HYDRO PUMPED STORAGE DYNAMICS

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***Abstract** - The work discussed in this paper is the development of a hydro pumped storage dynamics simulator using a system dynamics approach. Hydro pumped storage schemes cycle water between two dams situated at an elevation relative to each other, while generating power through a reversible turbine-pump set when water is allowed to flow but consuming power when in pumping mode. This hydro pumped storage system is a net energy consumer requiring more energy to pump than it provides while generating. The amount of water available in the dams influences the amount of power that can be generated, more importantly, the three pumped storage schemes (Drakensberg, Palmiet and Ingula) included in this simulator have unique operating parameters (such as capacity factors, cycle efficiencies, head, etc.) and have been explicitly modelled. The scenarios that can be generated include the variation of dam levels for Drakensberg, Palmiet and Ingula pumped storage schemes with the change in electricity demand. The levelised cost of electricity for each of the pumped storage schemes is evaluated with changing capacity factors as well as impacts of modifications to the existing hydro pumped storage infrastructure. The other scenario that can be generated based on the model structures above is the impact of additional pump/turbine units on the dam levels and the energy sent out.*

***Keywords:** Pumped storage; dam's behaviour; levelised cost of electricity; peaking.*

1. INTRODUCTION

Eskom Holdings State-Owned-Company (SOC) is an electricity utility in South Africa that holds the monopoly in terms of electricity generation. Eskom SOC owns and operates 27 power stations in South Africa with a total nominal capacity of 41 995 MW. Eskom's generating capacity comprises of 35 726 MW from coal-fired power stations, 1 860 MW from nuclear power, 2 409 MW from gas-fired power fuelled by diesel, 2 000 MW from hydro and pumped storage stations as well as 3 MW from a wind farm at Klipheuwel [13,14]. Eskom SOC utilizes the hydro pumped storage schemes for generation of electricity during peak hours and Department of Water Affairs (DWA) utilizes the existing schemes for water transfer [3]. This report investigates the operating dynamics that occur at the hydro pumped storage schemes using a system dynamics approach.

The purpose of this project was to evaluate the feasibility of modifying the existing hydro pumped storage facilities in order to increase pumped storage capacity. The current existing hydro pumped storage facilities (Drakensberg and Palmiet) in South Africa were as well as the committed future build (Ingula) were simulated. The parameters that were modelled include the effect of changing dam levels, the energy sent out, the levelised cost of electricity and the impacts of the scheduling order of the hydro pumped storage schemes. The electricity demand data that is used in the model is based on monthly averages and projections obtained from the Generation Planning Department in Eskom SOC.

The use and flexibility of a system dynamics methodology allowed understanding of the factors that affect hydro pumped storage generating capacity through sensitivity analysis.

2. BACKGROUND

Eskom supplies 95% of South Africa's electricity [1] and it has been observed that the demand for electricity has increased over the years. It has been shown in the previous study investigated in [2] that the peak demand profile has also increased over the years as the overall demand for electricity has increased [2]. The types of peaking stations available at Eskom are hydro pumped storage power stations and open cycle gas turbines. The peaking stations are utilized when the demand is higher than the base load supply.

There are two different types of hydro-electric systems namely [5]:

- Pumped storage: This hydro system allows water to be recycled between an upper reservoir and lower reservoir.
- Run-of-river: This hydro system only utilizes the available natural water in the river and diverts the water without storing it.

Hydro-electric operates such that the potential energy of water stored in a dam is converted into electrical energy. The water is used to drive the turbine shafts and then is discharged back into the river.

Hydro pumped storage schemes cycle water between two dams situated such that the upper dam is elevated from the lower dam, while generating power through a reversible turbine-pump when water is allowed to flow to the lower dam, but consuming power when pumping water to the upper dam. As with any mechanical system, the reversible pump turbines utilized in the pumped storage schemes are not perfect electricity generators, that is, they are subject to mechanical inefficiencies. This means that only around 75% of the electricity used to pump water from the lower dam to the upper can be generated when the unit is switched to the generating mode [3,8,9]. Eskom's hydro pumped storage schemes have been designed to be weekly balanced, which implies that the upper dams can only be restored to their initial volume over the weekends. However, shorter pumping periods can be experienced during the off-peak hours of weekdays.

The model was simulated using iSee STELLA and provided an engagement platform for senior managers to understand and interrogate those factors which affect hydro pumped storage dynamics for better future planning with respect to being able to meet peak demand.

3. METHODOLOGY

The system dynamics approach used in this project is defined in this section, which includes:

- Problem definition

- Model Boundary Chart (MBC) – developed to define the boundary of the system being simulated. With any technical project, scope creep is always imminent, but defining the problem up front including variables that are to be excluded, helps to manage this and establish the system boundaries.

- System Architecture Map (SAM) – This tool was developed by Eskom's System Dynamics Centre of Expertise (CoE), in addition to the conventional system dynamics modelling approach to assist the modeler in understanding the sub-elements of the system being modelled, specifically the technical process or material/energy flows. It is also a useful tool to use when communicating with project stakeholders who generally do not have technical knowledge of system dynamics modelling tools.

- Causal Loop Diagram (CLD) - The CLD is drawn up at the outset of the project and reviewed upon completion. Eskom senior management have had exposure to CLD's and they are accepted as a useful tool when discussing the system and its many variables and influences. Reviewing the CLD upon completion of the project allows stakeholders to gain a comparison view of how they thought the system behaved versus how it actually happens.

- iSee STELLA model structures – The actual simulation model which forms the core of the project.

3.1 PROBLEM DEFINITION

As stated above, the hydro pumped storage schemes are net consumers of electricity, requiring more to pump than they are able to generate with an equivalent amount of water. Their value, however, is not defined by their generating ability, but rather their ability to essentially "store" electricity as potential energy of water in an upper dam, so that this water can then be released to the lower dam during peak demand times when conventional generating capacity falls short. The potential energy can then be restored over weekends when excess generating capacity is available by pumping water from the lower dams to the upper dams.

A diagram of the Drakensberg pumped storage scheme can be seen in **Figure 1**. Due to the weekly balanced nature of these schemes, the simulation time frame was defined as a period of two weeks running at an hourly resolution.

