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ANALYSIS OF MAINTENANCE METHODS AND DEVELOPING STRATEGIES FOR OPTIMAL MAINTENANCE OF WELLHEAD POWER PLANTS AT OLKARIA GEOTHERMAL FIELD IN KENYA

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ABSTRACT

A wellhead power plant (WHP) is a new paradigm shift in geothermal utilisation that has been extensively exploited in Olkaria geothermal field in Kenya for the past seven years by KenGen. This study examines aspects impacting the availability factors of the WHPs and benchmarks with approaches in select conventional geothermal power plants in Kenya and Iceland, with regards to maintenance management. Critical resource requirements to support the optimal maintenance of current and future WHP development in Olkaria are examined in the wake of the unique challenges faced, and the unique functional configuration of the existing WHP plants. The study explores maintenance management optimisation options and recommends strategies for enhanced plant uptime by optimising planned maintenance, condition based maintenance, response to corrective maintenance and pilots optimisation using Single Minute Exchange of Die (SMED).

1. INTRODUCTION

A wellhead geothermal power plant (WHP) is defined as a modular miniature geothermal power plant for electricity generation which is built and located within the dimensions of a well pad. In the Olkaria geothermal field the units have an installed electricity generation capacity of at least 2.4 MW each and are optimised or standardised to generate up to the limit of the well(s) located in the well pad. Often they are characterised by relatively short steam gathering systems that are networked within the well pad, and are connected to one or more wells in the vicinity. The layout is comprised of the following components:

- Steam gathering system components that include the wellhead assembly, the working valve, two-phase delivery piping, moisture separator, brine disposal system, pressure control system, brine level control system, a silencer or rock muffler and saturated steam delivery piping to the turbine.
- A small single flash, backpressure or binary turbine generator unit, and its ancillaries.
- A compact cold end, comprising of surface, direct contact or air-cooled condensers, hot well pump, cooling towers, cooling water circulation pump, a collector sump and associated control systems.

- Non-condensable gas extraction system that can be a pure ejector, vacuum pump or hybrid system.
- A compact switchgear and control room in a container or compact permanent structure.
- A standard centralised or compact switchyard on a portable skid and transmission line.

Maintenance is the work or act of keeping something in proper condition or upkeep. In a geothermal utilisation scenario, it implies actions taken to prevent a device or component from failing, maintain normalcy, and the repair of normal equipment due to degradation experienced with use in order to keep it in proper working order. Conventional geothermal power plants are typically associated with a life expectancy of 20 to 25 years, with predetermined power purchase agreements lasting for a similar time. Initially, when KenGen delved into the wellheads concept, the main drive was early generation by building modular units on a well pad soon after well tests, which can be operated while a sufficient steam reserve for a conventional power plant is developed. A number of operational and maintenance problems not frequently observed in conventional power plants have been experienced at the geothermal wellhead power plants with regards to availability. In this study, the maintenance practices in the KenGen WHPs are analysed, including the approaches used during the pilot phase, defects liability period phase and the current methods being employed. An analysis of the current gaps in infrastructure is also discussed in subsequent chapters with recommendations for potential ways of optimising equipment uptime and resource utilisation. The study further outlines a comparative study of how Icelandic power plants (Hellisheidi, Nesjavellir) have developed methods to address the maintenance challenges experienced, with a view of benchmarking on potential strategies and optimisation approaches. Optimisation strategies are derived based on benchmarking results in Iceland, best practice guides from reputable reliability engineering studies and the application of the scientific thinking approach coined by Shigeo Shingo in his industrial engineering approaches, documented in the books *Key Strategies for Plant Improvement* and *Single Minute Exchange of Die (SMED).*

1.1 Facility location

The KenGen WHPs are located within the greater Olkaria and Eburru fields in Kenya, comprising a total of 16 power plants, out of which 15 are located in the Olkaria field and 1 is located in the Eburru field. The fields consist of a number of concessions under mixed public and private ownership. KenGen has been responsible for about 79% of the development of this field dating back to the 1950s, and currently has an installed capacity of 533.8 MW in electricity production in this field. The KenGen power plants are: Olkaria I (45 MW), Olkaria II (105 MW), Olkaria IAU (150 MW), Olkaria IV (150 MW), and Olkaria wellhead power plants (83.5 MW). Ormat (an independent power producer) owns the Olkaria III concessional area and has developed about 140 MW of binary power plants in phases between 2000 and 2016 (Ormat, 2017). In addition, Oserian Development Company (a cut flower developer) entered into a steam purchase agreement with KenGen and developed a total of 3.4 MW of binary and backpressure types of geothermal power plants for the primary purpose of powering its greenhouse farms and associated energy savings. In total, the greater Olkaria and Eburru geothermal fields have an installed capacity of about 676.9 MW and the figure will rise further when the Olkaria V power plant project (158 MW) comes online in the near future. The Eburru wellhead plant is located approximately 60 km to the northwest of Olkaria. Geothermal exploration activities in the Eburru field began in 1972 leading to the drilling of six exploratory wells between 1989 and 1991. In 2012, a pilot 2.4 MW single flash WHP plant was installed, connected to the single productive well at Eburru geothermal field.

Figure 1 is a general map indicating the geothermal development activities within the greater Olkaria geothermal field.

