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Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi basin and South Africa

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HIGHLIGHTS

- The study introduced reliability assessment method of integrated wind–hydropower operation.
- The method identifies optimum target power operations that maximizes the firm generation.
- We test the proposed method on interconnected system of reservoirs in Southern Africa region.
- Results indicate that higher penetration of wind power can be achieved through the proposed frame work of operation.

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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 hydropower. A combination of water resources model for a system of reservoirs that implements a demand–priority based linear programing algorithm and a single node power grid system model is implemented on hourly time step. This model was accompanied by a global 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 was applied on the reservoir storages and hydropower system in the Zambezi river basin to test if the storage reservoirs could be efficiently be used to offset wind power intermittence in South Africa subjected to the 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 45% increase in the 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 toward reducing greenhouse gas emission and the efforts to build green energy supply and resilience to the impacts of climate change.

1. Introduction

Technologies utilizing wind energy have made considerable progress in recent years with notable improvement in efficiency of wind power harvesting as well as forecasting. Due to its clean and cost-effective renewable supply of energy, wind power has become an attractive investment and one of the world's fastest growing energy resources. Yet the penetration of this renewable resource remains low in most power grid systems due to the inherent intermittent nature of sufficient wind availability to power turbines. In addition to its variable characteristics it is also often difficult to control or easily adjust the power output, making it a highly non-dispatchable source of energy. Consequently utilization of this resource to its maximum potential remains one of the biggest challenges both for planning and operation. The use of

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complementary or other dispatchable energy resource in integration with wind has been found to be one effective way to make wind power more usable.

Hydropower is one of the least expensive and environmentally clean energy options; furthermore, hydropower stations with a storage reservoir are highly dispatchable, power generation can be scheduled in less than an hour, and even frequent startups and shutdowns can be executed without a significant damaging effect on the infrastructure service life. These qualities make it an excellent complement to intermittent power sources such as wind. Water reservoirs are 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 many 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 source both at planning stage as well during operation. Generally, these studies have shown an increase in overall penetration of wind energy in the power system through integrated operation with hydropower. Proposed different operation strategies to get maximum benefit of the coordinated operation.

Methods employed in previous studies of wind–hydro integration can be viewed in two categories based on objectives: (1) Short term operational models utilize mathematical techniques to optimize or simulate the system for short term operational goals based on meeting some economic objectives, either in terms establishing optimum daily operational strategy that reduces total operating cost, or maximize the 24-h total economic gain [1–3] of wind and hydro operation; and (2) Long term reliability assessment models which look at longer time scale of operation and try to achieve overall increase of firm power available in the system [4–6]. Reliability assessment tools are mostly useful during planning or assessing the reliability of existing system and depend on either stochastic techniques of wind generation pattern or uses a perfect foresight wind generation pattern [6]. Operational models are mostly of high value for day-to-day operations of meeting management objective and make use of a short term, 24–48 h, forecast for wind power. We could further identify models based on scope of analysis and complexity of the components, whether the models are looking at single reservoir in isolation or over interconnected power grid systems [7].

The level of market penetration or extent of reliability of wind power that can be achieved through wind–hydro integration is dependent on several variety of factors. The capacity to which water storage dams are able to address the variability and unpredictability of wind energy is function of factors such as infrastructural capacity, policy and physical constraints in reservoir operation, characteristic of power demand and hydrological conditions. It is important to consider these parameters in reliability assessment models during planning as well as operation as their contribution to overall effectiveness of the integrated operation is highly variable and they are often system specific.

