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# Leliefontein Pump-As-Turbine Station – Utilising Hydropower Potential Within the Drakenstein Muncipal Water Network: A Case Study


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## ABSTRACT

The Leliefontein Pump-As-Turbine (PAT) Station is deemed to be a first of its kind in South Africa. Originally intended as a booster station to supply water to Wellington during peak summer, Leliefontein has evolved into a practical, easily maintainable and exciting green energy solution which can be utilised by various municipalities.

As per its original intention, the booster pump station, along with the local reservoirs, would operate as a back-up water supply to Wellington when the Wemmershoek water treatment works supply is unavailable during planned and unplanned maintenance. This occurs for about two weeks per year, which meant the booster pump station's mechanical equipment would be severely underutilised, leading to premature equipment failure. To address this problem of underutilisation, the design engineers, together with the Drakenstein Municipality, identified Leliefontein's location within the municipality's bulk water network as a prime opportunity for a productive mini hydropower station. This led to the idea to convert the booster pump station to a Pump-As-Turbine station, an installation with the dual functionality of pumping water and generating electricity. While using pumps as turbines is not a new technology, Leliefontein uses the same set of pumps to pump water and generate electricity, which ensures that the PATs are active for most of the year, solving the problem of underutilisation. This dual functionality is accomplished by reversing flow through the pumps and controlling the speed of the PATs to generate electricity at the available flow rates. This is achieved through the innovative application of active front end variable speed drives to lower the speed of the PATs, actuated valves, a centralised control system, off-the-shelf pumps, and some creative pipe work.

The estimated annual generation for Leliefontein is 320MWh, depending on water demand and load-shedding, translating to 44 days of free pumping for Drakenstein Municipality. The power generated at Leliefontein is distributed into the municipality's electrical grid, offsetting the power consumed during pumping with the remaining balance of the generated power reducing the Municipality's electrical consumption bill. The municipality can utilise the savings, due to these reduced power purchase costs, to reinvest into the community through avenues such as service delivery.

Leliefontein is a collaboration between a municipality, design consultants and a contracting team spread through the Civil, Mechanical and Electrical engineering disciplines and serves as an example of how municipalities can use low cost, off-the-shelf equipment like centrifugal pumps and induction motors to generate clean power using potential energy in their existing infrastructure. The knowledge gained from Leliefontein also allows the adjustment of a PAT's characteristic curve to ensure it is able to match the available hydropower potential of a specific site.


## INTRODUCTION

Small-scale hydroelectric power is a field of growing interest in the South African Municipal community. With the drive for clean energy being at its peak in the country and projects including in-line turbines within water pipes and Pump-As-Turbine (PAT) installations gaining traction, particularly in the northern regions of South Africa, new and existing municipal networks are still an underutilised resource, rich in potential renewable energy [Van Vuuren et al. 2013]. For small-scale hydroelectric power to be feasible, low cost hydraulic and electrical

