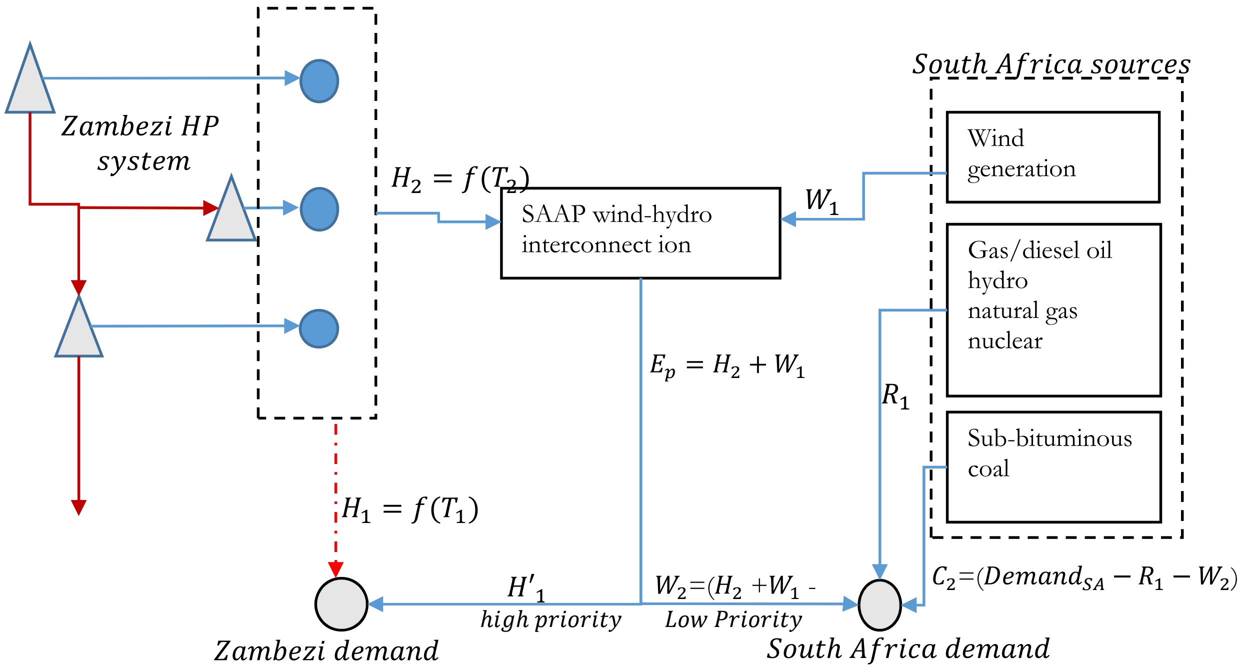
Subjected to

- 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)

$Next\ time\ step$

Source: Generated by the authors.

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



Source: Generated by the authors.

Where

W_1, Wind generation for South Africa under 'Green' scenario

H_1 , Total hydro power generation from Zambezi basin in the present operation

H_2, Hydro power generation from Zambezi basin in the modeified wind/hydro operation

T_1, Current target power operation of all hydro power in Zambezi

T_2, Modified wind/hydro target power operation for all hydro power in Zambezi

E_p, Combination of wind and hydro power, 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