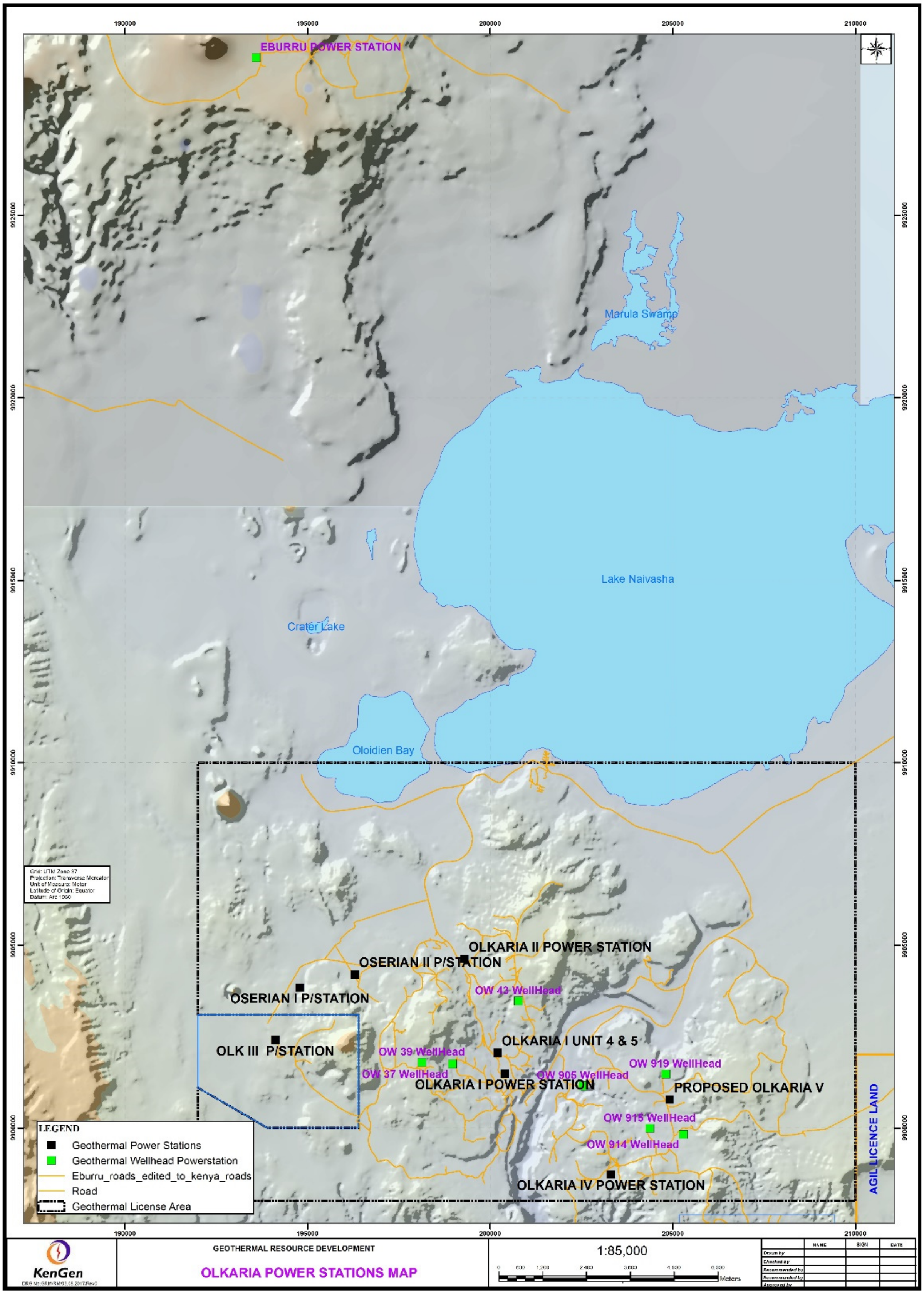

FIGURE 1: Map showing spatial location of wellhead plants in the greater Olkaria and Eburru geothermal fields

1.2 Study objectives

This study aims to review the maintenance practices in the existing WHPs and make a comparison with select conventional geothermal power plants in Kenya and Iceland for benchmarking, with an aim to develop a strategy to optimize the availability and load factors. This proposed strategy will be based on established key resource requirements for the optimal execution of plant maintenance through comparative studies and benchmarks. This is expected to go a long way to ensuring the cost-effectiveness, attainment of target returns on invested capital, equipment uptime, reliability, safety, and energy efficiency.

1.3 Problem statement

Having operated geothermal wellheads units for more than five years, rare failures that are generally infrequent for geothermal equipment have been observed. The general trend of availability factors, capacity utilization and load factors exhibited at the Olkaria WHPs are marginally lower in comparison to the conventional geothermal power plants under study. This study aims to establish a customised approach to ensure that these modular units operate reliably and deliver availabilities comparable to conventional power plants. In 2015, KenGen engaged Mannvit to undertake an optimization study of the wellhead plants with the purpose of analysing the technical design, operation, maintenance and resource utilization (KenGen, 2016). The study revealed that the overall availability of the wellheads was rather low compared to the expected availability factors for geothermal power plants of at least 94%. In addition, the capacity factor was also variant due to a decline in steam output in a number of units as illustrated in Figure 2.

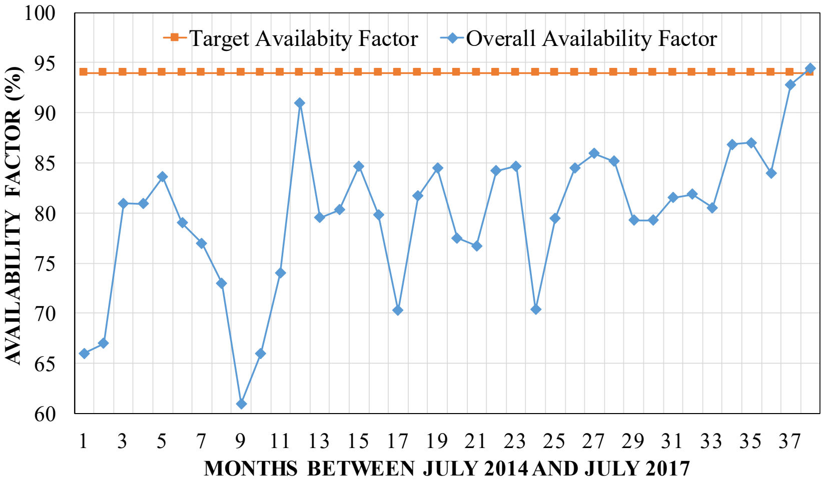

FIGURE 2: Overall availability factor of the Olkaria WHPs over a period of 38 months

2. BACKGROUND OF WELLHEAD TECHNOLOGY DEVELOPMENT AND LITERATURE REVIEW

2.1 Background study

Horizon I of KenGen's Good to Great (G2G) transformation strategy spanning more than a decade, entailed opening up new influences requiring new thinking in the wake of fundamental changes in the company. These included market dynamics in the external environment, such as the listing of 30% of shares in the Nairobi Stock & Securities Exchange, reforms in the energy sector affecting the electricity regulatory environment, significant demand growth from forecasts and increasing regionalisation of the electric power market in Eastern Africa (KenGen, 2008). KenGen's electricity generation mix is composed of hydro (819.9 MW), geothermal (533.5 MW), thermal (253.5 MW) and wind (25.5 MW). Although hydro still commands the largest share in installed capacity, it has often failed to meet the base load demand owing to its heavy reliance on weather conditions. For instance, drought conditions in 2006 exacerbated the problem of low reserve margins in the country by reducing the production capability of the hydroelectric plants, hence putting KenGen in the spotlight on the high risk of over-reliance on hydro-electric power plants to secure power supply to the country. This, coupled with a significant energy demand growth in Kenya, made the company embrace a strong geothermal development strategy that entailed heavy investment in drilling of a significant number of production wells in Olkaria that culminated in the commissioning of a 280 MW project in 2014, and a focus on cheaper early generation that gave birth to the wellheads technology. KenGen has harnessed geothermal energy for over thirty years in conventional plants in which motive steam from several wells is gathered to run a geothermal plant. In this approach, the wells are drilled and preserved awaiting connection to a plant, however the inherent deficiency of this process was identified as the long period taken to construct the plants. It was further observed that whilst KenGen repaid invested capital, no returns were realized from the wells yet and this tended to infringe on a sustainable bottom line. The wellheads concept was considered in which modular containerized plants were to be designed, customized and built on a well pad for optimized well potential. The expectation was early generation of electricity and hence early returns on investment, as well as portability and ease of relocation. KenGen therefore embarked on the execution of a wellhead plant under a research and development program culminating in the successful implementation of two 5.5 MW and 2.4 MW plants in 2012 within the Olkaria and Eburru fields, respectively. This marked a paradigm transferral in the geothermal generation mix. Figure 3 illustrates a typical KenGen WHP within Olkaria geothermal field. The arrangement comprises 2 x 6.4 MW plants and 3 x 5 MW plants that were installed and commissioned in phases between December 2013 and December 2014 at the OW 914 well pad. There are five WHP plants with four connected production wells taking the total installed capacity on this one well pad to 27.8 MW.