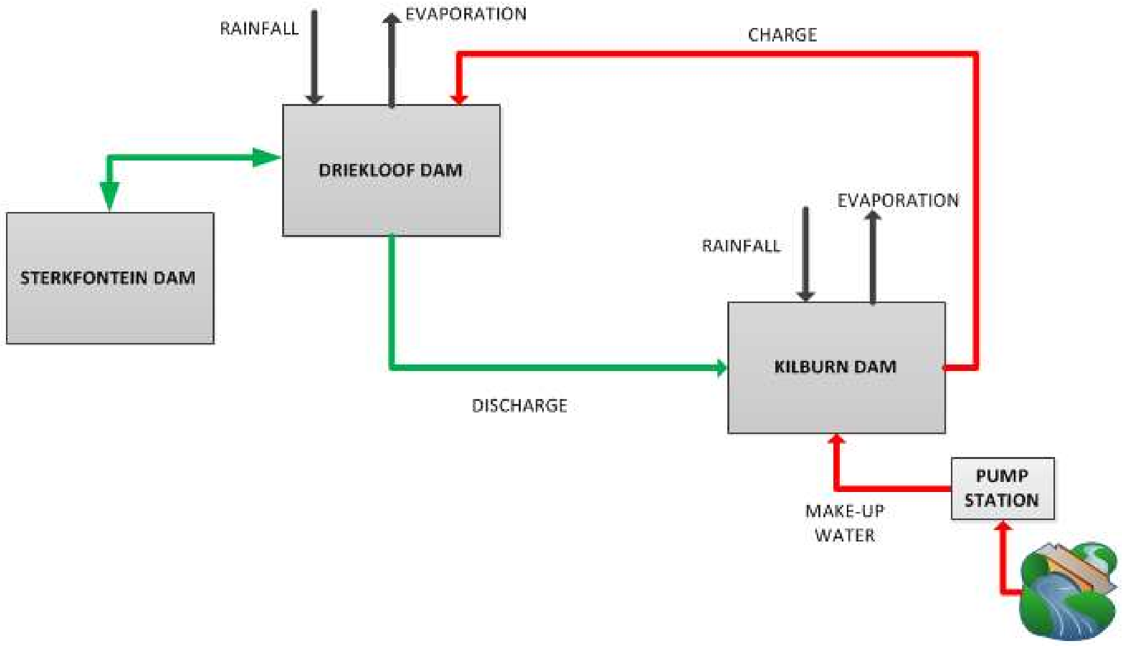


Figure 1 – Diagram of the Drakensberg Pumped Storage Scheme

Table **1** describes the operating parameters at the Drakensberg pumped storage facility.

Table 1 – Drakensberg Operating Parameters

Parameters	Drakensberg Pumped Storage
Upper dam volume	Driekloof dam 27.5 million m^3
Lower dam volume	Kilburn dam 27 million m^3
Weekly operational cycle pumping hours	39 hours
Number of installed units and capacity	4 (250 MW)
Load factor	30 %

Due to a backlog of planned maintenance required in conventional power stations, coupled with an aging generation fleet, Eskom SOC is currently in a position where electricity demand outstrips conventional supply options on almost a daily basis. This has placed incredible pressure on the existing pumped storage schemes to generate far more frequently than they were operationally designed for, during the week.

This implies that the pumped storage schemes have shifted from being weekly balanced to daily balanced systems and are in their current state, unable to pump sufficient volumes of water from the lower to the upper dam in order to optimise generating capacity during the week.

A system dynamics simulator was developed using iSee Stella to model the existing pumped storage facilities in South Africa, as well as the scheme currently under construction. The interactions of the dams with the mechanical components will be linked as seen in Figure 4.

The behavior of the dam levels for the pumped storage schemes was evaluated as well as energy sent out and levelised cost of electricity.

3.2 MODEL BOUNDARY CHART

The model boundary chart developed for the hydro pumped storage dynamics simulator is shown in **Table 2**. The components of the model boundary chart are defined below:

Exogenous variables: are defined as the variables that are used in the model to give simulation results, but are not calculated by the model.

Endogenous variables: are defined as the variables that are calculated by the model.

Excluded variables: are defined as the variables that are eliminated when developing the model based on their complexity or relevance to the problem.

Table 2 – Model Boundary Chart

Exogenous Variables	Endogenous Variable	Excluded Variables
• Maximum and minimum dam capacities • Maximum volumetric flow rates • Electricity monthly demands	• Energy sent out • Pump load required • Dam overflow volumetric flow rates • Dam volume	• Water loss through evaporation and erosion as well as rain water inflows • Physical constraints of the pumped storage sites to accommodate infrastructural changes.

3.3 SYSTEM ARCHITECTURE MAP

Figure 2, the System Architecture Map (SAM), shows the influence of each component in the hydro pumped storage scheme on another component, and will be explained moving from the left hand side to the right hand side.

Water is obtained from the rivers feeding into both upper and lower dams. When there is sufficient water in the upper dam and the lower dam has not reached its maximum capacity; generation can occur. Conversely, when there is sufficient water in the lower dam and the upper dam has not reached its maximum capacity; pumping can occur. However, both pumping and generation are restricted by whether the grid requires electricity to be generated, or if there is additional auxiliary electricity available to be used for pumping.

The amount of water flowing into the lower dam and the upper dam needs to be evaluated to establish whether the hydro pumped storage schemes should pump water or generate electricity. The energy supply and demand balance can be achieved by finding the difference between the actual supply and demand for electricity. If excess electricity supply is available, the decision path marked “yes” will be followed. This would imply that pumping can be accomplished, and this is dependent on the pump efficiency.