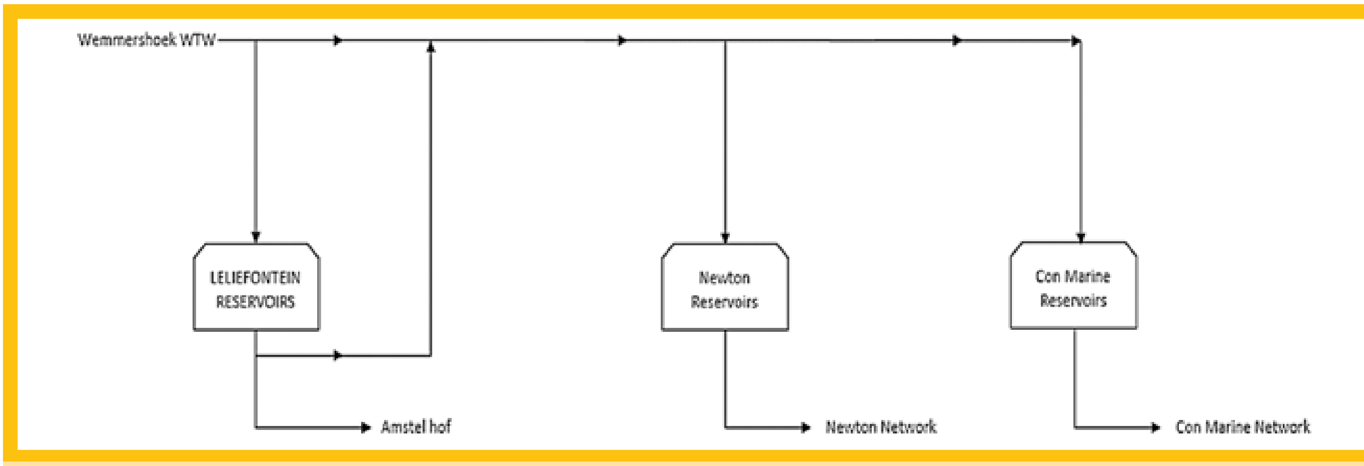


**FIGURE 1:** Existing Network Under Gravity Flow

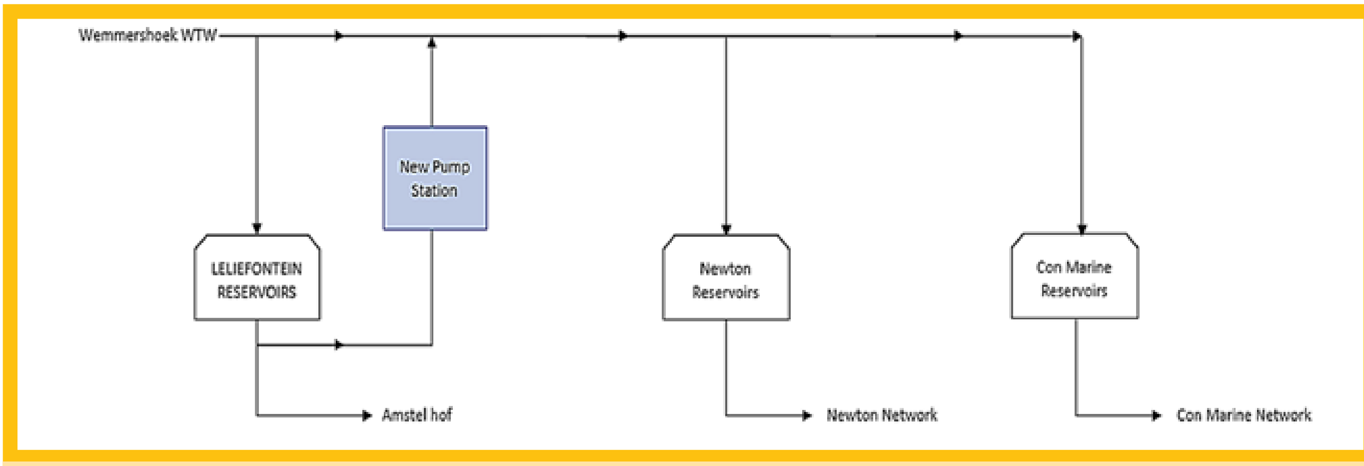


**FIGURE 2:** New Leliefontein Booster Pump Station Addition to Existing Gravity Network

equipment is required [Carravetta et al, 2013]. A limiting factor thus far for small-scale hydro has been the cost of turbines, where PATs would be a more successful solution [Agarwal, 2012]. This paper looks at a PAT station installed for the Drakenstein Municiplity in the Western Cape. This installation is considered a first in South Africa due to its unique challenges and solutions, which have resulted in a productive pumping and generation station. The purpose of the project and project conditions and criteria/requirements leading to a PAT solution being selected will be discussed.

## PURPOSE OF PROJECT

Wellington is home to a growing industrial and agricultural sector which is highly dependent on a reliable water supply. Wemmershoek Water Treatment Works (WTW) (owned and operated by the City of Cape Town) supplies water to the Leliefontein Bulk Reservoir Complex (LBRC) via a 19 km gravity pipeline and to Wellington's Con Marine and Newton zone reservoirs, via a further 11 km pipeline, at a maximum capacity of 19 Mℓ/d. Figure 1 shows a schematic representation of the system.

The supply capacity to Wellington is deemed sufficient to meet the summer peak demand of Wellington up until the year 2034. However, there are periods when the supply from Wemmershoek is interrupted, due to planned and or unplanned maintenance. These interruptions in water supply are expected to occur for a period of 1 – 2 weeks in the year. When this occurs, water from LBRC can gravitate towards Wellington at a maximum capacity of 11.2 Mℓ/d. This capacity is deemed sufficient to meet Wellington's lower winter demand for the foreseeable future, but