FIGURE 3: 27.8 MW WHP located at OW 914 well pad in Olkaria, Kenya (courtesy of Lýdur Skúlason, 2017)

Due to the successful implementation of these initial plants, a second project development phase of 14 plants was undertaken in phases between 2013 and 2016 with an additional cumulative installed capacity of 75.6 MW, taking the total capacity to 83.5 MW. It became clear that wellheads play an appreciable role in the revenue generation and sustainability of KenGen's bottom line, and so in 2015, the company contracted Mannvit (a reputable global player in geothermal consultancy) to assess the status and recommend potential optimization options with the view of ensuring the optimized utilization of proven steam reserves available, production response and potential technological options for future WHPs. In 2016, KenGen developed an implementation strategy for current and future WHPs which recommended that the existing WHPs be considered as permanent modular plants in order to maximize the return on invested capital. To a large extent, production well capacity and existing infrastructure were used to optimize the generation and capital requirements. This will be scaled up in phases in subsequent years, meaning the capacity in future WHPs will certainly increase.

2.2 Classical maintenance methods and management systems

Maintenance methods can be defined as documented information entailing maintenance planning, scheduling, execution feedback and follow up actions. Classical industrial engineering maintenance methods include preventive maintenance (PM), condition based maintenance (CBM) and corrective maintenance or run to failure without scheduling. A maintenance management system is integrated documented information regarding procedures and methodologies for assessing and assigning maintenance tasks into maintenance methods (Bore, 2008). A number of management methods exist in industrial engineering applications that include reliability centred maintenance (RCM), Single Minute Exchange of Die (SMED), Lean Six Sigma, Total Quality Management (TQM), Total Production Maintenance (TPM), ISO 9001 quality management system and Good to Great (G2G).

2.2.1 Preventive maintenance (PM)

A preventive maintenance strategy is the most common and entails taking assets offline periodically for inspection at predetermined intervals for repairs if necessary (Deilir, 2017). Preventive maintenance is any planned activity that is aimed at improving the overall equipment reliability and availability. Normally, original equipment manufacturers recommend the ideal interval for preventive maintenance scheduling, based on equipment performance in the field and burn-in tests of models. Its popularity can be pegged on the fact that it is easy to execute, but can be costly in the long run since most of these inspections yield ineffective findings (Deilir, 2017). Preventive maintenance can also be optimised using a scientific thinking mechanism such as Single Minute Exchange of Die (SMED).

2.2.2 Condition based maintenance (CBM)

This approach can also be referred to as predictive maintenance which is a condition based approach to asset management that typically entails the use of integrated predictive measurement and monitoring tools and a computerised maintenance management to plan for service just before failure. It can also be as simple as visual inspections, a walk about inspection on asset condition and automated work order generation. The advantage of effective condition based maintenance is the potential for cost saving by minimising unnecessary stops, reduced manpower costs associated with maintenance, maximising the use of items before replacement and a focus on equipment performance.

2.2.3 Reliability centered maintenance (RCM)

Reliability centered maintenance is the apex of maintenance management that is built on the principle that equipment failure is not linear, but an in-depth process that seeks to analyse all possible contributions to failures with a view of establishing a customised strategy to each component. The general consensus is that RCM is a too sophisticated management philosophy to be practical for use in any application. It is therefore reserved for an elite class of organisations that have demonstrated maturity in classical methods such as preventive maintenance and predictive maintenance (Deilir, 2017).

2.3 Scientific thinking approaches and Single-Minute Exchange of Die (SMED)

Single-Minute Exchange of Die (SMED) or quick changeover in under 10 minutes is a scientific thinking mechanism for improvement that has proven to be revolutionary in industrial engineering since the late 1960s when one of the greatest contributors to this technique, Shigeo Shingo, coined and applied it effectively in improving leading motor vehicle manufacturers such as Toyota Motors and Ford Motor company's Van Dyke plant (Shigeo, 1987). This method proved so revolutionary that by applying it to the Toyota Motors set up, it cut setup time on a 1000-ton press, for example, from four hours to three minutes and it is believed to be a key turning point and contributor to Toyota Motors market dominance on the global scale. SMED is more than merely improving techniques but it entails a basic conceptual approach to methods. Shigeo Shingo undertook initial improvement surveys at the leading geothermal power plant equipment manufacturer Mitsubishi Hitachi Power Systems (formerly Mitsubishi Heavy Industries) between 1956 and 1958 by shortening the hull construction time to two months which was a world record then. In SMED, changeovers are made up of steps that are called elements. The elements are classified into two broad categories: internal elements which are elements that must be completed while the equipment is stopped, and external elements which are elements that can be completed while the equipment is running. The SMED process focusses on making as many elements as possible external, and simplifying and streamlining all elements as illustrated in Figure 4 (LeanProduction, 2017).

3. MAINTENANCE REQUIREMENTS IN A WELLHEAD POWER PLANT

3.1 Configurations in a wellhead power plant (C-64 and C-50 setups)

It's important to note a key distinguishing feature in which a WHP is unlike conventional power plants: They are not housed in a permanent civil structure. The original concept entailed ensuring that all major components fit into standard 40 feet containers for purposes of ensuring compactness and portability. All civil foundations are made of pre-cast concrete piles that can easily be transferred and reused at new locations with almost no footprint. The foundation for major components such as the turbine and generator are made in such a manner that the steel reinforcement rods can be accessed at the periphery and cut to enable the removal of the top portion block, and the rest can be buried leaving no visible footprint. In summary, the design of the civil works is such that about 70% can be recovered and reused. The turbine is housed in a simple steel structure with a canopy shed of iron sheets and is thus more or less exposed to the vagaries of nature or prevailing outdoor conditions.

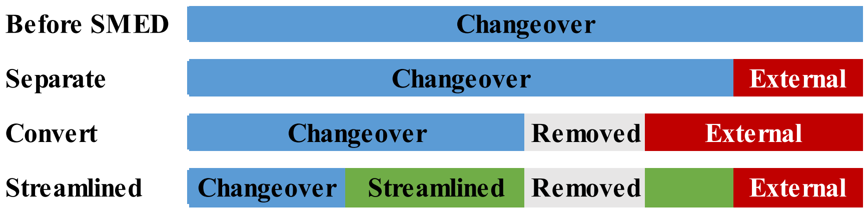

FIGURE 4: A representation of SMED system phases of implementation. Courtesy of Lean production, 2017.