One of the key knowledge gap that exists in most previous wind–hydro studies is the lack to consider longer time scale regulation of wind variability by storage facilities. In addition to short time power balance, hydropower plants with large storage capacity are able to modulate longer time scale of variability such as weekly and seasonal, which is often present in power demand, hydrology and wind power generating potential [8]. In order to accommodate this seasonal variability reservoir rule curves should be adjusted to take the intermittency of wind power, longer time scale variability and variability in power demand into consideration. This is often complicated particularly for multi-purpose reservoirs with prior commitment to other water resources regulating functions, such as irrigation, flood control and downstream environmental flows as the operation strategy is often established to cater to the highest priority function. Most previous studies focused on establishing optimum daily operational strategy do not consider this since primarily the models employed only look at shorter time scale in the future. At present, there are few studies in reliability assessment methods of wind–hydro integration available in the scientific literature that consider longer time scale of regulating capacity. Efficient use of wind energy and ‘battery’ coordination can be achieved through looking at longer time of optimal coordination as longer scale variability is an essential element that needs to be taken into consideration when developing reservoir operation strategy of wind and hydro coordination.

When looking at infrastructural capacity, previous wind–hydro studies have addressed effect of storage capacity and flexibility of other energy sources that might be used in conjunction with hydropower such as cycling capacity of coal and gas. Interconnected system of reservoirs, as in the case of power pools, present additional opportunity that is crucial to effectiveness of wind–hydro integration. Hydrologic characteristics and thus availability of storage could potentially be different spatially. Operation of the reservoirs in coordination can create additional flexibility that could be utilized to modulate intermittent power source, distribute demand fluctuations and variability spatially. For example, if we consider two multi-purpose reservoirs with primary target for flood protection but having different flood season. They will have different pattern of rule curves for flood storage and thus different pattern of available storage. Adding an intermittent energy source to this system will have further advantage through choosing which reservoir to use for regulation depending on the storage availability in that particular season. This effect is which is often overlooked by many studies. No studies to date have considered this effect in reliability assessment of integrated operation of Wind and Hydropower reservoirs.

Policy constraints in reservoir operation such as downstream environmental flow requirements of dam release are often significant in limiting the capacity of the reservoir to modulate the intermittency of wind. Some system-based study on wind–hydro have realized this and have taken this into consideration [1,7] However as mentioned before, reservoirs with other function such as operation for irrigation demand downstream could narrow the range of operation to regulate wind–hydro integration. This is dependent on the priority assigned to each function of the reservoir. This aspect has not been adequately covered in studies available in scientific literature.

The above three key knowledge gaps are the motivation behind this work. This study represents an attempt to filling this gaps in wind–hydro assessment practice through the development of reliability assessment methods that address the knowledge gaps discussed. We are proposing a method for assessment of wind resource reliability using optimum reservoir target power operations that maximizes the firm generation of integrated wind and hydropower, a frame work that optimizes resource utilization both at a time step level for short time scale operation as well as over a longer period of simulation. The key contribution of the method presented here is in illustrating three level of optimization that capture (1) hourly allocation of power between different supplies, (2) long term seasonal variability of water resource for hydropower generation, (3) lateral distribution across demands and interconnected hydropower sources to considers optimal distribution of load for offsetting the gap in energy supply and storage.

A combination of demand-supply priority based linear programming hourly water resources model and Genetic Algorithm (GA) solvers are combined to determine operation strategies of multiple storage reservoirs linked in power pool simultaneously to yield maximum firm generation over one year of the simulation period. 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. The case study makes a good specimen to taste the model proposed because it contains interconnected system of reservoirs with different hydrologic characteristics, multi-purpose reservoirs and different energy demand variability.

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 complementary dispatchable energy sources the penetration goal might be too optimistic. A possible opportunity to explore through the existing coordination of power trade within South African Power Pool (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 resources.

2. Material and methods

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 describe the intermittency of wind power as well as to conduct a robust assessment of the long term reliability through capturing the effect of inter-annual variability of both resource availability and power demand fluctuation [9]. We used an hourly time step models 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[1].

Ummel [10] made use of hourly wind speed data from the GEOS-5[2] 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 [11]. 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 (see Table 1).

Environmental flow requirement and policies related to pattern and amount of downstream release for reservoirs were compiled from different sources. Cahora Bassa investment report [12] recommends seasonal environmental releases from the dam. Environmental Impact Assessment reports of feasibility studies for the reservoir projects and other sources were also utilized to get downstream release policies and the current practice of accommodating environmental flows from dams, [13–15].

