The Ingula scheme is located 23 km north-east of Van Reenen, within the little Drakensberg mountain range. It consists of a concrete faced rock-fill dam (CFRD) upper dam and an roller compacted concrete lower dam. The powerhouse complex consists of a 23 m wide machine hall and transformer hall, housing four pump-turbines which will generate at a rated head of 441 m. The powerhouse complex is linked to the upper and lower reservoirs by underground waterways. The Lima scheme is located near Roossenekal in the Limpopo province and has a capacity of 1500 MW and a rated head of 636 m. The upper reservoir is an off-channel cut-to-fill CFRD and the lower reservoir an earth fill embankment with clay core. Lima is earmarked for completion in 2014.

The prime objective in planning the capacity expansion of an electricity supply system is to produce a plan which enables anticipated future power and energy demands to be met as economically as possible. Such a plan is prepared by Eskom on a regular basis, called the Integrated Strategic Electricity Plan (ISEP), and consists of three groups. One group focuses on possible supply side options, the other on demand side management options and the third on demand forecasting. Various supply side options, such as coal fired, gas fired, nuclear (PBMR), imported power and pumped storage schemes, are considered in this plan, each fulfilling a different function in the total supply mix.

Pumped storage schemes play an important role in supplying power during peak demands, improving the power factor of the system, providing black start facility, and “smoothing” the load demand curve. The ISEP has identified the need for a number of these schemes in the future, with the first one required for commissioning in 2012. To meet this need, a comprehensive search was started in the mid 1980s. In this process, ninety potential sites were identified and systematically reduced to two.

Pumped storage technology

A pumped storage scheme is effectively a large storage battery. Energy is stored in the form of water during off-peak periods and released during peak electricity demands. The scheme involves the construction of two adjacent water containment reservoirs, one at a significantly higher elevation than the other. During periods of low demand, energy from the transmission grid is used to pump water from the lower reservoir to the higher reservoir. During periods of peak electricity demand, the process is reversed and stored water flows to the lower reservoir through hydraulic turbines driving generators. Normally, the pumping and generating modes at pumped storage plants use the same turbo-machinery and generator-motor equipment, their direction of rotation simply being reversed depending on which role is required. Hence the term “pump-turbines” or “reversible turbines”. To avoid cavitation damage to these machines, they are located in deep underground caverns or, in some cases, deep shafts. The schemes investigated are 60 to 80 meters below the low water level of the lower reservoir. Underground water tunnels, 6 to 9 m in diameter, link the pump-turbines to the lower and upper reservoirs. A typical layout of this arrangement is illustrated in Fig. 1.

A pumped storage plant is actually a net consumer of energy; it returns approximately 3 kWh of electricity for each 4 kWh required for pumping. However, it offers the following important benefits:

- Energy generated during peak periods has a higher monetary value than the energy required for pumping during off-peak periods.
- Continuous operation of the highest efficiency plants is possible, reducing overall fuel consumption of the total system. Pumped storage generation, by using large quantities of off-peak power for the pumping process, enables coal fired power stations to operate under much more stable loading conditions.
- Rapid and flexible response to system load changes. Very large load swings can typically be accommodated.

Pumped storage could be combined very effectively with a water transfer scheme. Both Drakensberg and Palmiet pumped storage schemes fulfill this dual function. The Drakensberg pumped storage scheme, for instance, pumps an additional quantity of water for the Department of Water Affairs and Forestry (DWAF) from the lower located...
Tugela catchment to the higher located Sterkfontein dam, which supplements the Vaal dam.

**Key design criteria**

**Reservoir capacity**

In the past, the live (operating) volume of the reservoirs was set at an equivalent of 28 hours continuous generation, starting with a full upper reservoir. This volume allows 50 hours of generation per week, resulting in a 30% utilisation factor. As the demand for electricity has become peakier, a different approach is now followed. The storage volume is set to allow a minimum utilisation factor of 20% plus 4 hours of emergency operation. This results in an equivalent generating period of approximately 38 hours per week. Once this volume has been established, an optimisation study is carried out to compare the additional cost of a larger dam with the associated saving in system production cost. A larger storage volume costs more to construct, but increases the utilisation of the scheme and reduces the operating cost of other more expensive plant.

**Waterways**

The horizontal distance between the upper and lower reservoir is normally limited to 6000 m. Long waterways are costly and result in higher hydraulic losses.