3.1.1 A functional description of the C-64 configuration of a wellhead plant

The sequence of the C-64 WHP in Olkaria is a modified version of the pilot WHP as shown in Figure 5. It comprises the following major subsystems:

- Steam system (hot end);
- Condensing system (cold end);
- Turbine generator sets;
- Electrical and control system; and
- Switchyard and power evacuation system.

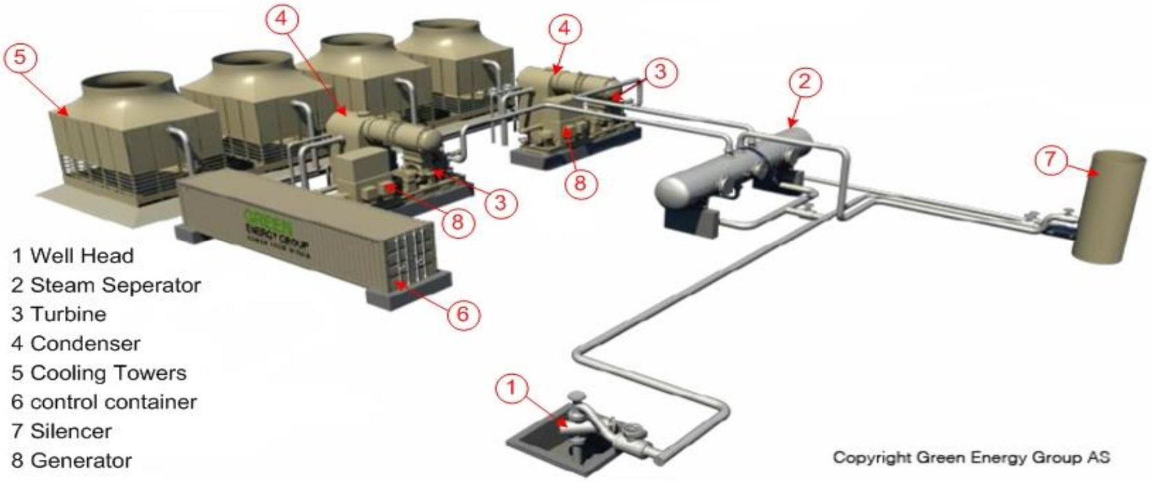

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FIGURE 5: A 3D illustration of major components in a typical C-64 WHP erected in Olkaria, Kenya

A C-64 WHP consists of two identical turbine and generator units of 3.2 MW each (normal continuous rating) that operate on one common steam system and two separate condensing systems as illustrated in Figure 5. The units share a well head, two phase piping, a moisture separator, a brine level control and disposal system, a pressure control system, a silencer or venting system and a switchyard system. This set up has been installed at the OW37, OW43 and OW914 well pads comprising ten WHP units with a combined installed capacity of 31.1 MW.

The sequence of key C-64 WHP processes is as follows: Two-phase steam is discharged from the well (1) and channelled to a horizontal type steam moisture separator, equipped with demister elements to separate traces of liquid or brine droplets that can be detrimental to the turbine (3). These process elements up to the turbine inlet are termed *the steam system or hot-end*. The steam is subsequently expanded through the turbine (3) resulting in the mechanical propulsion of the turbine and generator rotors leading to the generation of electricity at 11 kV. In the condenser (4) the steam is mixed with cooling water to initiate the desired back pressure vacuum through the shrinkage of a partial volume of exhaust steam. The non-condensable gases in the mixed exhaust are cooled further in the condenser (4) and extracted with a two-stage steam ejection system. The condensed steam/cooling water mixture is pumped to the cooling towers (5) where it is cooled further to about 21°C and reused as coolant for the lubrication oil, condenser gas coolers and heated generator air. This process from the turbine exhaust end to the cooling towers is termed the *the condensing system or cold end.* The Olkaria C-64 WHP turbines are comprised of multistage single cylinder straight condensing impulse reaction turbines of *Man India* make (formerly *MaxWatt Turbines*).

There are eight C-64 units rated at 3.2 MW with a combined installed capacity of 25.6 MW and a further two C-64 units rated at 2.75 MW at the pilot plant with a combined installed capacity of 5.5 MW. A steam turbine is a heat engine which enables the heat energy of steam to be transformed into kinetic energy or useful work by serving as a prime mover for the coupled generator unit. The WHP turbines use a large fraction of the heat energy rendered available through the expansion of the steam and translate it into mechanical work, thus propelling the generator. The turbine depends on the dynamic action of the steam through nozzles fitted on diaphragms, which creates a drop in pressure, due to which a portion of heat energy is converted into mechanical kinetic energy and the steam velocity is increased. This high-velocity steam jet enters the moving blades on the rotor and causes them to change the direction of motion that gives rise to momentum, and thus resulting in an impulse force (useful rotary work). These turbines expand steam in a series of up to seven steps (pressure compounding) as the steam flows axially. The last three blading arrangements are of a reaction type that is typically designed to extract energy from expanded and relatively wet steam. The C-64 WHPs are high-speed turbines with the typical operating speed of 6804 rpm for maximum efficiency.

The Olkaria WHPs can be termed as semi-automatic since they require manual start-up at the cold and hot ends. The shutdown, however, is automatic through a stop command in the electro-pneumatic governing system or emanating from pre-programmed trip parameters of functions. The plant is controlled and monitored via Process Logic Controller (PLC) systems with a human-machine interface through a Supervisory Control and Data Acquisition (SCADA) screen located in the electrical container (6). The SCADA/PLC systems monitor the plant condition, proved data logging, plant process controls, reactions, and alarms history when measurements deviate from set-points. The electrical container contains switchgear for all plant components, including an instrument air compressor and fire suppression and HVAC systems. The Main Control & Supervision System located in the Electrical Control Unit (ECU) supervises and controls all major parts of the plant. The control system is wired to temperature, pressure and level transmitters as well as signalling contacts, and sends operating signals to valves, motors, switches, etc. in the process. Important signals that are used to protect the turbine and are operative even if the process computer fails, are directly connected (hardwired) to the turbine control system and will shut down the steam supply to the turbine immediately. This includes high level/pressure trip signals from the steam separator and condenser and trip signals from the vibration monitoring system.

The Olkaria WHPs generate at 11 kV that is stepped up to 33 kV (OW43 and Eburru clusters), 132 kV (OW37 and OW39 clusters) or 220 kV (OW905, OW914, OW915 and OW919 clusters) depending on the high tension transmission system they are connected to. Initially, the WHPs were connected to a 33 kV evacuation system because of portability and low-cost considerations. Since they have been stable and reliable, they have been systematically shifted to more stable conventional 132 kV and 220 kV network clusters.