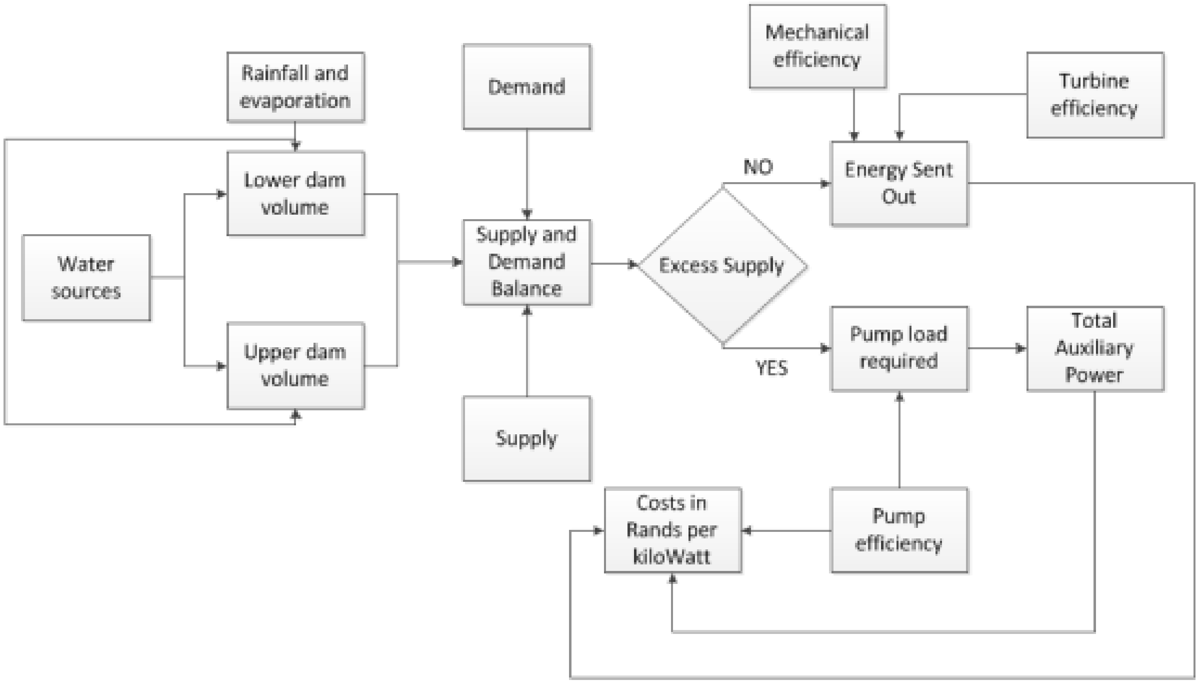


Figure 2- System architecture map for hydro pumped storage

Alternatively, when there is no excess electricity supply, the decision path marked “no” is followed. When there is no excess electricity supply and the demand has not been met yet, it implies that the hydro pumped storage schemes are required to generate electricity. The associated costs of pumping and generating can be calculated using a simplified equation for levelised cost of electricity, shown in equation 2 where O&M is Operating and Maintenance costs and CRF is the Capital Recovery Factor:

$$\frac{Capital\ Cost\left[\frac{R}{kW}\right]*CRF+Fixed\ O\&M\left[\frac{R}{kW}\right]}{8.76*Capacity\ Factor}+\frac{Fuel\ Cost\ \left[\frac{R}{GJ}\right]}{Efficiency\ [\%]}*3.6+Variable\ O\&M\ \left[\frac{R}{MWh}\right] \qquad [2]$$

The efficiency of the schemes is documented in fact sheets [3,8,9] and the capacity factor is calculated by the simulator based on the period of time that the pumped storage scheme is generating for. The other factors were obtained using a report by the Electric Power Research Institute (EPRI) detailing operating parameters of generation technologies [15].

3.4 CAUSAL LOOP DIAGRAM

The causal loop diagram (CLD) in Figure 3 illustrates the core feedback relationships present in this system, and is made up of two balancing loops. Loop B1 shows the driving force behind the utilisation of pumped storage technology for electricity generation, while B2 describes the need to expand pumped storage capacity.

Starting in balancing loop B1, *Electricity Demand vs Supply Gap* describes the key variable to consider for any power generation utility as it shows the shortfall between available electricity and electricity demand. If this gap increases, it follows that *Frequency of Pumped Storage Utilisation* will also increase, as this technology becomes vital to maintaining uninterrupted supply. When pumped storage facilities are utilised, *Electricity Generation* increases and this serves to reduce the *Electricity Demand vs Supply Gap*, thereby closing loop B1.

An increase in electricity demand implies not only an increase in overall MWh required, but also an increase in capacity terms i.e. instantaneous MW requirements. It follows then that increasing the *Electricity Demand vs Supply Gap* will also increase the *Size of Demand Peaks*, thereby reducing the *Ability to meet Demand Peaks*. This is a major issue and must result in capacity expansion of the power utility. It is more likely for a utility to construct more *Pumped Storage Capacity* in this instance as opposed to traditional base-load generation options, as it is cheaper to construct. The cost savings comes at a trade-off with the smaller peak generation options such as pumped storage not being able to generate for long periods of time, but due to the fact that additional capacity is only required for peak load times (around 4 hours per day), this is reasonable.

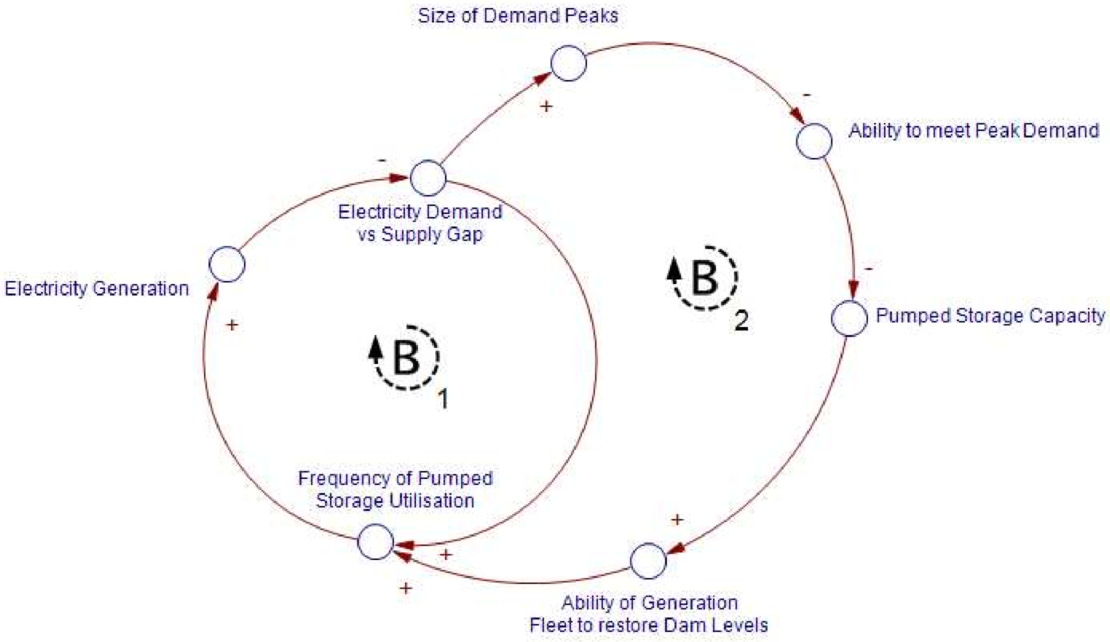


Figure 3 – Causal Loop Diagram

With an increase in *Pumped Storage Capacity*, the *Ability of Generation Fleet to restore Dam Levels* also increases. This is because the higher capacity of the pumped storage facilities will allow them to utilise as much auxiliary capacity as may be available to pump water in a shorter time compared to a pumped storage facility with lower capacity. There is a physical limit on this dynamic, namely the amount of auxiliary capacity available. Conventional generation fleet is limited and so an optimal point exists where pumped storage stations have a high enough capacity to restore dam levels, but not so high as to become redundant capacity. Finally, the increase in *Ability of Generation Fleet to restore Dam Levels* will also increase *Frequency of Pumped Storage Utilisation* as water will be available in the dams more often. This link closes balancing loop B2.