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. Since the reservoirs are multipurpose, 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. [16] but adopted to a smaller time step with integration of an hourly fluctuating hydropower operation target, river routing component and different policy constraints.

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).

Power source	Installed capacity (MW)	Remark
South Africa		
Gas/diesel oil	1680	Existing (2010)
Pumped hydro	2000	Existing (2010)
Natural gas	746	Existing (2010)
Nuclear	1930	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	9605 MW	Including capacity expansion

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 then 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 Zambezi water resources system.

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 Fig. 1.

3.2. Power interconnection model

For power grid interconnection, a simplified single node interconnection model is implemented that assumes no transmission or distribution constraints. Schematic diagram of this model of interconnection is illustrated in Fig. 2.

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 modified wind/hydro operation.
T_1, current target power operation of all hydropower in Zambezi

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[1] ESKOM is a South African electricity public utility.

[2] 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.

```
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 hourly energy generation
        Subjected to
            • Water balance Constrains
            • Equality Constraints of Solution from Previous priority group iteration
            • Fluctuations of downstream flow constraints (see section 3.4)
            • Coal power generation cycling constraints (see section 3.5)
Next time step
```

Fig. 1. Algorithm of linear programming based water resource allocation model.

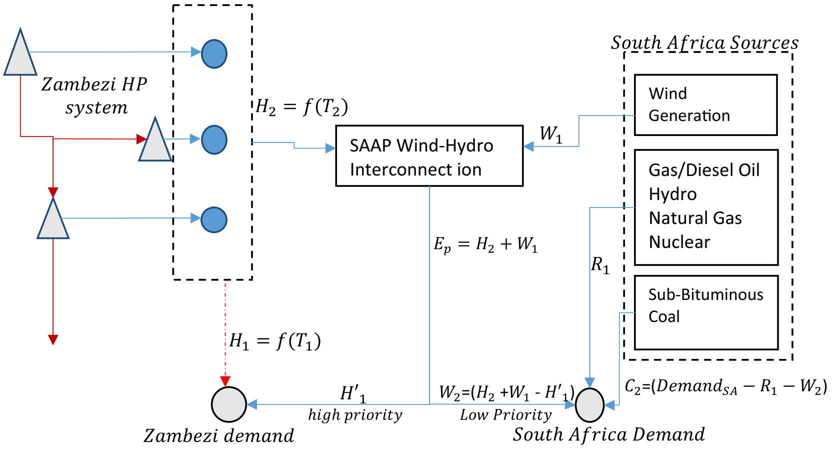

Fig. 2. Schematic representation of power interconnection model for Zambezi and South Africa wind–hydro integration.

T_2, modified wind/hydro target power operation for all hydropower in Zambezi
E_p, combination of wind and hydropower, total energy available 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, required coal generation to offset generation to meet demand
R_1, other source of energy generation 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 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 Eq. (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 Eq. (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 target power which was expressed only by the first part of Eq. (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 [17].

Eq. (1) requires the calculation of T_T^t. This is first calculated from the wind generation data given by Eqs. (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 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.

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

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

The definition of α_i^s and β_i^s together with the corresponding two components of Eq. (1) are illustrated in Fig. 3.

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 setup 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 Fig. 2. The decision variables α and β are 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 Eq. (1).

3.4. Environmental flow constraints

Achieving a realistic understanding of the effects of integrating high wind penetrations and hydro system operations depends highly on how well operational constraints are accurately represented in the hydropower generation model [18–20]. 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 over a river segment. Minimum stream flow requirement is specified in the water resources model as a demand with the highest priority. This is given as

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

And to account for fluctuation restrictions

$$\frac{\Delta Q_i}{\Delta t} \leqslant \varnothing_i \tag{6}$$

where

Q_i^t: Refers to stream flow at location i for time step t
$\varnothing_i$: Maximum level of unnatural stream flow fluctuation allowed at location i
D: Refers to time domain of our simulation.