A geothermal production well yields a mixture of steam and liquid (brine) transported in a two phase flow to the horizontal type separator which separates the steam in three steps: Gravitational, droplet separation and mist separation. This aims to provide dry steam containing a maximum of 0.01% of brine mist droplets carry-over to the turbine inlet. The wellhead pressure-flow relationship follows a characteristic curve that is unique to the connected well but largely shows increased flow with decreasing well head pressure. The well opening is adjusted through a manual working valve to provide enough steam for the plant at a rated pressure which is restricted by an orifice plate. Any surplus steam is kept at a minimum and is dumped through the silencer to the atmosphere.

The brine level control system maintains the level in the separator, measuring discharges to the silencer. The steam pressure control system maintains the steam pressure close to a given set point, by routing the excess steam to the silencer. If the steam pressure rises above the set point, the controller increases the opening of the steam pressure control valve, routing more steam to the silencer and the opposite applies when steam pressure decreases. The steam controller is configured in such a way that in case of a sudden pressure increase due to, for instance, a partial load throw-off, the system reacts fast enough to limit the pressure rise. The system is also equipped with a secondary safety system in case the pressure continues rising, in which case the rupture disc located in the two-phase pipeline between the wellhead and separator will operate as a final safety measure.

Steam condensate pumped from the condenser is used to supply make-up water requirements to compensate for evaporative losses in the cooling tower, and to the discreet cooling tower modules. The non-condensable gases accompanying the steam are extracted from the condensate via ejectors driven by motive steam from the separator. The can pumps discharge a mixture of condensate and cooling water from the condenser to the cooling towers, maintaining the condenser level at the set point. The level in the condenser is measured by a level transmitter attached to the condenser unit. The pumps are rated at more than 100% capacity and run exclusively for each condenser to full power generation. The cooling tower fans are manually operated with on/off switches with mechanical vibration switches that cut off power supply to the motors in case excessive mechanical vibrations are picked up from the cooling tower structure. The plant can be run at partial load with a cell of the cooling tower not being in operation depending on ambient temperature and relative humidity.

3.1.2 A functional description of the C-50 configuration of a wellhead plant in Olkaria

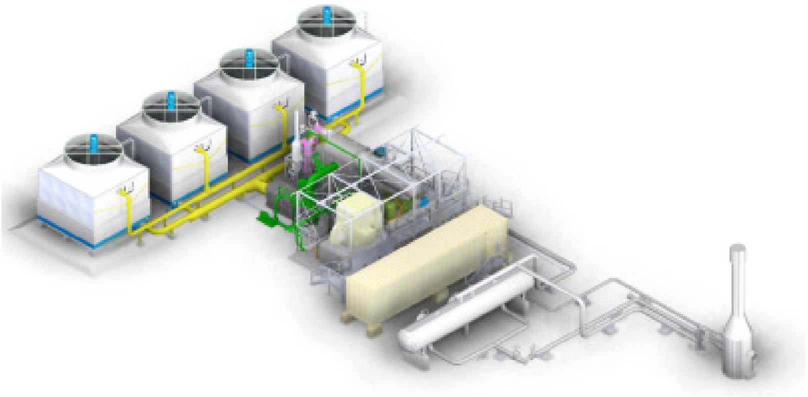


FIGURE 6: Major components in a typical C-50 WHP erected in Olkaria Kenya

The C-50 configuration WHP developed at Olkaria has similar functional characteristics as the C-64 units described in Section 3.1.1. The key distinction is that the C-50 configurations have a larger, single 5 MW turbine-generator unit with complete hot and cold end systems just like a conventional power plant as illustrated in Figure 6. A number of improvements were incorporated in the later designs of the C-50 units that include: An automatic gland steam control system, dual steam admission and a dual governor control valve system that replicates typical setups for conventional geothermal power plants. There are ten C-50 units with a normal continuous rating of 5.0 MW with a combined installed capacity of 50.0 MW in Olkaria geothermal field.

3.2 Evaluation of maintenance requirements of a wellhead power plant

The maintenance requirements for a WHP are more or less derived from typical set ups for conventional geothermal power plants, depending on the maintenance management models and approaches employed and problems facing the installations. The failure mode and effects analysis indicate that in addition to common problems in geothermal applications, WHPs experience unique kinds of failures that are uncommon in the typical geothermal equipment product cycle as outlined in subsequent sections of this report. The requirements are attributable to the following considerations:

- Standard typical set ups that are applicable to geothermal power plants;
- Unique requirements depending on the design configuration, technology and physical location in the environment they operate in currently;
- Requirements emanating from failure patterns, Failure Mode Effects Analysis (FMEA) and lessons learnt;
- Specified requirements that arise from a training need assessment, operational, take over-preparedness and technical gaps that need to be addressed;
- Equipment and tooling requirements that will augment the proposed optimal maintenance management strategies; and
- Results from benchmarking studies in select geothermal power plants.

3.3 Equipment, tooling and software requirements

3.3.1 Available infrastructure for leveraging

The conventional approach to the operation and maintenance of geothermal power plants entails the establishment of a workshop for machine tools, instrumentation and electrical plant equipment in the precincts of the power plant. The development of Olkaria I, Olkaria II, and Olkaria I AU and Olkaria IV power plants followed a similar pattern whereby customised machine tool workshops were built and installed in close vicinity of the power plants. In addition, a rig workshop, steam field, infrastructure and motor vehicle workshops are attached to the various functions in Olkaria to aid in specialised repair of infrastructure associated with the KenGen geothermal development aspects in Olkaria. Table 1 summarises the available pooled workshops and infrastructure that support the geothermal development aspects in Olkaria.

TABLE 1: A list of the existing workshop infrastructure in KenGen and maintenance service providers in Kenya

Workshop	Components	Strategic function
Existing KenGen facilities		
Olkaria I, Olkaria II and Olkaria I AU	•Centre lathes •End and face milling machines •Hydraulic presses •Power saws •Work benches •Radial drilling machines •Lifting equipment i.e. tackles, chain blocks, slings etc. sufficient for plant mechanical components	Facilitate the cost-effective maintenance of the plants such as correction of defects, manufacture of components, specialized assembly/disassembly of plant components and supporting major overhauls.