3.5 MODEL STRUCTURE

While the entire STELLA simulator structure cannot be discussed in detail in this paper due to its complexity, two key structures have been highlighted and discussed below.

(a) Drakensberg Pumped Storage Scheme

The image shown in Figure 4 illustrates the model structure built for the Drakensberg Pumped storage scheme. This structure was repeated for the Palmiet and Ingula schemes with their specific operating information included where relevant.
Two stocks can be seen in this figure, the topmost representing the volume of water in the upper dam is labelled *Driekloof Upper m3*, Driekloof being the name of the dam in question. The bottom stock is labelled *Kilburn Lower m3* and represents the volume of water currently in the Kilburn (lower) dam. In the real world system, the Driekloof and Kilburn dams will empty and fill, based on the action of four reversible pump-turbine units currently in operation at the Drakensberg scheme. During electricity generation, water will flow from Driekloof to Kilburn, and in the reverse direction during pumping. Instead of simulating the reversible units using four bi-flows, it was decided that eight uni-flows would be used, simply to reduce the complexity of the equations that would be required in these flows.

The four flows representing the **generating mode** of the four pump-turbine units at Drakensberg can be seen on the **right** of Figure 4 and are labelled from right to left as follows: *Drak Unit 4 Flow Supply, Drak Unit 3 Flow Supply, Drak Unit 2 Flow Supply* and *Drak Unit 1 Flow Supply*.

The four flows representing the **pumping mode** of the four pump-turbine units at Drakensberg can be seen on the **left** of Figure 4 below and are labelled from left to right as follows: *Drak Unit 4 Flow Pump, Drak Unit 3 Flow Pump, Drak Unit 2 Flow Pump* and *Drak Unit 1 Flow Pump*.

In addition to the existing infrastructure, the user is given the option to include additional pump-turbine units at the Drakensberg facility, essentially increasing its capacity. The accommodation for these additional units is made through the two flows directly in the centre of Figure 4 connecting the two stocks. These flows are named *Drak Additional Units Pump* and *Drak Additional units Supply*. The ghost converters to the right and left are calculated flowrates for each of the pumping or generating modes respectively and are calculated in the structure shown in Figure 5.