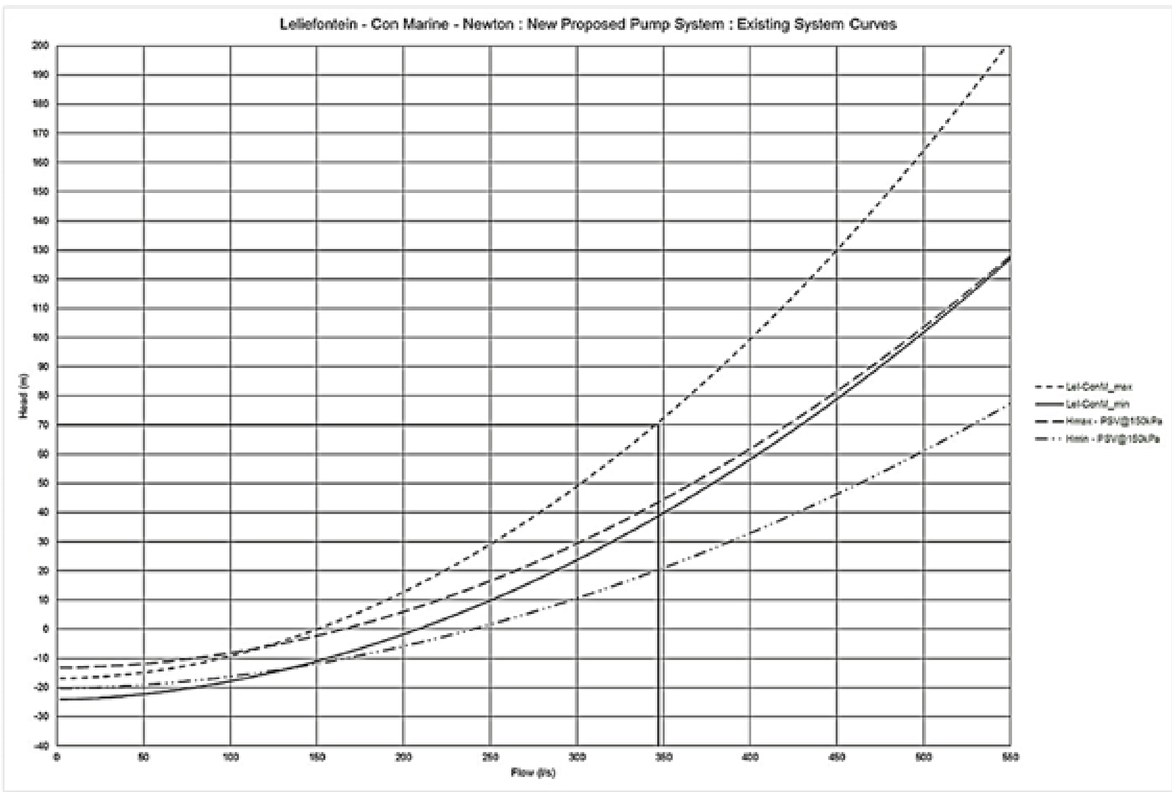


**FIGURE 3:** Leliefontein Pump Station System Curves - Initial System

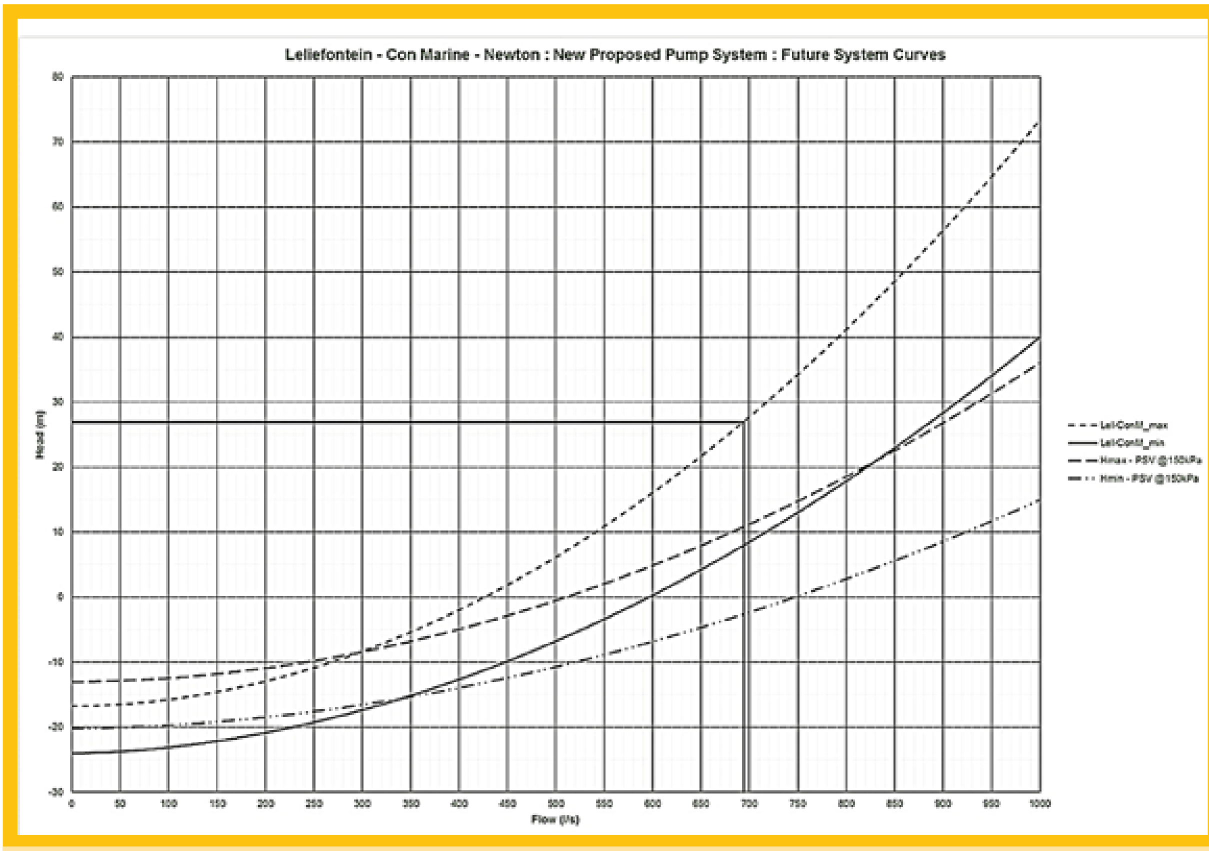


**FIGURE 4:** Leliefontein Pump Station System Curves - Future System

if this would occur during summer, when the demand is at it's highest, there is high probability that Wellington would suffer water shortages.

Drakenstein Municipality initiated a project to augment the supply of potable water to Wellington during the WTWs down periods during summer, to ensure a reliable supply is maintained to Wellington. A pump station was identified as the most suitable method to increase the conveyance capacity to 30 Mℓ/d, with the potential for a further increase to 60 Mℓ/d capacity possible by upgrading the pipeline from Leliefontein to Con Marine reservoir by adding a new DN 700 parallel gravity pipeline.