TABLE 1 cont'd: A list of the existing workshop infrastructure in KenGen and maintenance service providers in Kenya

Workshop	Components	Strategic function
	•Measurement equipment i.e. outside and inside micrometres, Vernier callipers. Dial test indicators. •Special tools supplied by MHPS to aid maintenance of the plant •Welding equipment •Gas cutting and welding sets •Craftsmen tool boxes for fitting and maintenance •Insulation testers •HART field communicators •Circuit breaker testers •Primary and secondary injection test kits •Current transformer analyser •Insulation resistance testers •Tan-D tester •Process meters •Signal generators •Calibration benches (pneumatic and temperature)	
Equipment and infrastructure	•Standard machine tools just as in enlisted workshops attached to power plants •Specialised equipment for the maintenance of heavy duty earthmoving equipment and mobile cranes	Support the maintenance of drilling rigs and infrastructure such as pumps and piping systems.
Central engineering workshop in Nairobi	•Motor rewinding mandrels •Transformer oil purification plant •Transformer oil dielectric breakdown voltage tester •Battery capability tester •Transformer oil acidity number tester •Tan-D tester	Specialised equipment for the maintenance of electrical plant equipment across the company i.e transformers, battery banks and motors
Existing maintenance service providers facilities in Kenya		
Green Energy Geothermal (GEG)	•Plant installation equipment including tools, mobile crane, welding equipment, lifting tackles •Instrumentation and electrical tooling •Sand blasting machine •They have an arrangement with Man India and installed a dynamic balancing machine at Steel stone workshop in Nairobi for rotor repairs and reblading	GEG has made extensive use of its facilities to undertake warranty related repairs to Olkaria WHPs. A framework contract was entered into with KenGen in 2017 for spares and technical support supply for a period of three years.
Soni Technical Services Workshop in Kisumu	•Machine tools •Dynamic balancing and rotor straightening services •Fabrication services •Rotor straightening using hot spotting technique only	This was the first service provider with which KenGen & GEG partnered between 2014 and 2016 for the straightening of bowed rotors, dynamic balancing and re-blading
Steelstone Workshop in Nairobi	•Machine tools of higher capacity •Rotor reblading and dynamic balancing services	For many years Steelstone has played a key role in offering machining and maintenance services to KenGen installations. In 2017 KenGen entered into a short-term framework contract with Steelstone for the manufacture of diaphragms through reverse engineering to reduce the lead time and improve on material selection related defects.

3.3.2 Specialised requirements for existing and future WHPs

It is important to note that unlike conventional power plants, WHPs were developed without accompanying workshops to support maintenance. This was likely inspired by the thought that existing infrastructure tabulated in Table 1 above will be sufficient in meeting routine WHP maintenance needs, which added to the low-cost aspect of WHPs to make them financially viable. Since WHPs are many in number and are scattered in Olkaria and Eburru fields, it is not economically viable to justify the attachment of a maintenance workshop to each WHP plant. An optimal strategy will entail making use of the existing pooled resources located in Olkaria and establishing a mobile workshop equipped with sufficient tools and equipment that will go a long way in eliminating delays in the mobilization and demobilization of repairs and services from the specific site. In addition, WHPs have suffered unique failures that are infrequent in conventional power plants. The specific WHP needs are summarized in Table 2 below.

TABLE 2: A list of recommended machine tools and equipment for optimal WHP maintenance

Equipment	Strategic significance to KenGen
A 3-tonne dynamic balancing machine	To address static and dynamic imbalances associated with infant mortality failures experienced in existing WHPs.
Heat treatment/stress relief equipment	To eliminate secondary failures related to thermal straightening techniques employed on rotors that bend. There is an increased likelihood of turbine rotor failures when put back to service without requisite stress relieving.
A 20-tonne mobile workshop complete with suitable machine tools and lifting equipment. Preferably set up is a containerised truck mounted workshop on a side loader complete with HIAB crane  Sideloader image (Hammar, 2017)	The WHPs lack an integral overhead gantry crane. A considerable amount of generation time is lost in planning for the use of pooled mobile cranes and mobilising WHPs to nearby workshops for repairs. On a number of occasions, these resources are stretched thin by drilling rig requirements and existing power plants to the extent that maintenance work stops for many hours or days owing to the unavailability of a crane. Therefore there is an urgent need to have a dedicated mobile crane and workshop to support maintenance of the WHPs since the current configuration lacks a fixed crane at the site to facilitate lifting operations. Up to 40 % of PM or Corrective Maintenance time is lost in mobilising a mobile crane to site for maintenance work.
Pneumatic wrenches, power tools and portable air compressor	This will go a long way in ensuring time spent in bolting and unbolting mechanical equipment is reduced by up to 80%. On average it takes up to 30 man hours to loosen or fasten turbine and crossover duct elements using hand-operated wrenches in Olkaria WHP.
Vibration analyser	It will go a long way in optimising scheduling for PM and Condition-Based Maintenance (CBM) by necessitating a focus on failures just before they occur and eliminating catastrophic failures experienced in cooling tower motors and gearboxes.
Portable multifunctional welding machine	At the moment WHPs rely on pooled welding services available in Olkaria that often creates hurdles in the planning and realisation of welding repair services, leading to a considerable loss in machine uptime during maintenance.
Ultrasonic inspection and testing equipment	This will be a handy CBM equipment in the inspection of welds, pipe thickness or corrosion rate, and underlying material defects to mitigate catastrophic failures.

TABLE 2 cont'd: A list of recommended machine tools and equipment for optimal WHP maintenance

Equipment	Strategic significance to KenGen
Non-Destructive Testing (NDT) thermal imaging camera	This will go a long way in aiding CBM. According to FLIR (a leading player in thermal imaging in industrial engineering) cameras with lock-in, transient, and pulse capability possess the ability to perform advanced inspections such as NDT or stress mapping that resolves temperature differences as low as 1 mK. NDT is a widely used method to evaluate the properties of a material, component or system without causing damage. Thermal imaging cameras can detect internal defects through target excitation and the observation of thermal differences on a target's surface. It is a valuable tool for detecting defects and points of failure in composites, solar cells, bridges, and electronics. It is also a great tool for thermal mapping of stress when performing materials testing.
Video borescope camera	This enhances CBM and PM through intuitive imaging of hidden or unsafe components in WHPs. It provides the benefit of avoiding arduous overhaul or opening up of components for visual inspection, hence saving up to 90% of maintenance time (FLIR, 2017)
Sandblasting equipment	This will optimise PM and CBM by ensuring scaling build up is removed and minimising imbalances. At the moment KenGen lacks such a component and relies on GEG for sandblasting at a cost.
Special tools for maintenance	Unlike conventional plants, WHP contracts have lacked a specific requirement for the contractor to hand over special tools, therefore it is vital to equip them with adequate sets of special tools, i.e. for alignment fixtures for the turbine.
General tools for maintenance	This will go a long way in ensuring that the maintenance team is well equipped in responding to challenges.
A portable horizontal line boring machine and automatic welder	This will necessitate in-situ machining of casings and or diaphragms, removal of scales or cleaning and repair of surfaces. A great deal of time is spent on removing diaphragms bonded with silica for repairs. KWG04 Unit 1 steam path repairs, for instance, took an arduous period of one and half months to extract the diaphragms, repair and re-assemble. This task entailed transporting the entire casing assembly to nearby workshops for repairs and eventual re-assembly at the site.
3-D scanner, CAD modelling software and workstation	According to Deilir Technical Services, an investment in this equipment has been handy in enabling reverse engineering at ON Power plants. Over the years the engineering team has mapped and documented critical plant components into a CAD format. The benefits realised include: •Easy importation of scanned parts to machine tools for manufacture of spare parts, •Part to part comparison to enable comparison with datasets of existing OEM drawings and modifications necessary. Alignment is performed by best fit or predetermined data and displayed in a visually interactive colour-coded 3-D model that outlines deviations in the internal and external geometry of parts. This equipment will be useful to KenGen WHPs and its companywide installations since it will aid in documenting missing technical data and drawings and go a long way in forming a support system for maintenance decision making. At the moment there is scant information on existing WHPs and KenGen is highly dependent on GEG and Man India regarding precise technical data and efforts to obtain the full information remain futile owing to business interests.
Dedicated emergency response pickups with a small generator, lights and general hand tools for minor repairs	Timely response to potential or actual breakdowns is key in the attainment of availability. Considering that existing WHP access roads are marram roads, it's imperative to provide sufficient off-road vehicles for maintenance team members on standby.
Portable oil purifiers	This will enhance PM and CBM by eliminating contaminants in lubrication oil, prolonging the mean time between oil replenishment and effectively cutting down on maintenance costs. Currently, the existing WHPs lack oil purification systems, leading to expensive scheduled replacement cycles.