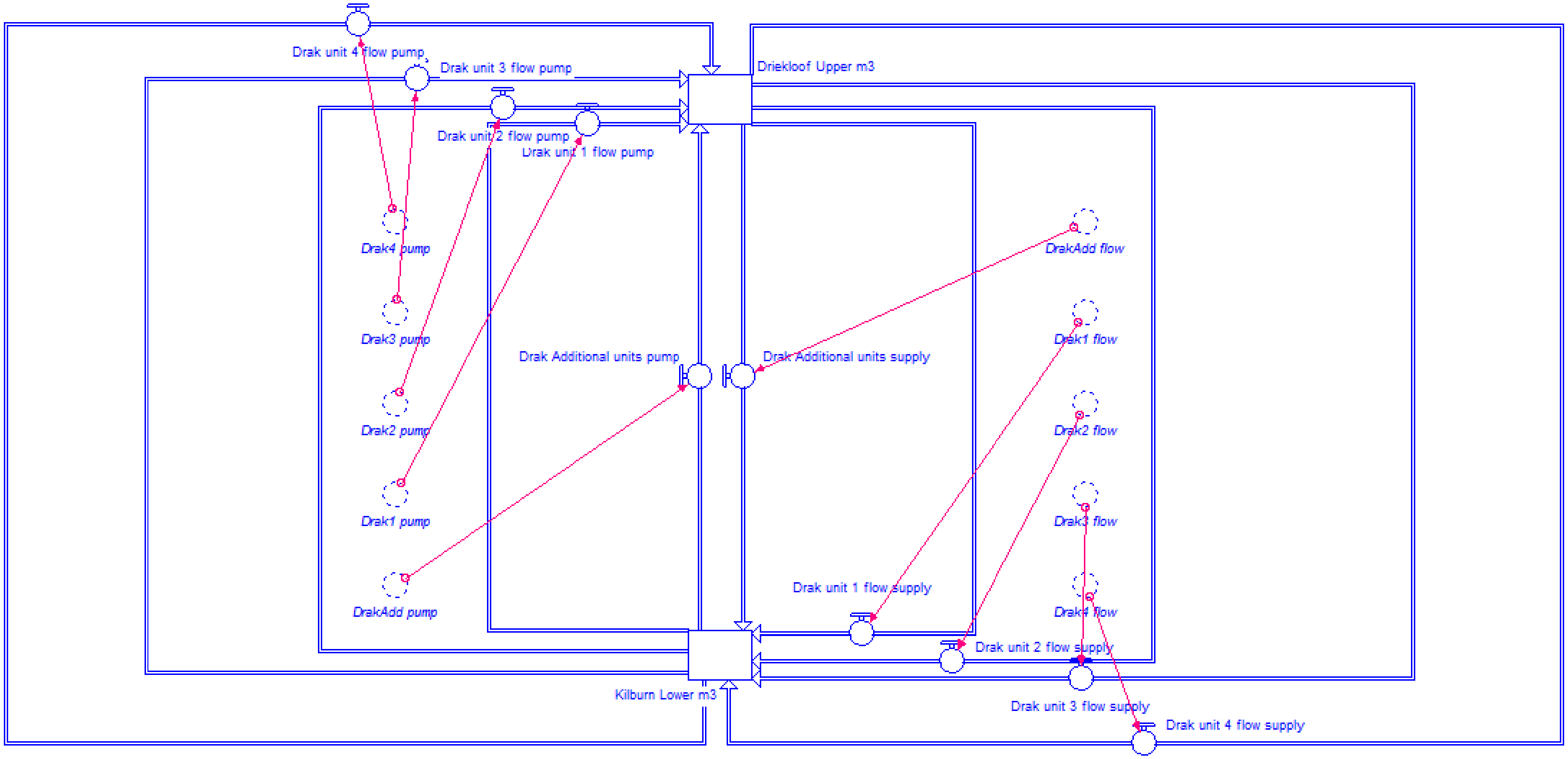


Figure 4 – Structure a – Drakensberg Pumped Storage Dams and Flow

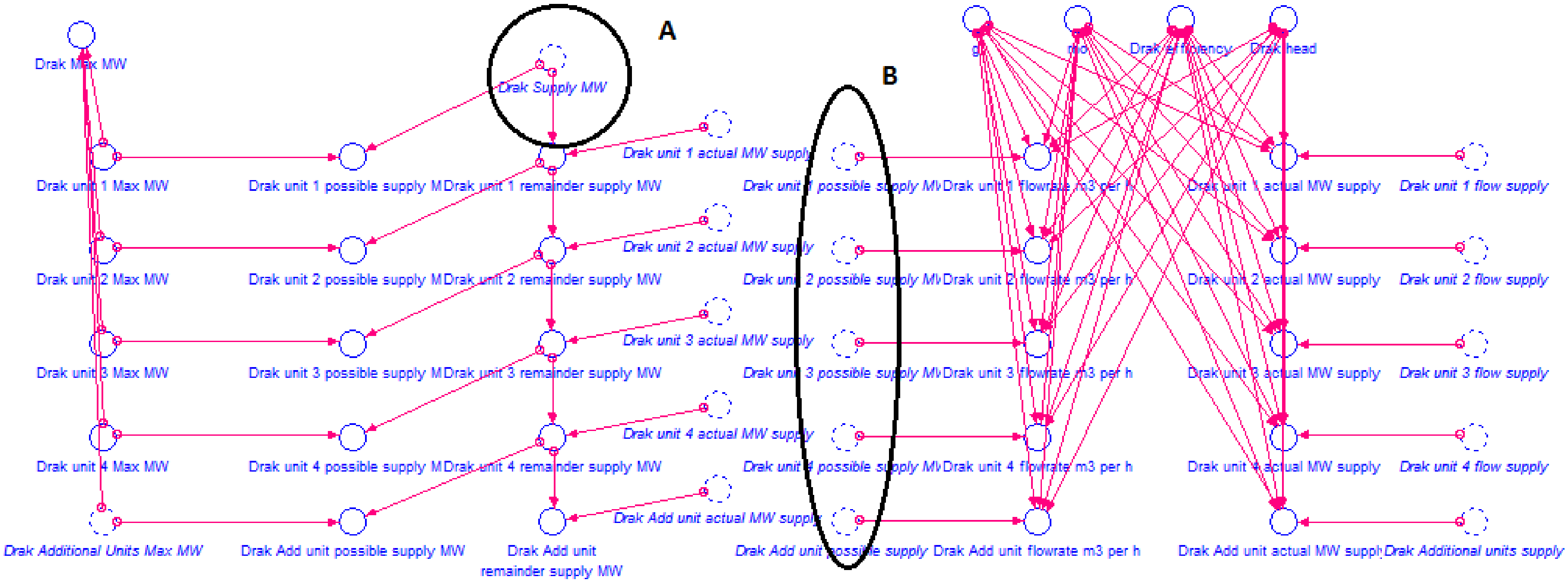


Figure 5 – Structure b – Calculation of Drakensberg Flowrates

(b) Drakensberg Calculation of Flowrates

The structure in Figure 5 describes the calculation of flowrates specifically for the generating mode of operation. The pumping mode calculation is done in exactly the same way so only the generating mode will be discussed.

Starting from the left of this structure, the maximum capacities (MW) of each unit at Drakensberg are fed in using converters labelled *Drak Unit Max MW*. These feed information to the next column of converters called *Drak unit possible supply MW*. The *Drak Supply MW* converter, labelled “A”, is the key to this structure’s functionality. Calculated elsewhere in the simulator, *Drak Supply MW* represents the (MW) capacity of electricity that is as yet unmet by other means of generation and that Drakensberg pumped storage must now supply. This capacity is scheduled from one unit to the next using cascading logic.

The simulator compares the total electricity supply requirement to the maximum capacity of a specific generating unit in the *Drak unit possible MW supply* column of converters, if the requirement is lower than the maximum, the requirement itself can be generated and no other units are necessary. If the requirement is higher than the maximum unit capacity, the maximum unit capacity is used and a “remainder” value is generated. This remainder is equal to the difference between the total requirement and what was actually supplied. The remainder value is then passed on to the next unit for the same comparison to take place.

If, after all the units have been utilized at their maximum values, and there is still electricity that needs to be supplied, this electricity is classified as electricity unserved by Drakensberg and must be supplied by the pumped storage facility next in terms of merit order, in this case the Palmiet facility.

This cascading logic only checks MW capacities and does not take into account the availability of water for generation, and as such, a second layer of calculation is required. The *Drak unit possible supply MW* converter column is ghosted to the right of the cascading structure in the column labelled “B”. The possible supply capacity (MW) is converted into a possible supply flowrate using equation 1 below:

$$P = (Q\rho g h)\eta \qquad [1]$$

Where:
P=Supply capacity requirement in MW
Q=flowrate in m^3 per second
ρ=density of water in kg per m^3
g=acceleration due to gravity in m per second
h= Head pressure in metres
η=efficiency of the pump turbine

This required flowrate is compared to actual dam levels in a separate structure and an actual flowrate is calculated. The actual flowrate is ghosted back into the structure shown in **Error! Reference source not found.** and this column of converters can be seen all the way to the right of the structure labelled *Drak unit flow supply*. The actual flowrate is then calculated back into a capacity in MW using equation 1 and is stored in *Drak actual MW Supply*.

4. RESULTS AND DISCUSSION

4.1 Demand and supply profile

The results obtained for the weekly demand profile for a winter and summer month are shown in Figure 6. The green line illustrates the supply curve which excludes the peaking stations and is constant throughout the week because the hourly capacity is assumed to have not changed throughout the week. The red graph illustrates the July demand curve and is based on the simulated hourly averages for weekdays and weekends. The blue graph illustrates the October demand which is also based on the simulated data.

July, being a winter month in South Africa, is showing a larger demand profile than October, which is a summer month. During 150 hours, a decrease in both the July and October demand can be seen. The reason for this decrease is that after 150 hours, it is during the weekend and usually the demand for weekends is lower than that of the weekdays.

When the overall country electricity demand is larger than the overall electricity supply, then pumped storage schemes can generate electricity. When the electricity supply is larger than the demand, the pumped storage schemes can use the excess (auxiliary) electricity for pumping. The results shown in Figure 6 are calculated using actual data. The hourly demand data for 2011 was separated into specific months in order to account for seasonal variation. Average weekdays, average Saturday and average Sunday were then calculated for each month.