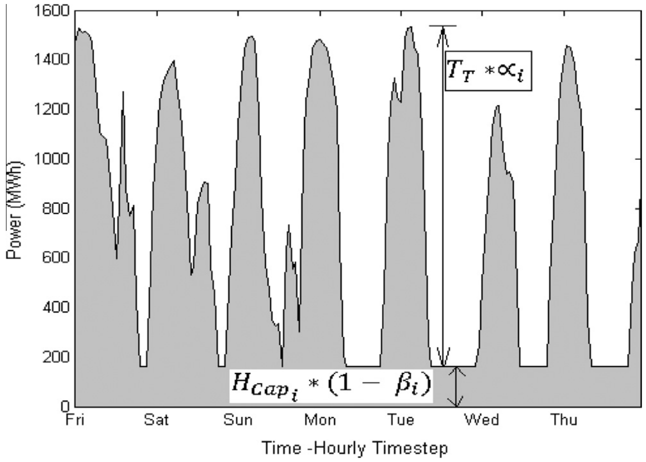

Fig. 3. Sample of one week hydropower target energy schedule.

The water resource model algorithm implements these restrictions as a constraint at each time step when solving the LP problem outlined in Fig. 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 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 additional cycling cost and other implication on coal-fired power plants has been a topic of some renewable energy resource integration studies [21–23].

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 Eqs. (7)–(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. [23] 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,

$$C_2^t \geqslant 0.35 C_{cap} \tag{7}$$

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.

$$\frac{\Delta C_2}{\Delta t} \leqslant 32\% \tag{8}$$

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.

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

γ is set as a linear percentage ranging from 0.5 at $C' = 0.35C_{cap}$ to 1.0 at $C' = 0.65C_{cap}$, which can be formulated as Eq. (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 actual efficiency curve of coal generating plant in South Africa but author's subjective estimate from studies based on other countries [21–23].

4. Result and discussion

4.1. Optimization of target generation

Optimization output for selected iterations corresponding to different values of $(1 - \beta)$ is shown in Fig. 4. One of the interesting outcomes 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 $(1 - \beta) \geqslant 0.2$, 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. 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.

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.

For the second optimization decision variable α, which accounts for distribution of total target among the reservoirs in Zambezi, the

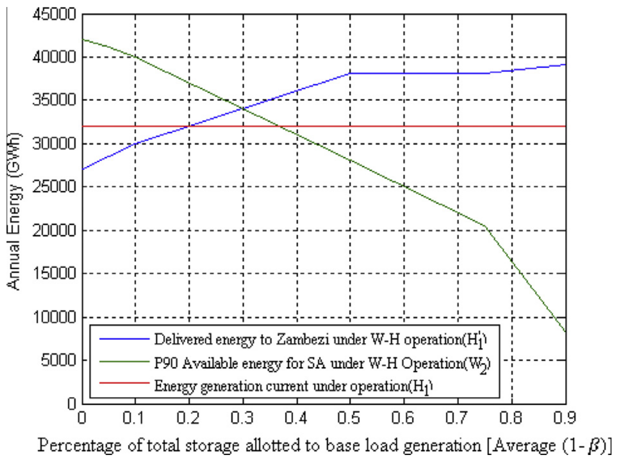

Fig. 4. Power system simulation result for different levels fraction of installed capacity used for base load generation.

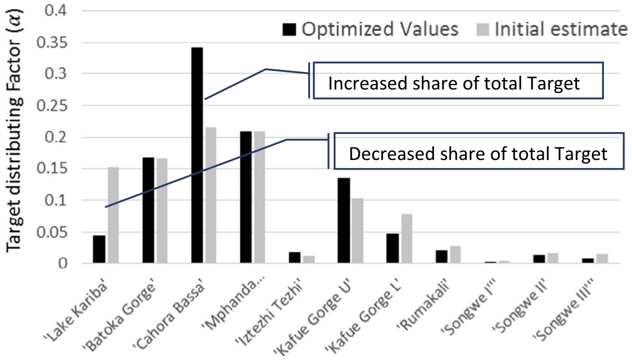

Fig. 5. Optimized values for seasonal target distributing factor (α) for winter season.