## IDENTIFYING THE SITE LOCATION

The evaluation of the optimal pump station location took cognisance of a range of factors, including security of the installation, the impact the operation of the pumps would have on users along the pipeline, as well as hydropower potential. Based on the investigations and results, the LBRC was identified as the most appropriate location within the network for the new Leliefontein pump station, as shown in Figure 2.

## PUMP SELECTION

The guaranteed duty point of the pump station for the initial capacity of 30 Mℓ/d was 347 ℓ/s at a differential head of 70 m, pumping into the 11 km DN500/450 Asbestos Cement (AC) pipeline towards the Con Marine and Newton reservoirs. The pump selection and pump control design had to consider the various operating scenarios under which this system should be able to operate, due to it delivering water to either Con Marine or Newton reservoirs, or both at the same time, depending on the level in the reservoirs. The system curves for the various scenarios for the initial system is depicted in Figure 3.

The pump selection for the initial duty took into consideration the final design duty of 694 ℓ/s for the capacity of 60 Mℓ/d, at a differential head of 27 m, pumping into the 11 km DN500/DN450 with a new DN700 pipe installed parallel to the existing pipeline. As with the initial system, the future system would also have different operational scenarios, the system curves of which are depicted in Figure 4.

The selection of the type and number of duty pumps was to ensure that the same pumps are used for the initial and future pump duty, removing the need to make changes to the pump station pipework or oversize the civil structure to accommodate future equipment. Due to the varying head requirements between the initial (70 m differential pressure) and future (27 m differential pressure), finding a fixed speed pump selection that will operate efficiently over the entire range of the system's flow-rates, was impossible. The only feasible way to prevent changing of pumps, suitable to operate under the initial conditions and under the future conditions once the pipeline system is upgraded, was to incorporate the use of variable speed drives (VSD) in the pump control system. This would allow the control system to adjust the pump's rotational speed and thus it's performance curve to meet the different system duties. The optimum pump selection to meet the criteria for the pumping operation of the station was to install two duty pumps for the initial duty point, with one standby, and to add another pump for the future duty point.

## UTILISING THE HYDROPOWER POTENTIAL AT LBRC TO SOLVE THE UNDER-UTILISATION OF THE LELIEFONTEIN PUMP STATION

With the booster pump station together with the LBRC expected to operate for two weeks in a year as a back-up water supply to Wellington when the Wemmershoek WTW and/or the supply pipeline are undergoing maintenance, the pumps installed at the Leliefontein pump station were at risk of being severely underutilised. This underutilisation increased the probability of premature failure of the mechanical equipment, putting Wellington's water supply at risk, should the pumps fail to run when required.

As part of the investigation into the location of the pump station, discussed earlier in this paper, it was identified that there is hydropower potential at the LBRC, due to the Wemmershoek supply pipeline operating under gravitational energy. To confirm the feasibility of utilising this hydropower, the quantum of the available hydropower potential at Leliefontein was calculated. It was found that at the average inflow rate to LBRC over a 30-year period, estimated at 31 Mℓ/d, the residual head within the Wemmershoek supply pipeline at LBRC was calculated to be 19 m. This equates to a total hydropower potential of 46.8 kW, at an assumed generator efficiency of 70%. It was evaluated whether it would be feasible to augment the available hydropower using fit-for-purpose turbines, such as Francis turbine or a PAT, which are both reaction water turbines. The reason reaction water turbines were considered was that these turbines can operate with a flooded draft tube, which means the turbine can be installed below the tail race water level, which would allow them to also be used as pumps. Due to the topography of the Leliefontein reservoir site, the pumps would have to be installed below ground to ensure sufficient suction head.

The major disadvantage of PATs versus turbines, according to [Williams, 1996], is that the characteristic curves in turbine modes are not supplied with the pump, which makes it harder to select the appropriate PAT for your application. Other differences between turbines and PATs are summarised in Table 1 below.

**TABLE 1: Differences between turbines and PAT [Teuteberg, 2010]**

| | Turbine | PAT |
|---|---|---|
| Advantages | Well-documented | Cost-efficient |
| | Best efficiency | Widely available in South Africa and abroad |
| | Variable guide vanes for varying flow | Simple design and easy maintenance |
| Disadvantages | Expensive | Difficult to find correct turbine operation curves |
| | Very few South African suppliers | Lower efficiency |
| | Complex design may require expert maintenance | No variable guide vanes for varying flow |
| | | Not as well-documented as turbines |

Budget quotes were obtained for a suitable Francis turbine and PAT to be used as a dedicated turbine for the LBRC site. The budget costs from different suppliers for a Francis turbine varied between R5 500 000 and R6 400 000, whereas for a PAT the budget costs ranged between R150 000 to R200 000. Although a Francis turbine is able to reach mechanical efficiencies in excess of 90%, whereas PAT efficiency is around 80%, due the low hydropower potential of the site, the gain in increased power generated is insufficient to reimburse the owner for the much higher capital cost of the Francis turbine. The conclusion was that the quantum of hydropower potential isn't significant enough to consider the installation of a dedicated turbine-installation at LBRC. However, the Drakenstein Municipality, together with the design engineers, considered that if it would be possible to use the proposed Leliefontein pump station equipment, to generate electricity using the hydropower potential at LBRC, i.e. use the same pumps to pump water and generate electricity, this would have a number of positive impacts on the project, such as:

- It would solve the problem of under-utilisation of the Leliefontein pump station,
- It would allow the Drakenstein Municipality to augment the available hydropower at LBRC at a reduced capital investment compared to a dedicated turbine installation,
- The power generated at the LBRC can be off-set against the power that the Drakenstein Municipality purchase from the national energy provider,
- It would reduce the carbon footprint of the pump station, when operating as a pump station, and
- It would not introduce complexities to the Municipality's maintenance operations as all equipment would be as per the pump station design, which they are familiar with.