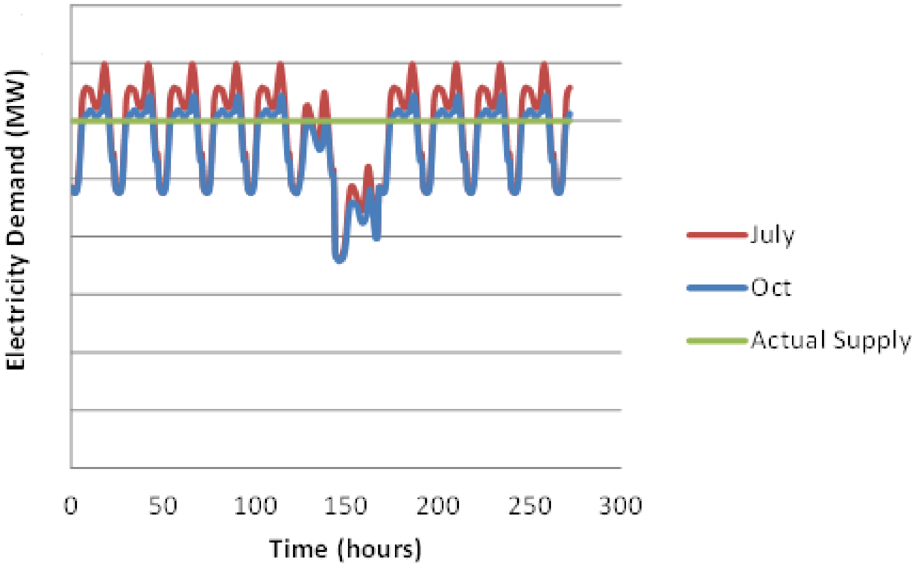


Figure 6 – The Demand and Supply Profile

The total pumped storage supply for the three pumped storage schemes corresponding to Figure 6 profiles is shown in Figure 7.

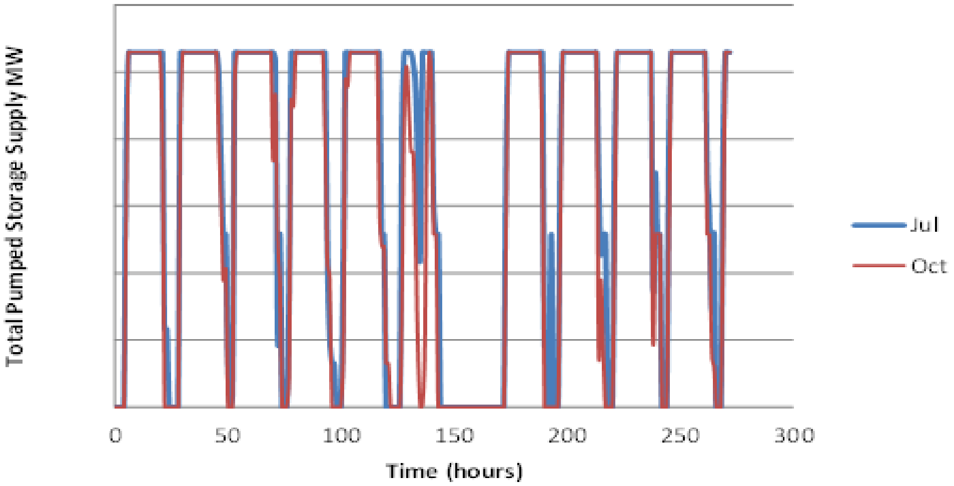


Figure 7 - Total pumped storage energy sent out

The shape of this graph is indicative of the pumped storage system behavior. Given that pumped storage is a peaking technology, a steady supply curve for a 2 week duration is not expected. Instead, this graph shows energy sent out for a number of hours each day at the maximum capacity of the 3 pumped storage schemes.

4.2 Energy Sent out by the pumped storage schemes

The energy sent out by the three pumped storage schemes is shown in Figure 8. During weekdays, pumping occurs for fewer hours because the electricity demand is higher as

compared to the weekends. Simulating the Ingula pumped storage scheme shows that it would have the largest energy sent out because it has the highest cycle efficiency, followed by Drakensberg and then by Palmiet with the lowest cycle efficiency.
This is because the scheduling order programmed into this simulator is such that Ingula will supply load before any of the other schemes, so a lesser energy requirement remains to be supplied by Drakensberg and Palmiet.

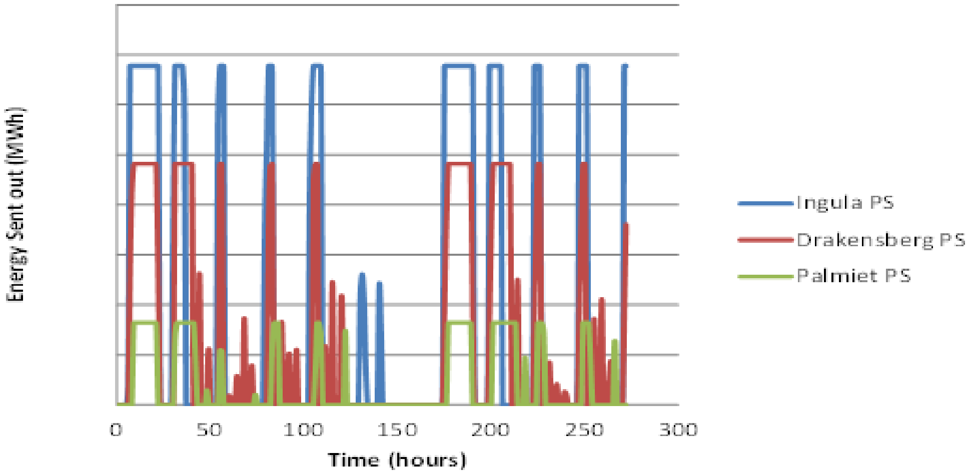


Figure 8- Illustration of the energy sent out by the pumped storage schemes

4.3 Scheduling order of the pumped storage scheme

When developing this model, it was assumed that the hydro pumped storage schemes should supply most of the available capacity prior to the open cycle gas turbines. The reason for incorporating this assumption into the model is to save diesel costs to operate the open gas cycle turbines by allowing pumped storage schemes to supply most of the peak demand. The results that are discussed in this section are based on the peaking stations scheduling order with the pumped storage schemes taking the priority. The demand curves that are used in the model are based on the simulated data and the logic that has been built for each of the pumped storage schemes to allow for maximum possible supply.