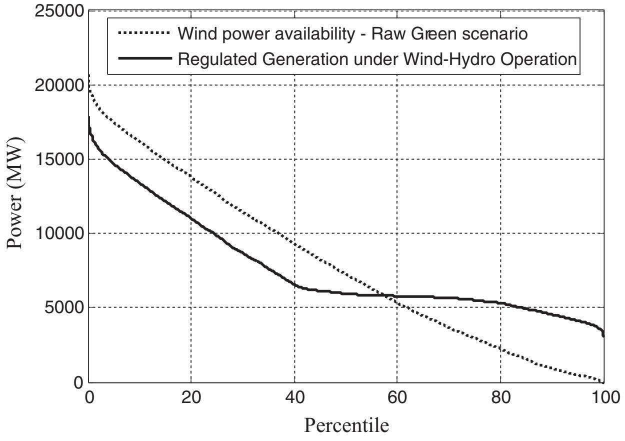

Fig. 6. Power duration curve of wind power generation – under Green scenario capacity and regulated wind power availability under the Wind/Hydro operation.

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 Fig. 5, a larger share of the total target was assigned to the Cahora Bassa plant and the opposite to Lake Kariba. One of the main reasons for this is 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.

4.2. Simulation result

Duration curve of power generation over the entire simulation period is given in Fig. 6. 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.

With the implementation of the planned reservoir schemes in the Zambezi water resources system, the storage capacity is going to adding more battery for wind regulation, which will increase the reliability of combined wind/hydro energy considerably, accordingly improving the penetration. Further regional cooperation within the SAPP framework will result in benefits in the area of auxiliary services, such as the sharing of spinning reserves [17]. This will further relax the constraints in operation of the reservoir to offset the wind power availability.

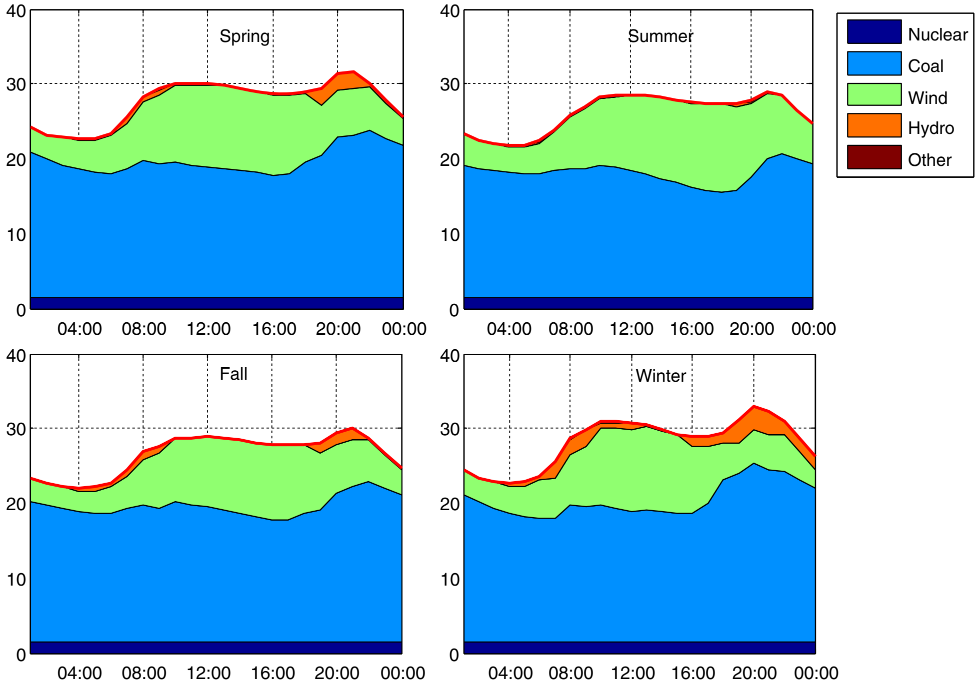

Fig. 7. Mean diurnal generation profile in the analysis period, reference case for default Green scenario capacity of wind generation by season.