## CONVERSION OF DESIGN FROM PUMP STATION TO PUMP-AS-TURBINE STATION

A multidisciplinary design team, comprising of civil, mechanical and electrical engineers, collaborated to design an installation never done before in South Africa. The LBRC receives approximately 73% of the total volume of water conveyed through the Wemmershoek pipeline, with the balance conveyed to the Wellington reservoirs. As the Leliefontein reservoirs are located closer to Wemmershoek Water Treatment Works, the flowrate into the Leliefontein reservoirs is controlled by means of two electric-actuated sleeve valves. The residual head available at the Leliefontein reservoirs is dissipated across the sleeve valves.

A PAT is essentially a centrifugal pump which can be used as a turbine. The most efficient way for a PAT to operate is by reversing the direction of water flow through the volute. In addition to reversing the direction of water flow, the rotational direction of the pump shaft is also reversed, thus a PAT's shaft rotates in the opposite direction as to that of a similar pump.

The Municipality gave approval to proceed with the PAT station design, with the condition of designing an efficient pump station rather than efficient generation station, since pumping is the primary purpose of the project. The pumps were therefore sized to be efficient pumps rather than efficient generators.

For an induction machine to generate power, the rotor needs to be rotating at speeds greater than the synchronous speed of the machine, which in this case is over 1 500 rpm for a 4-pole motor, at a frequency of 50 Hz. It was found that there is insufficient hydropower potential available at the LBRC to push the rotor of the induction machines of the selected pumps above synchronous speed. Figure 5, shows the selected Leliefontein pump's turbine curves, with flow-rate in liters per second plotted on the horizontal axis and differential pressure across the turbine in meters plotted on the vertical axis. The black line curving upwards with increasing flow-rate is the turbine generating curve. The black lines, curving slightly downwards with increasing flow-rate is the available residual head from the Wemmershoek system. For the selected PAT to be able to generate power, the two lines should intersect between the "Qmin" and "Qmax" marks on the turbine generating curve. It is clear that with the PAT's rotational speed at 1 520 rpm (turbine/generation speed), this will not occur. This was a significant stumbling block for the design team.

The project team, in consultation with the PAT suppliers, used their knowledge of pump affinity laws and applied it to the turbine curve of the selected PAT. Through reducing the rotational speed at which the turbine