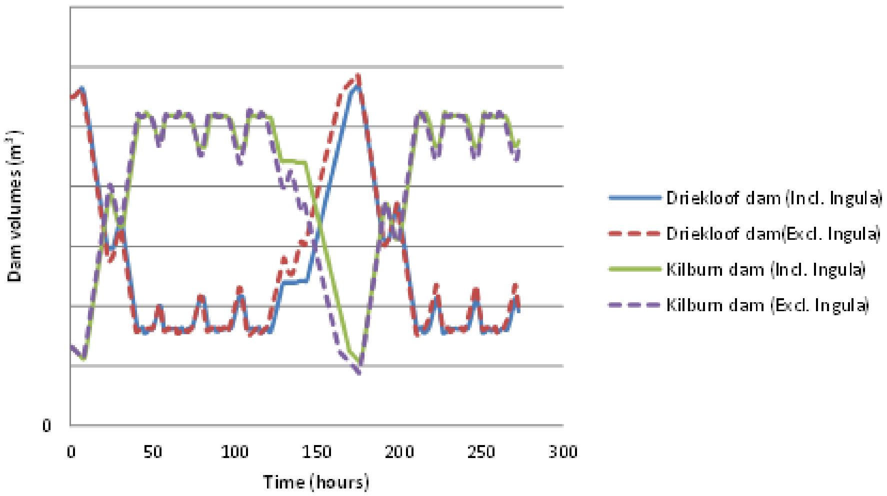


Figure 9-The behavior of the dam levels for Drakensberg pumped storage scheme

A scenario to evaluate the impact of commissioning Ingula was generated. Figure 9 shows the behaviour of the Driekloof and Kilburn dams at Drakensberg when Ingula is included. The dotted red graph shows the behaviour of Driekloof dam when Ingula is excluded from the total pumped storage supply. This is compared with the blue solid line for Driekloof when Ingula is included. It can be observed that when Ingula is excluded, the Driekloof dam level increases faster because it is now the first on the scheduling order, however when Ingula is included, the Driekloof dam increases slower because pumping is first allocated to Ingula.

4.4 Additional units at Drakensberg pumped storage

Scenarios were generated to evaluate the dam levels of Drakensberg pumped storage when additional pump/turbine units are included. In the model there are two capacity options that can be selected namely, 250 MW and 333MW.

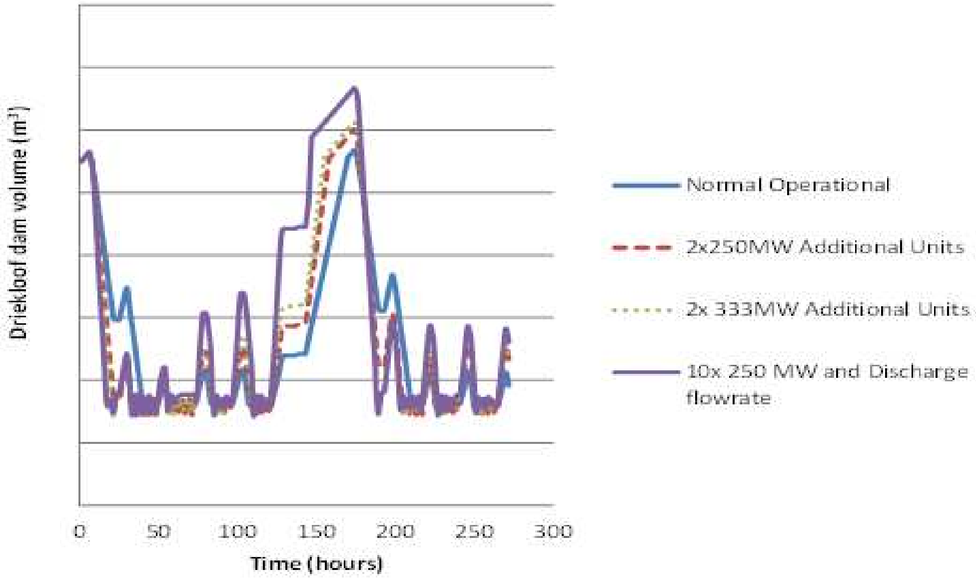
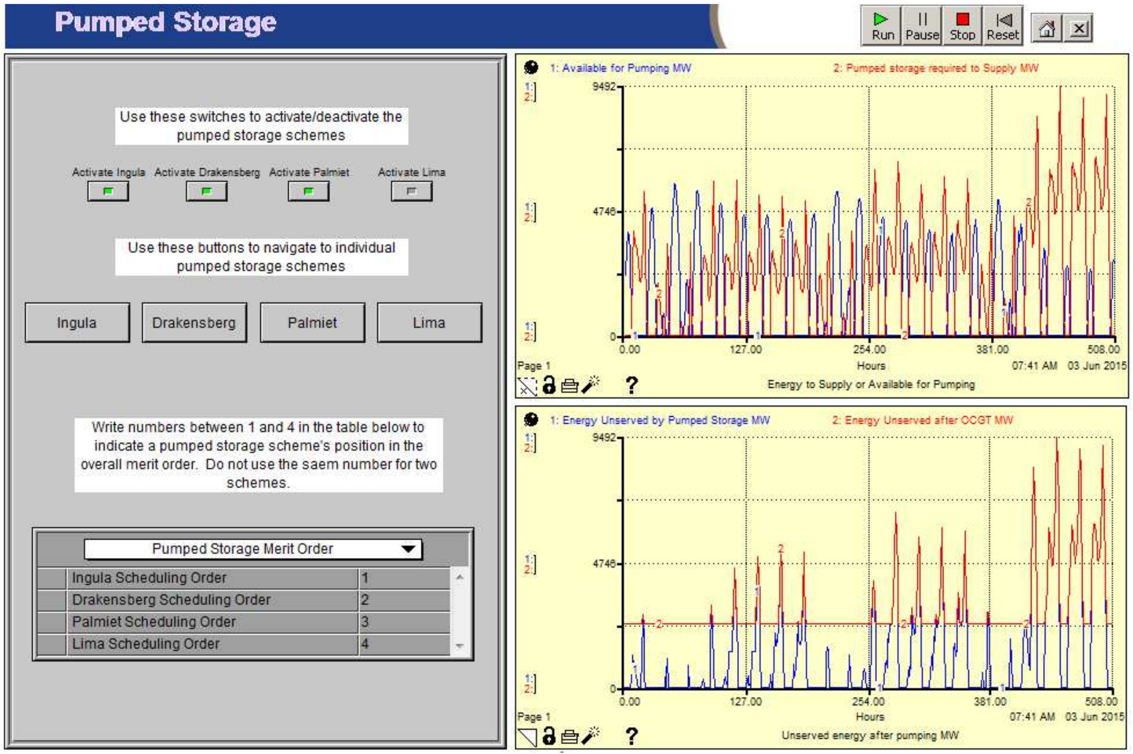


Figure 10-The behaviour of the upper dam of Drakensberg pumped storage scheme

From Figure 10, it is observed that when additional units are included, Driekloof dam will deplete faster than with normal operation (four units). The extreme case is to include ten extra units at Drakensberg, which would imply that by Friday (136 hours), water should be pumped into the Driekloof dam.