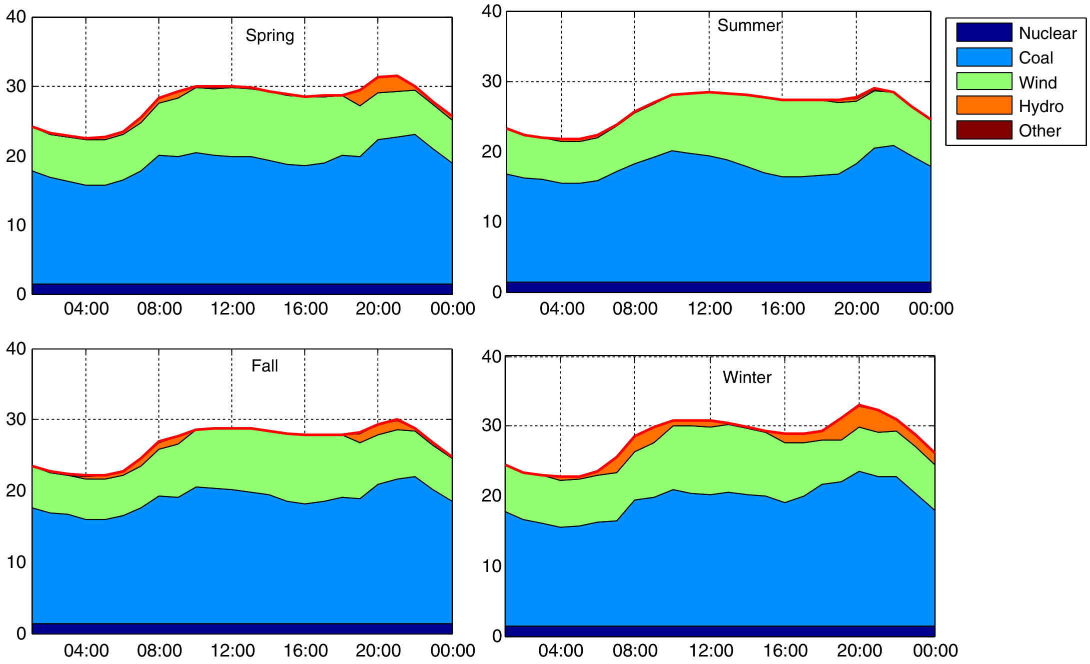

Fig. 8. Mean diurnal generation profile in the analysis period, wind–hydro operation.

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.

In 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. Other 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 Eqs. (7)–(9). Fig. 7 shows the mean diurnal generation profile, by season. In this operation 13% of wind penetration can be achieved.

In Wind/hydro operation scenario, 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 Fig. 8.

5. Conclusion and remarks

The approach presented in this paper has several clear benefits over models presented in previous studies. 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. This is one major addition to the studies conducted before. Since seasonal fluctuation of water resources has a strong influence on both storage availability as well as hydropower generation capacity.

The model allocates a target for each reservoir with an operation rule combination that gives the best possible hourly allocation of power output. An hourly time step water resources and power grid system model is presented in this paper to assess reliability of combined wind/hydro energy operation simulated over one year period of time. Although the analysis conducted is based on observed wind generation and it assumes a perfect foresight 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 h of generation with a reasonable accuracy sufficient for the power system management or energy trading [24]. The optimization routine illustrated in this study can be made to look at maximizing the net benefit over 48–72 h of generation. Furthermore, coefficient obtained based on optimization over observed longer time scale can serve as guiding values which can be incorporated when developing operating policies of the interconnected reservoirs to achieve optimum benefit and high level of penetration over the system. This however requires that stochastic properties of wind generation and complexity of water resource system remains constant.

For many African counties both the wind as well as hydropower resource have not been well developed yet but many of them 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 so that the synergetic benefit that can be obtained with operating them together can fully be exploited.

Some studies strongly recommend a longer time scale of analysis [9]. Therefore in order to report the findings on the actual reliability figures with more confidence this study need to be extended into a longer time scale of analysis to capture the effect of interannual variability of both resource availability as well as demand fluctuations. However, 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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