**Lining system**

Reinforced concrete is normally used as tunnel linings where the maximum internal water pressure under transient conditions is less than the minimum rock stress by a safety margin of 1.2. Steel linings are used where minimum rock stresses are inadequate to resist the internal water pressures.

**Design velocities**

Concrete lined tunnels: 5.0 to 5.5 m/s

Steel lined tunnels: 8.5 m/s

**Machine characteristics**

Rated power is calculated as:

\[ P_g = \eta \cdot \rho_w \cdot g \cdot Q_g \cdot H_g / 1000 \]

where:

- \( P_g \) = rated generating power in kW
- \( \eta \) = efficiency (approximately 0.90)
- \( \rho_w \) = density of water in kg/m³
- \( g \) = gravitation constant in m/s²
- \( Q_g \) = rated generating flow in m³/s
- \( H_g \) = rated generating head

**Pumping power**

\[ P_p = \rho_w \cdot g \cdot Q_p \cdot H_p / 1000 / \eta \]

where:

- \( P_p \) = pumping power in kW
- \( Q_p \) = pumping flow in m³/s
- \( H_p \) = pumping head

The pumping power is approximately the same as the generating power.

**Specific speed for pumping**

Each turbine is characterised by a constant, called the specific speed defined as:
Where:

\[ n = \text{rated speed in rpm.} \]

\[ n_q = \text{specific speed} \]

Pump-turbine selection

\[ k = n q H_p^{0.75} \]

\( n \) and \( P_p \) are selected so that \( k \) is a maximum of 3500.

To ensure that practical machine configurations are selected, \( N_q \) and \( H_p \) are plotted and compared with previously used pump-turbines.

**Rated speed**

The rated synchronous speed can be calculated once the specific speed, rated power and head are known.

\[ n_r = 50 \times 60/n_q \text{ (in a 50 Hz system)} \]

\( n_r \) = rated speed

\( n_q \) = number of pairs of poles in the generator (i.e. 4, 5, 6, 7 etc. Certain numbers such as 9, 11, 13 are not preferred)

**Rated head**

The rated head is the head under which the pump-turbine can just produce rated power with the guide vanes fully opened. At lower heads than rated, the output will be lower than the rated generating power.

The criteria used to select rated head are:

\[ H_r = 0.3(H_{\text{max}} - H_{\text{min}}) + H_{\text{min}} \]

where:

\( H_r \) = rated head in m

\( H_{\text{max}} \) = maximum generating head

\( H_{\text{min}} \) = minimum generating head

**Turbine submergence**

In order to prevent cavitation in pumping mode, the turbine should be placed a certain depth (submergence) below the minimum downstream pressure. An initial submergence can be calculated as follows:

\[ H_s = H_b - H_v - H_{\sigma} \]

where:

\( H_s \) = submergence in m (negative value)

\( H_b \) = barometric pressure in m

\( H_v \) = vapour pressure in m

\( \sigma \) can be derived from model tests but a number of empirical formulae may be used in the initial design stage. One of these formulae is:

\[ \sigma = 0.00195 n_q^{1.14} \]

The ratio of the maximum pumping head to the minimum generating head is limited to the range 1.2 to 1.3. The 1.3 limit is applicable for a pumping head of approximately 400 m and 1.2 for approximately 700 m.

**Hydraulic stability**

If the momentum of the water dominates the inertia of the machine, no equilibrium is reached between the driving force and the power output. In this case the flow has to be adjusted continuously in order to maintain a constant power output. To prevent this, a ratio of at least 3.0 is used between the mechanical and water starting time. The mechanical starting time is the time during which the machine increases its rotational speed from standstill to rated speed when the hydraulic driving force is applied, and is normally expressed in hydro technology as:

\[ t_m = \frac{GD^2 \cdot n}{360000 \cdot P} \]

where:

\( n \) = rated speed in r.p.m.

\( P \) = power in kW

\( GD^2 \) = inertia of rotating masses expressed in kgf.m².

The water starting time is the time in which the water reaches the rated velocity from standstill, and is expressed as:

\[ t_w = \frac{\sum l \cdot v_i}{g \cdot H} \]

where:

\( l \) = length of \( i^{th} \) waterway in meters,

\( v_i \) = velocity in \( i^{th} \) waterway in m/s

\( g \) = gravitation constant in m/s²

\( H \) = head in m

\( m \) = number of waterways

The summation is carried out for waterways between the free water surfaces (reservoirs and/or surge shaft/chamber). In general, the shorter the length between the free surfaces, the higher (better) the ratio. The inertia of the rotating masses may also be increased to improve the situation, but this will result in higher machine costs.