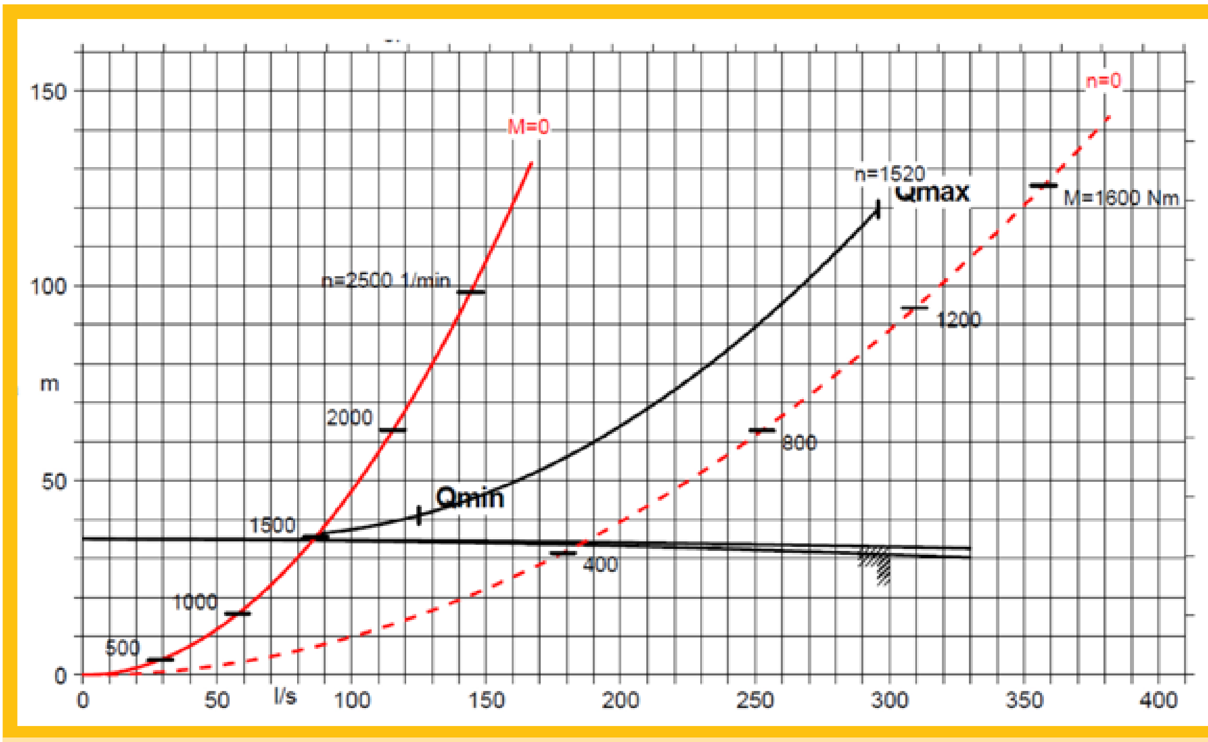


**FIGURE 5:** Leliefontein PAT turbine curves at 1520 rpm (Source: KSB South Africa)

should generate power, the properties of the turbine generating curve changes, as shown in Figure 6. By reducing the turbine's rotational speed from 1 520 to 920 rpm, which is just above the synchronous speed of a 6-pole induction machine at 50 Hz grid frequency, the turbine generating curve and the residual head curve intersects within the operational range of the turbine. Therefore, reducing the rotational speed of the PAT would allow the system to generate electrical power at the available residual pressure.

For a dedicated turbine-installation, i.e. having a dedicated turbine set and a dedicated pumping set, the adjustment of the turbine's characterstic curve, by changing it's rotational speed, would allow the engineer to ensure the turbine is operating at it's peak generating efficiency. To achieve this, the simplest method would be to use a 6-pole induction machine for the turbines which would need to rotate at 920 rpm to generate electricity. However, as the intention was to also use the PAT as a pump and a turbine, reducing the rotational speed in pump mode would have caused the selected pump's characteristic curve to also be adjusted. This would result in the pump not being able to meet the required conveyance capacity of 30 Mℓ/d and the installation not meeting the Municipality's condition of having an efficient pumping station. Thus, a solution had to be found to allow the PAT to operate at a rotational speed of 920 rpm (generation speed) when in turbine-mode and at 1 495 rpm (pumping speed) when in pump-mode. It should also be considered that the direction of rotation of the PAT is different between the Pump-As-Turbine- and pump-mode, thus this would require the phases of the inducation machines to be changed between the two modes. A possible solution to this problem would have been to fit two induction electrical motors to the centrifugal pump, with the one motor being a four pole motor, which would be used in pump mode and the other motor being a six pole motor, which would only be used in turbine mode. The 4-pole induction machines phases would be orientated for clockwise rotation and the phases for the 6-pole induction machine rotated for anticlockwise rotation.

Although attaching two different electrical drives to horizontal split-casing or horizontal multi-stage pumps is relatively easy, the selected pump for this application was of end-suction configuration. Attaching two different electrical induction drives to an end-suction pump, would have required significant alteration to one of the electrical motors. This would also have resulted in an increase in footprint of the pump station building to allow space for the additional electrical motor.

The solution for this problem was to change the single quadrant variable speed drives, required for pumping at varying flow and pump head conditions, to active front end variable speed drives (AFE VSDs). The AFE drives allowed for four quadrant operation, which meant they could change the speed of the PATs in pump and generation modes as well as allow discharge of electrical power into the municipal grid at the required power quality. It would also be possible to easily change the shaft rotation, depending on whether the unit is in turbine- or pump mode, through the AFE settings.

To allow the Leliefontein PAT station to operate as either a pump station or a power generation station, some modifications were also required to the pipeline configuration at the LBRC. As noted earlier, for a PAT to operate as efficiently as possible both the shaft rotational direction, as well as the flow direction, through the PAT, should be reversed.

In summary, the conversion of the pump station design to a PAT station required the following alterations:

- Addition of high-pressure turbine supply pipeline (DN630 HDPE) from the Wemmershoek-Leliefontein pipeline up to the pump delivery pipeline valve chamber.
- Addition of turbine return pipeline (DN630 HDPE) to the Leliefontein Reservoirs Inlet Valve Chamber.
- Converting the pumps to PATs, which required locking screws on the pump impellers to allow reverse rotation.
- Converting the single quadrant variable speed drives to active front-end drives to allow the conversion of the 30 Hz generated power to 50 Hz grid power and bi-directional flow of electricity.