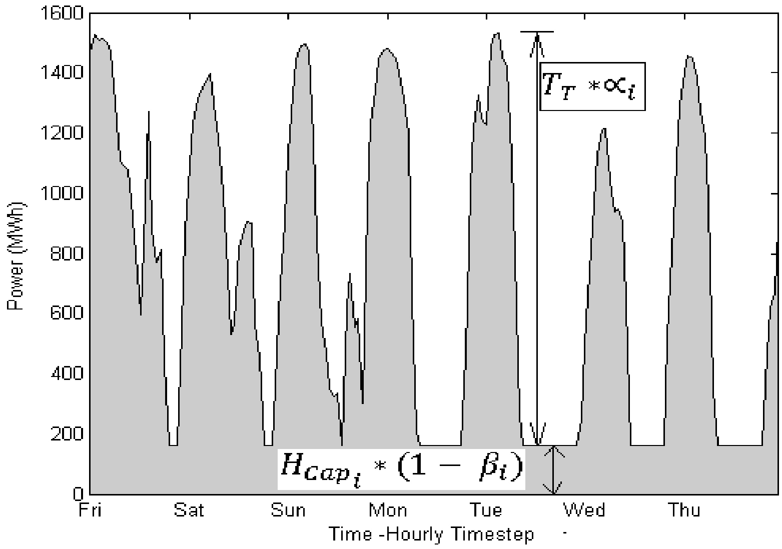
C_2, requred coal generation to offset generation to meet demand

R_1, Other source of energy geenration in South Africa

$Demand_{SA}$, South Africa total power demand

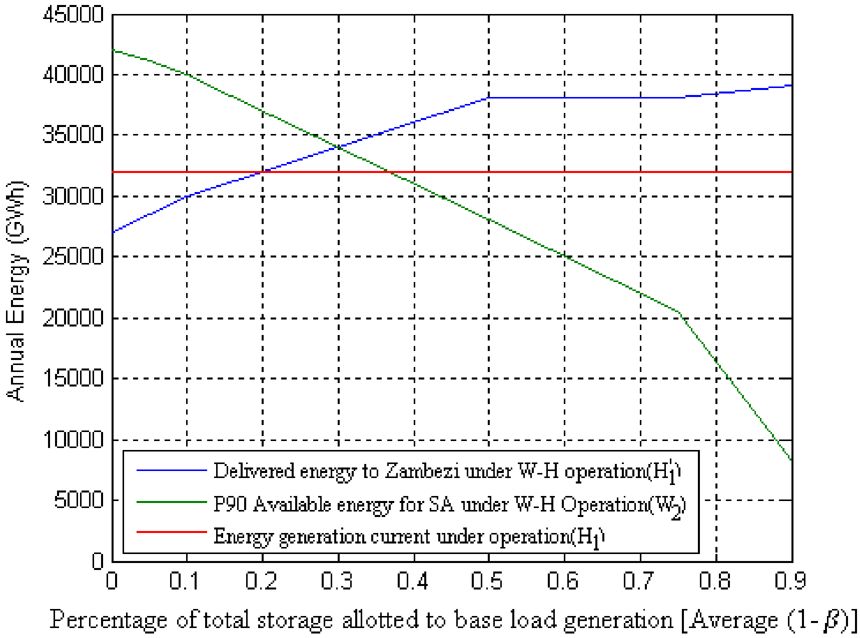
$Demand_{ZA}$, Zambezi hydro power demand

Figure 4: Sample of one week hydro power target energy schedule



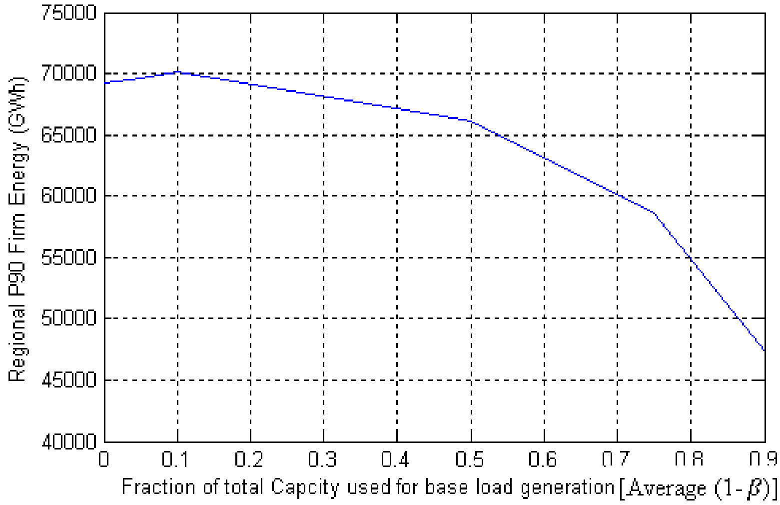
Source: Generated by the authors.