**Site selection process**

**Site identification**

Eskom initiated an extensive programme in mid 1980’s in the search for possible pumped storage sites throughout South Africa. In order to identify as many sites as possible, no limitations (such as capacity and location from demand centres) were set in this search. This process resulted in the identification of ninety sites in total. Apart from the key design criteria discussed above, no other restrictions were followed in this study. As a result of this, potential capacities of the schemes varied from approximately 400 MW to 2 000 MW with heads ranging from 220 m to 610 m, and in the case of a few sites bordering Lesotho, as high as 1050 m.

**Preliminary site selection**

Once the 90 sites were identified, more appropriate sites were filtered out using the following criteria:
• **Potential capacity:** The increasing need for pumped storage schemes indicated that each scheme should be at least 1000 MW.

• **Location from main demand and generating centres:** To avoid excessive transmission integration cost and transmission losses, it was important that the scheme was located in the vicinity of the generating centres and near the main national grid.

• **Water availability:** Although a pumped storage scheme does not consume water (except for a small quantity lost to seepage and evaporation), the water source had to be sufficient to allow priming within a period of 2 to 3 years.

• **Head conditions:** The higher the head, the less flow is required to generate the same power, resulting in smaller waterways and reservoir sizes. An operating head criterion between 400 m and 700 m was decided on. No single stage pump-turbines with pumping heads in excess of 700 m had been implemented at the time.

• **Accessibility:** The site had to be reasonably accessible from existing infrastructure as access roads could contribute a substantial impact and cost to a scheme.

• **Costs:** Capital cost of the scheme and transmission integration and Operation and Maintenance costs.

• **Multi-purpose potential:** Perfect examples of multi-purpose facilities are the current Drakensberg and Palmiet pumped storage schemes. Multi-purpose potential has not only a cost advantage but could also have environmental benefits, especially where dams can be shared.

Of the original 90, seven schemes were selected for further consideration:

- Impendle located in KwaZulu-Natal
- Ingula located in KwaZulu-Natal
- Mutale located in Limpopo Province
- Lima located in Limpopo province
- Strijdom located in Mpumalanga
- Waayhoek located in KwaZulu-Natal
- Hogsback located in the Eastern Cape

Final selection

Pre-feasibility studies were successively conducted on these seven sites between 1987 and 1995 followed by a comparative study and ranking process. This resulted in the selection of three top schemes, namely Ingula, Lima and Mutale. Feasibility studies were conducted to confirm the ranking of the three selected sites in merit order. These studies focused on environmental impact assessments, more detailed geotechnical investigations supported by some 1200 m of drilling, updating of the preliminary designs and re-costing of the schemes. The Mutale scheme was discarded as a result of these studies.

The Ingula scheme was selected to be developed first. The basic design started in 2004, followed by the tender design a year later. When the DWAF decided to develop the De Hoop dam, approximately 20 km downstream the proposed Lima site, a supplementary feasibility study was conducted to investigate the possibility of supplying...
water from this dam and moving the lower reservoir out of the Steelpoort River and closer to the escarpment. This resulted in a revised Lima scheme.

**The Ingula pumped storage scheme**

The Ingula pumped storage scheme is located about 23 km north-east of Van Reenen, within the Little Drakensberg mountain range. The upper reservoir site is located in the Free State and the lower in KwaZulu-Natal. The escarpment forms the border between these provinces. The distance between the upper and lower reservoirs is in the order of 6 km and the elevation difference is approximately 470 m. An underground power house complex with access tunnels, houses 4 pump-turbines coupled directly with generator-motors. The rated generating capacity is 1332 MW and the energy storage capacity 21 000 MWh (15.8 generating hours).

**Geology**

The area is underlain by sedimentary rocks of the Cca and Beaufort Groups, which have been intruded by dolerites of the Karoo Dolomite suite. The sedimentary rocks comprise mudrocks, claystones, siltstones and sandstones. In the vicinity of the machine and transformer halls, thermal effects have altered the mudrock into a very dark grey massive rock with high uniaxial compressive strengths. In view of this reasonable quality of rock it is not necessary to construct a separate valve hall as in the case of the Drakensberg Pumped Storage Scheme. The rather large span of 23 m for the machine hall is possible, but systematic rock support, comprising pattern bolting with tensioned anchors, is required.