4.5 The User Interface

The images below are screen captures of the user interface developed in iSee STELLA. The interface is especially valuable for use in Eskom as the models are intended as management flight simulators to engage with the model structures through a simple platform.



Use these switches to activate/deactivate the pumped storage schemes

Use these buttons to navigate to individual pumped storage schemes

Write numbers between 1 and 4 in the table below to indicate a pumped storage scheme's position in the overall merit order. Do not use the saem number for two schemes.

Pumped Storage Merit Order

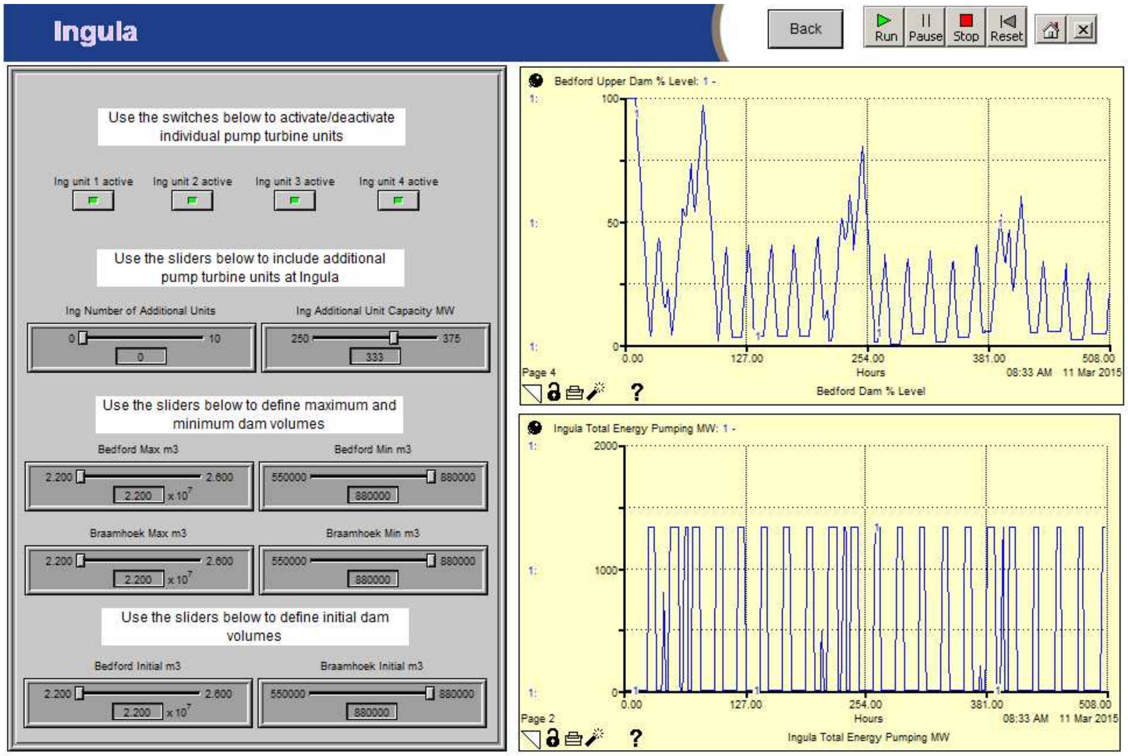
Ingula Scheduling Order	1
Drakensberg Scheduling Order	2
Palmiet Scheduling Order	3
Lima Scheduling Order	4

Figure 11 – Overall Pumped Storage Page

Figure 11 shows a page where the user is able to control and observe the action of all the pumped storage schemes. The user can activate or deactivate each scheme as well as define a merit order i.e. specify which scheme should supply electricity first when required and which should consumer electricity for pumping first when it is available.

The graphs on the top right show two lines, the blue line depicts the excess electricity available for pumping while the red line shows the amount of electricity that must be supplied by peaking technologies to prevent a shortfall.

The graph on the bottom right also shows two lines. The blue portion of the graph represents electricity that must be supplied by peaking that was successfully served through the use of pumped storage, while the red peaks represent electricity that must be supplied but that pumped storage could not supply. This electricity will need to be supplied through other means such as the use of Open Cycle Gas Turbines (OCGT).



Use the switches below to activate/deactivate individual pump turbine units

Ing unit 1 active
Ing unit 2 active
Ing unit 3 active
Ing unit 4 active

Use the sliders below to include additional pump turbine units at Ingula

Ing Number of Additional Units: 0 (0–10)
Ing Additional Unit Capacity MW: 333 (250–375)

Use the sliders below to define maximum and minimum dam volumes

Bedford Max m3: 2.200 x 10⁷ (2.200–2.600)
Bedford Min m3: 880000 (550000–880000)
Braamhoek Max m3: 2.200 x 10⁷ (2.200–2.600)
Braamhoek Min m3: 880000 (550000–880000)

Use the sliders below to define initial dam volumes

Bedford Initial m3: 2.200 x 10⁷ (2.200–2.600)
Braamhoek Initial m3: 880000 (550000–880000)

Figure 12 – Ingula Interface Page

Figure 12 shows an interface page developed specifically for the Ingula pumped storage scheme. Each scheme has its own separate page set up in the same way as this one. The user is able to activate or deactivate specific units, as well as make changes to the upper and lower limits specified for dam volumes. The user can also specify the initial dam volumes to change the simulator's starting conditions.

The graph on the top right shows the percentage level of the upper dam at Ingua, in this case Bedford, while the bottom graph sows the energy consumed while pumping. Each graph pad has multiple pages showing additional information for both dams as well as the electricity generated by the scheme.

5. CONCLUSIONS

The monthly averages for the electricity demand data has been used to generate a weekly demand profile in the model such that the balanced value between supply and demand is endogenous. This allows the user to generate various scenarios based on future electricity supply and demand and to evaluate the utilisation of pumped storage for these scenarios. It has been seen that including additional units at Drakensberg will allow for a daily balanced system when future electricity demand is high.

It has been shown that the scheduling order greatly impacts the utilisation of the three (based on cycle efficiency) pumped storage schemes. For example, Ingula has been placed first on the scheduling order and as such, is utilised to a far greater degree than Palmiet, which is last.

ACKNOWLEDGEMENT

I would like to thank Peter Langley and Pat Frampton for assisting with understanding the hydro pumped storage schemes.

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