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



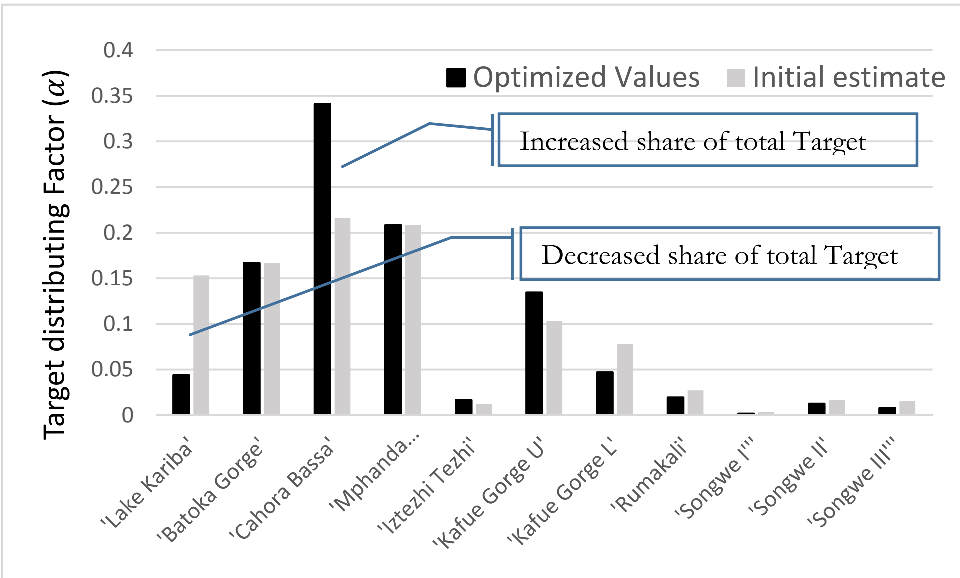
Source: Generated by the authors.

Figure 6: Total firm energy available for combined wind-hydro power generation for different level fraction of installed capacity used for base load generation



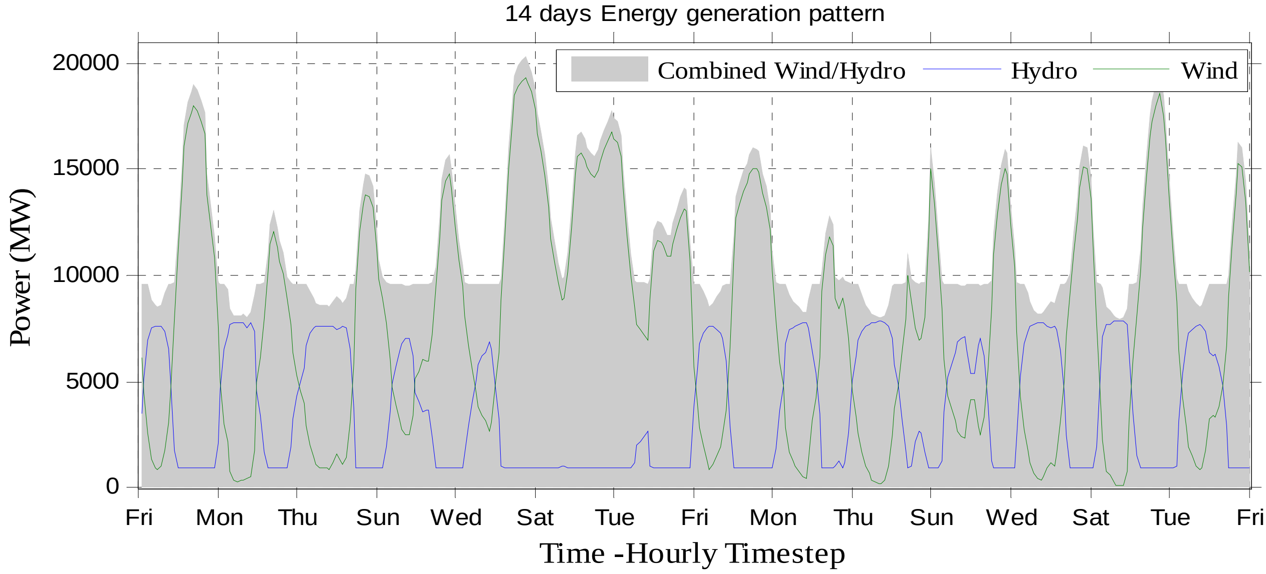
Source: Generated by the authors.