**Machine characteristics**

- Station capacity: 1332 MW (4 Units of 333 MW each)
- Static heads: Maximum 480.6 m, Minimum 450.0 m
- Rated head: 441 m
- Pump-turbine synchronous speed: 428.6 rpm.
- Maximum transient pressure head upstream of turbines: 726 m

**Dams**

The upper dam is a concrete faced rockfill type with a length of 810 m and a maximum height of approximately 41 m. An outlet facility with radial gate is provided to simulate floods of up to 1:10 year occurrence. The lower dam is a roller compacted concrete structure with a length of 310 m and a maximum height of approximately 39 m.

**Powerhouse complex**

- **Powerhouse Cavern:** There will be a single underground powerhouse cavern in rock to accommodate the main inlet valves, the pump-turbine, motor-generator units and their auxiliary equipment. The powerhouse will be served by two, 265 tonne overhead cranes with auxiliary hooks and a small eight-ton crane below the larger cranes. The powerhouse will have a central erection bay, three main floors (pump-turbine floor, motor-generator floor, and an operating floor). The floors, unit support structure, inlet valve support structure, etc will be in reinforced concrete. The powerhouse will include a control room, ablutions, battery room, workshops, etc.
- **Transformer Cavern:** The transformer cavern will be an underground rock cavern with a reinforced concrete floor and two intermediate floors. The four main generator transformers, the two static variable frequency converters, and the two station service transformers shall be located in the transformer cavern. The transformer cavern will be located next to and parallel with the powerhouse cavern.
- **Construction adits:** Construction adits are provided to allow access to the operating floor, the pump-turbine floor and drainage gallery for excavation purposes. Adits for access to the bifurcations and penstock anchorage gallery are also provided.

**Access tunnels**

The exploratory tunnel (ET) is used for initial access to the underground caverns during construction. Access will be improved once the main access tunnel (MAT) is completed. The MAT will provide access of the electro-mechanical equipment. The ET will also house the ventilation duct and the 400 kV cables from the transformers to the surface switch yard.

**Ventilation**

Fresh air is forced into the inlet ventilation duct and distributed to the various floors of the Machine hall. The discharge is divided into three routes, namely the ET for cable cooling, the MAT to force out exhaust gases and the smoke shaft.

**The Lima pumped storage scheme**

The Lima scheme is located on the escarpment between the Necho Plateau and the Steelpoort River valley, near the town Roossenekal in the Limpopo Province. The distance between the upper and lower reservoir is approximately 2 km and the elevation difference is approximately 646 m. The scheme consists of an upper off-channel cut-to-fill CFRD reservoir, a lower earthfill reservoir with clay core, an underground power house complex with access tunnels and associated waterways that link the two reservoirs, four pump-turbines coupled directly with generator/motor, and ancillary works that include building works, roads, transmission lines and temporary and permanent infrastructure.

The main differences to the Ingula scheme are:

- Good quality igneous granitic and gabbroic rock is present as opposed to sedimentary rock at Ingula.
- An off-channel upper reservoir as opposed to an on-channel reservoir at Ingula.
- A lower reservoir located on a small tributary. Water for filling and losses is planned to be supplied by a pipeline from the proposed De Hoop Dam located approximately 20 km downstream on the Steelpoort River.
- Installed capacity of 1500 MW at a rated head 636 m and a synchronous speed of 500 rpm.
- The Distance between the two reservoirs is approximately 2 km, as opposed to 6 km for Ingula.
- Powerhouse has five floor levels as opposed to three. The loading bays and access to them is from the sides as opposed to a central loading bay. The additional excavation provides more space for equipment which had to be limited at Ingula due to poorer rock conditions.
- No requirement for a tailrace surge chamber due to the relative short distance from the powerhouse to the outfall.

**Conclusions**

The selection process resulted in two feasible schemes which comply with South Africa’s system requirements. The Ingula scheme has been selected to be developed first, as the larger operating volume allows more flexibility and provides better backup to the national electricity grid during emergency conditions. Due to the high growth in peak demand, other pumped storage schemes, after Ingula, may be required as well. While Lima is earmarked to be one of them, further studies are currently in progress in the search for a third scheme. In this process, previously identified schemes are being “dusted off” and re-assessed.

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