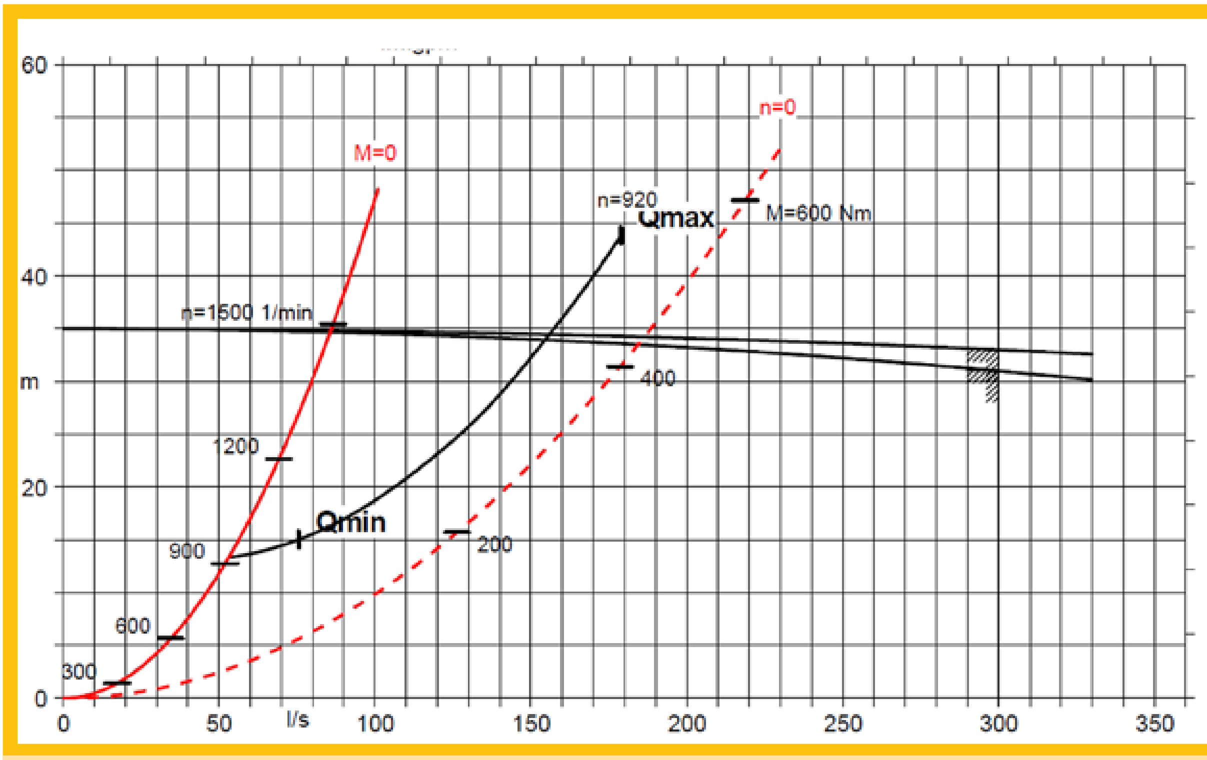


**FIGURE 6:** Leliefontein PAT turbine curves at 920 rpm (Source: KSB South Africa)

- Converting the non-return valves located on the pump discharge pipework to actuated ball valves, to allow flow in two directions through the PAT.
- Addition of power meter to measure the power generated and supplied to the grid and bi-directional electrical protection.

## PUMP-AS-TURBINE STATION PERFORMANCE

The PAT station has been in operation from June 2018 and has to date generated 271 236 MWh of renewable energy and consumed 53 577 MWh during pumping (Figure 8), it has thus generated more than five times the energy required for pumping over this period.

If the station is continuously active, the estimated power generated at Leliefontein would result in a saving of R198 000 in power purchase costs for the Municipality per annum and the estimated maximum monthly power generated (2018 to 2041) is 42 400 kWh (enough to power 63 households), with an estimated total power generation (2018 to 2041) of 9.9 GWh.

Due to the fact that the PAT station utilises the mechanical equipment almost continuously throughout the year, the risk of premature failure of the mechanical components due to under-utilisation is significantly reduced. Using a SCADA and SCADA reporting software and dashboard, the Drakenstein Municipality is able to monitor the status, performance and efficiency of the installation, making the municipality more effective in scheduling preventative maintenance services.

## FINANCIAL SUSTAINABILTY OVER THE LIFE CYCLE OF THE PROJECT

The conversion of the Leliefontein pump station into the Leliefontein PAT station increased the project's capital cost by about 10%, however through the hydropower generated from this installation, off-set against

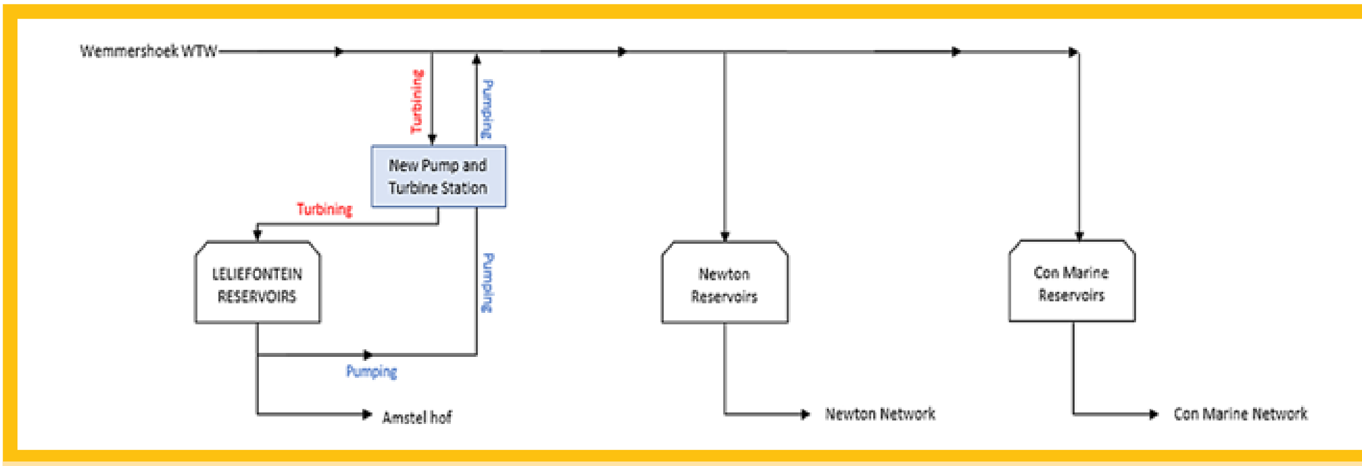


**FIGURE 7:** New Leliefontein Pump-As-Turbine Station addition to existing gravity network



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**FIGURE 8:** Bi-directional power meter at Leliefontein PAT