Figure 7: Optimized values for seasonal target distributing factor (α) for winter season



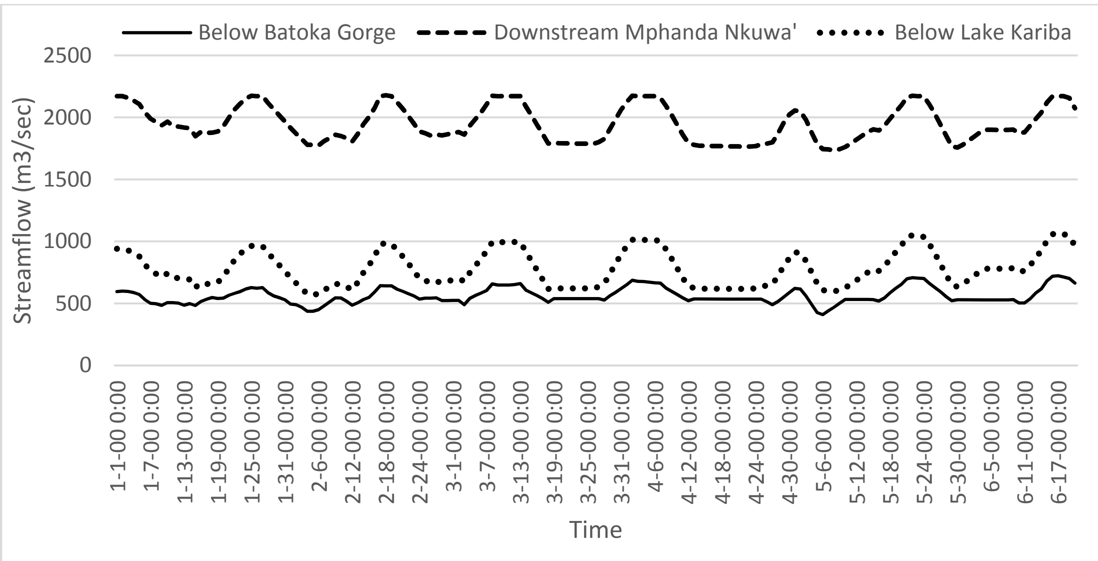
Source: Generated by the authors.

Figure 8: Total energy generation under the combined wind-hydro operation scenario