3.3.3 The concept and strategy of containerised workshop to support WHP maintenance

In support of in-situ repairs, it is necessary to fully equip and operationalize a mobile workshop in containers to various sites. The concept entails a side trailer mounted with a standard 40 feet container equipped with tools and compact machine tools as outlined in Table 2. Side trailers have been used effectively in leading logistics companies in Iceland such as Samskip, in which up to 36 tonnes capacity of cargo can be loaded and offloaded within 10 minutes without the need of a crane or extra manpower other than the operator and truck driver. A combination with containerised workshop facilities will enable the most cost-effective assembly, test and installation facility to be delivered to the site without the requirement for large capital investments and will greatly minimize maintenance set-up times. According to Hydrasun (2017), the utilisation of containerised workshops aligns with planned and unplanned equipment shutdowns and maintenance, where the speed of response, flexibility and adaptability are key deliverables. Figure 7 illustrates a typical layout of the proposed containerised mobile workshop, complete with compact machine tools and apparatus that can be used for maintenance works at site. This proposal will aid in on-site repairs and a quick response to calls for corrective maintenance works that will ultimately improve availability factors in the WHPs.

FIGURE 7: Examples of a containerised workshop for in-situ maintenance (Mr. Box, 2017: Specialists in container conversions based in the United Kingdom)

4. COMPARATIVE ANALYSIS OF MAINTENANCE PHILOSOPHIES IN SELECT GEOTHERMAL POWER PLANTS

4.1 Snapshot of Olkaria I, Olkaria II, Olkaria I AU and Olkaria IV power stations in Kenya

Olkaria I power station is the first geothermal power plant in Africa with an installed capacity of 45 MW. The main plant equipment consists of three 15 MW Mitsubishi Hitachi Power Systems (MHPS) single flash condensing steam turbines. Following successful appraisal drilling in the Olkaria field in the 1970s, construction began in phases with the first unit being commissioned in June 1981, the second unit came online in November 1982, and the third one in March 1985. In order to mitigate age-related failures and reliability, plans are underway to install optimised modern plant equipment with enhanced output that will serve a new power purchase agreement with the national off-taker, Kenya Power and Lighting Company. This plant has exhibited good availability factors over the years but lately it has declined owing to age-related failures as shown in Figure 8 below.

Olkaria II power station is located in the North East sector of the greater Olkaria geothermal field and comprises three 35 MW MHPS single flash condensing steam turbines with a combined installed capacity of 105 MW. It is important to note that drilling works to meet the steam requirements of Olkaria II were completed in the early 1990s and it took some time to secure funds for the construction of the power plant. Construction was undertaken in two phases where units 1 and 2 were commissioned in March 2003 and September 2003, respectively, while unit 3 was commissioned in October 2010. The station has been operated as a base load station since its commissioning with the three units registering high availability factors as indicated in Figure 8.

The 280 MW net electrical output is considered to be the largest single geothermal installation project to have been commissioned simultaneously in the world. This comprises Olkaria IV and Olkaria I AU power stations with an installed configuration of 4x75 MW Toshiba single flash turbine generator units. Both plants (300 MW gross output) were constructed by a consortium of Hyundai Engineering Co. Ltd, Toyota Tsusho, H. Young Company and Toshiba Corporation under the consultancy of Jacobs SKM, which served as the employer's representative. The first unit was handed over to KenGen for commercial operation on 12th September 2014 after a successful reliability run and performance tests and the other units were commissioned in phases in the subsequent months. Figure 8 shows the relative availability factors of the KenGen geothermal power plants in Olkaria.

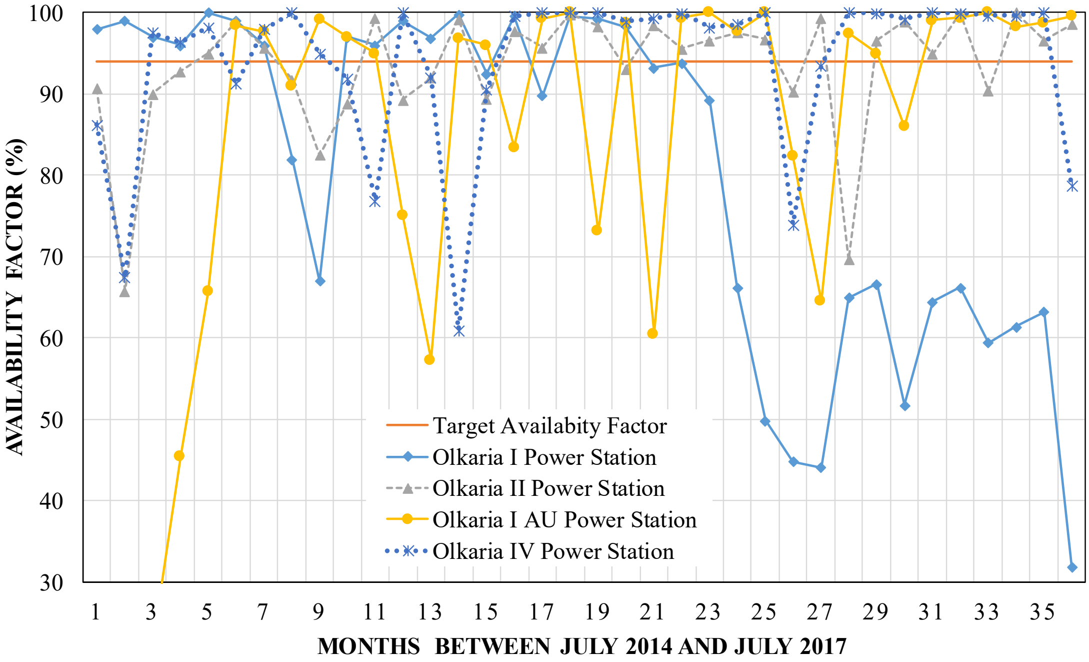


FIGURE 8: Overall availability factors of select conventional geothermal power plants in Olkaria for a period of 36 months

Figure 9 shows the cumulative and relative time spent in the operation of the WHPs in the period under study between 2014 and 2017. It is clear that the amount of time consumed by planned, grid forced and auxiliary forced outages is quite significant hence impacting on generation or running hours. This study will focus on strategies to maximise machine uptime.