**FIGURE 9:** Completed Leliefontein PAT station in foreground, with 36 Mℓ and 100 Mℓ reservoirs in background

**FIGURE 10:** Leliefontein PAT Motor Control Centre

the municipality's electricity bill from the national energy provider, the pay-back period for this conversion cost is estimated to be less than 10 years.

## ENVIRONMENTAL AND SOCIAL IMPACT

The PAT station generates green hydro-electric power, which offsets the Municipality's use of electricity generated from coal-fired power stations. The generated power is estimated to result in a reduction in carbon emissions of 346 tons of $CO_2$ over a 23-year period (2018 to 2041).

By generating a portion of its own power through the Leliefontein PAT station, the Drakenstein Municipality's power purchase expenditure has reduced, making additional funding available for other infrastructure projects to the benefit of the Municipality's residents and local job creation.

An interesting fact is that the PAT station would only need to generate at peak generating capacity of 57 kW for six hours to offset the energy consumption of the pump station operating as a pump station for one hour, when pumping at 30 Mℓ/d capacity (300 kW energy consumed). With the station only expected to operate as a pumping station for about two weeks in a year, it will generate more power operating as a turbine/generation station than it will consume during the two weeks of pumping (refer to Figure 8), thus making this pump station carbon negative.

Furthermore, most of the equipment used was manufactured locally in the Western Cape or in South Africa, with minimal imported equipment required, also reducing the carbon footprint. Stainless steel was used where metal pipes were required. In using stainless steel pipes, the necessity to protect the pipes against corrosion, through inorganic epoxy paint systems was negated. The pump station structure was constructed from reinforced concrete, with infill face brick, which reduces the amount of maintenance required to maintain the structure.

## CONCLUSION

The Leliefontein Pump-As-Turbine station is a true marriage between the civil, mechanical and electrical engineering disciplines, and serves as an example of how municipalities can use low cost, off-the-shelf equipment like centrifugal pumps and induction motors to generate clean power using potential energy in their existing infrastructure.

The successful PAT conversion is achieved through the innovative use of active front-end variable speed drives to lower the speed of the PATs to generate electricity at the available hydropower potential, a series of actuated valves and some creative pipework. The power generated at the station is fed back into the municipal grid, offsetting the power consumed during pumping. The PAT conversion cost an additional 10% more of the total contract value. The estimated average annual generation is 320 MWh, which is dependent on the water demand of the town of Paarl, which translates to 44 days of free pumping.

The power generated at Leliefontein can be offset against the power that the Drakenstein Municipality would have had to purchase from the electricity public utility. Not only does it reduce the Municipality's environmental impact through the consumption of renewable energy, but it also has a social impact because the client can invest the money saved by utilising the renewable free energy, back into the community through the delivery of services.

Through the innovative use of a simple off the shelf pump, the Municipality's supply capacity problem to Wellington was solved, clean electricity was generated, the Municipality's electrical bill was reduced and the mechanical equipment was kept active throughout the year without adding any complexity to the Municipality's maintenance procedures.

This project has been awarded the 2018 SAICE National Water Division Project Award and CESA AON 2019 Engineering Excellence Award for projects less than R50 million.

Although the Leliefontein PAT project is a unique solution to a client's problem, what was learned through this project could be applied to other projects, where a client wants to augment hydropower potential.

**FIGURE 11:** Leliefontein Pump-As-Turbines installed, with space for future unit in background

Some of the key points that would positively influence this technology being applied elsewhere are:

- Utilising PAT technology is feasible to augment sites within a utility owner's water network, even if the site's hydropower potential is deemed too low for dedicated turbine installations.
- As PATs are able to use mass-produced pump designs, the utility owner's maintenance staff will be able to succesfully maintain PATs.
- Adjusting the speed of a PAT allows that one selected PAT-model, could be used at different sites with different hydropower potential. This would reduce the maintenance complexity of the system. As the speed reduction would be fixed for each hydropower site within the municipality's network, this speed adjustment can be achieved through a gearbox or belt and pulley system.

## RECOMMENDATIONS

South African municipalities jointly hold a substantial amount of hydropower potential in their existing infrastructure. With the country facing power shortages through supply from conventional coal fired power stations, renewable energy is an environmentally responsible answer to increase power into the national grid or to use in standalone/islanded infrastructures, reducing pressure on the grid. Municipalities should actively evaluate their networks to identify areas to exploit hydropower potential in their existing infrastructures or new projects. Utilising familiar equipment, such as PATs and induction motors, would allow the municipalities to maintain this equipment, using existing staff and tools. The financial savings that would be made from generated electricity would further the national municipal agenda of reliable service delivery to their communities and the environmental benefit of producing green energy would reduce impact of our energy demands on the earth.

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