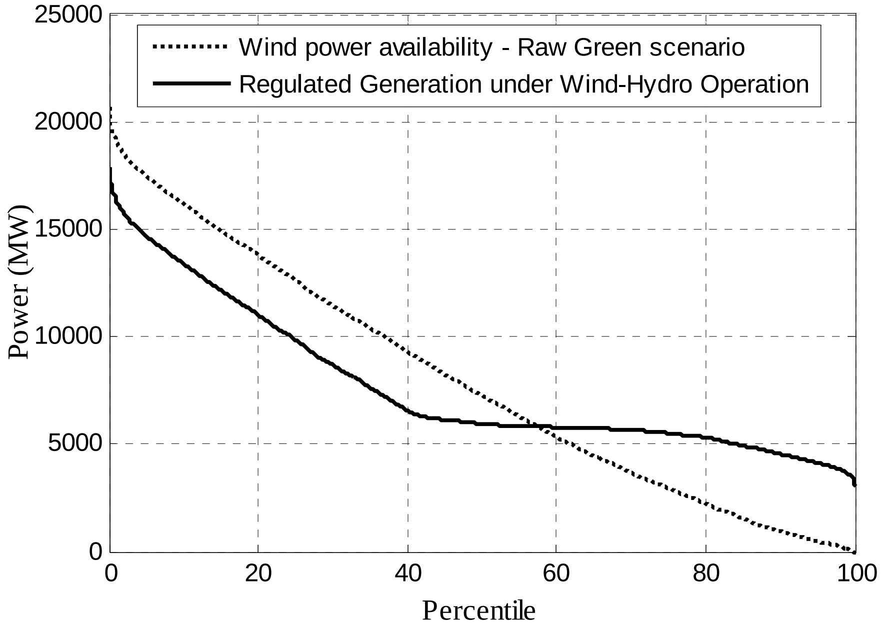
Source: Generated by the authors.

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



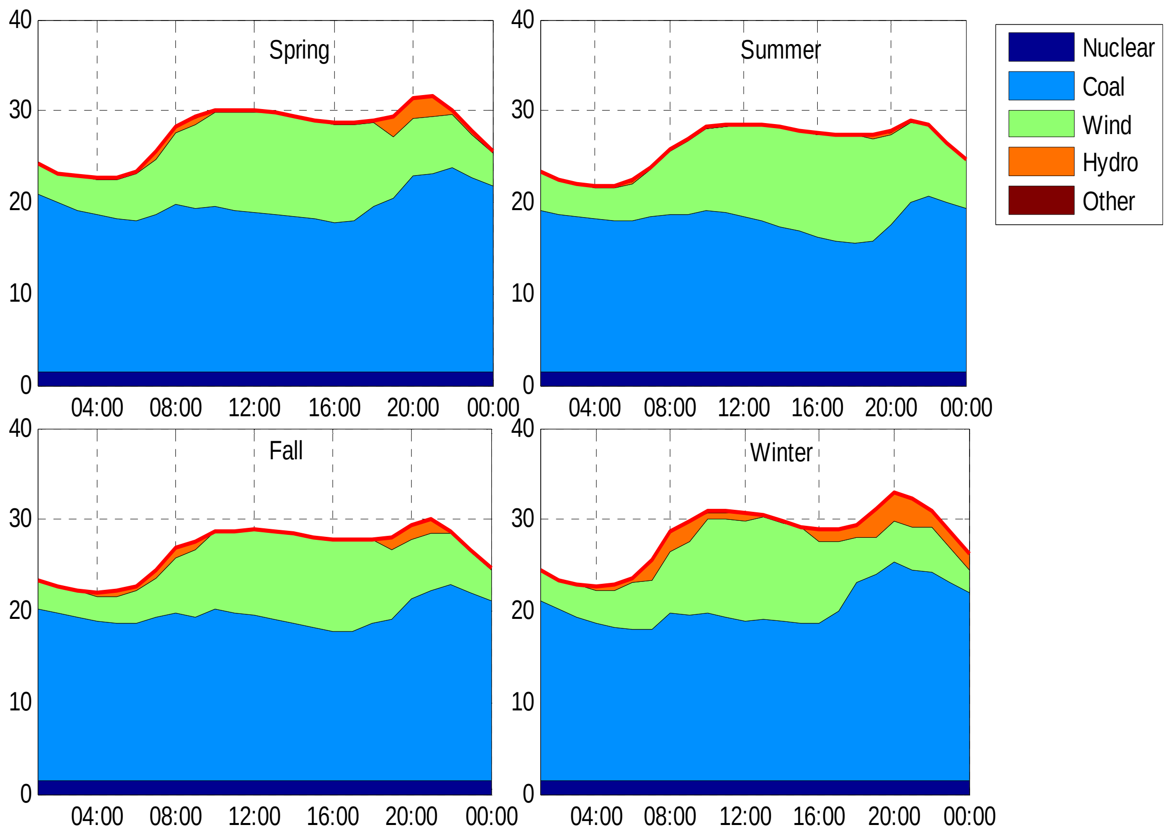
Source: Generated by the authors.

Figure 10: Power duration curve of wind power generation –under green scenario capacity and regulated wind power availability under the wind/hydro operation



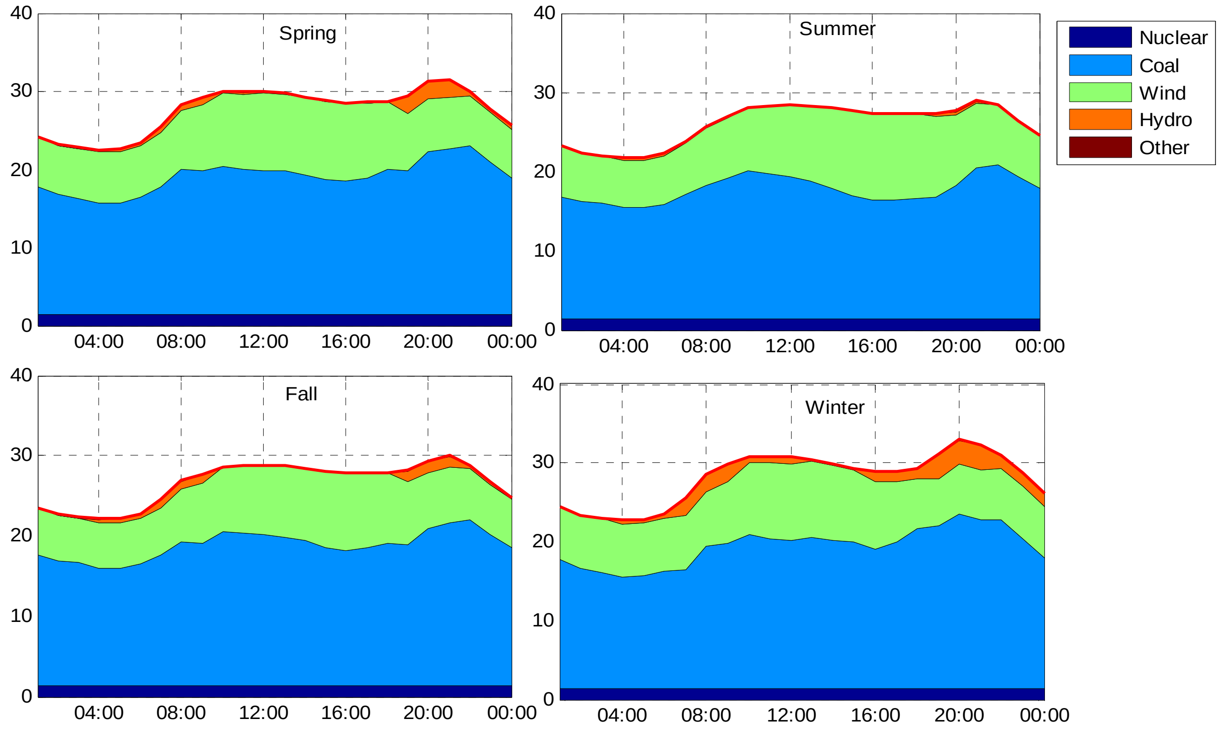
Source: Generated by the authors.

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



Source: Generated by the authors.

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



Source: Generated by the authors.

Table 1: Summary of information on power capacity and generation.

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		
Hydro power capacity	9,605 MW	Including capacity expansion

Source: (GFA INVEST 2012).