4.2 Description of the maintenance philosophy in Olkaria geothermal plants

In 2008 KenGen embarked on the Good to Great (G2G) transformation strategy following fundamental changes in the company that required new influences on thinking. The strategy outlines operational and maintenance improvements necessary to increase reliability and further reduce costs, which focused on the identification of primary causes of downtime and ensuring that the identified root-causes are resolved. Optimising maintenance practices through time reduction and reduction of operational costs was the priority. In striving towards operational excellence, KenGen has adopted a mixed maintenance management policy in its installations. Traditionally, preventive maintenance has been embraced as the predominant management approach entailing periodic routine checks as per the recommendations of the specific plant and auxiliary equipment manuals.

Generally, the availability factor of all KenGen geothermal plants is within internationally accepted standards and power purchase requirements as set out between KenGen and the Kenya Power and Lighting Company (KPLC). This is due to the good maintenance teams assembled by KenGen and maintenance strategies put in place which have ensured that all maintenance programs are executed efficiently and in a timely manner so as not to affect plant availability or any other contractual obligations.

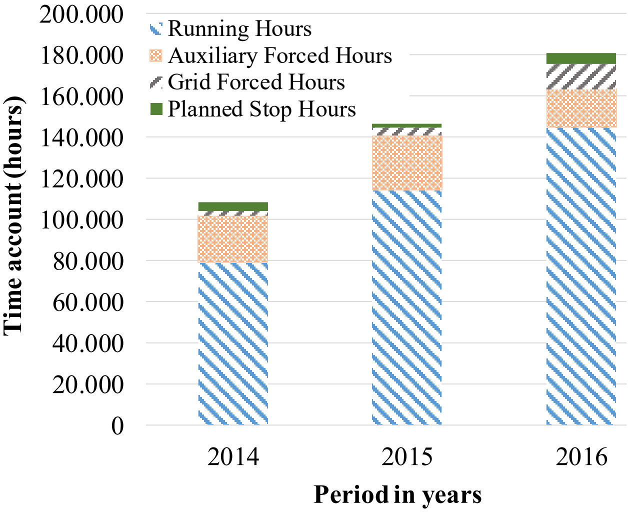


FIGURE 9: Cumulative time account of the WHPs in Olkaria in a period of 36 months

Maintenance methods undertaken include preventive maintenance, corrective maintenance and condition based maintenance. Condition based maintenance was embraced in the maintenance environment with a view of linking the operation reports to the maintenance function. Condition based maintenance is important as it ensures that no unnecessary downtime or money is spent on carrying out maintenance on equipment which does not require such interventions as is normally the case with time/cycle based maintenance programs. KenGen staff expertise covers all aspects of modern plants including and not limited to, mechanical, electrical, instrumentation and controls, automation (DCS or SCADA) and civil works. To achieve this, KenGen has trained its maintenance staff and adopted a SAP Plant Maintenance module as a way of ensuring that all maintenance jobs were done and defects noted are logged into the module for process auditing. This ensures that maintenance periods, logistics, costs, materials, methodology and any other occurrences are captured during every procedure and can then be studied for continuous improvement. KenGen has also introduced the Single Minute Exchange of Die (SMED) and Six Sigma principles in its operations and maintenance procedures so that minimum downtime occurs during equipment change over. For this to be achieved, the company has invested heavily in specialized mechanical handling equipment to ensure that any equipment in the plant can be replaced in the shortest time possible. Maintenance programs are set up for a financial year.

Other departments, that are not directly involved in the day to day power plant and steam field activities, offer services which are vital to the overall plant and field health. These include the central rig workshop at Olkaria, which services hydraulic systems, mechanical handling equipment etc., and the Central Engineering workshop in Nairobi, which carries out the rewinding of motors and other specialized electrical plant maintenance and testing procedures. The company has invested in significant machine tools and instrumentation workshops in close proximity to the main geothermal power plants in order to ensure that the response time to maintenance needs and work setup time are minimised. In addition, technical services are pooled and equipped in the area to ensure that electrical, instrumentation and control maintenance needs are fulfilled through a standardised approach across the company where experienced experts can be reached to enable synergies when faced with challenges.

Maintenance is reviewed over time during the formulation of maintenance procedures in line with the ISO 9001:2015 management system so as to conform to the realities of actual operating conditions. Corrective maintenance is undertaken as an emergency, especially on the main plant, as it directly impacts the plant performance. Routine preventive maintenance is carried out as per setup procedures without impact on overall plant performance.

Today, Enterprise Resource Planning (ERP) systems remain the backbone of KenGen's business operations, as a business transformation effort, not as a technological project. ERP implementation is about making changes for business transformation through defining the core business requirements, identifying and applying available best business practices to make end-to-end business processes more effective and efficient. Like any mission-critical business asset, there is a need to continually improve the system. KenGen upgraded and expanded the SAP plant maintenance module to manage more business processes through the ERP project in 2010. The Plant Maintenance and Project System was adopted to aid in operations and business development business processes.

4.2.1 Technical assurance and system audits

KenGen has been implementing the quality management system since 2004 and the environmental management system since 2009. The certification to ISO 9001 and ISO 14001 standards was a strategic decision based on KenGen's overall business plan and plays a role in the implementation of key G2G transformation initiatives of innovation and the continual improvement of the organization temple of strategies.

As required by the ISO 9001:2015 and 14001:2015 management systems, KenGen has embraced internal audits as a management tool to monitor all its activities. Periodically, an ad-hoc team of competent auditors are appointed to perform a process based audit of the organisation to:

- Confirm effective implementation and maintenance of the quality and environmental management systems, in line with the requirements of the ISO 9001:2015 and ISO 14001:2015 management standards.
- Confirm that the management systems are capable of achieving KenGen's policies, documented information and objectives.
- Confirm that the quality and environmental management systems contribute to the continual improvement of KenGen's processes.
- Assess the organisational effectiveness based on continual improvement initiatives such as improved structure, culture and processes as envisioned by the corporate strategy.

In a nutshell, a number of benefits can be derived to the certifications to the ISO 9001 management systems. They have assisted in providing a better control of KenGen's business operations based on the documented procedures. This is especially important in a tough business environment. With the inclusion of a risk-based management system in the 2015 version of the standard this will go a long way in assisting KenGen to identify and control risks. Documenting processes and locking in system changes has helped ensure that the business can continue to operate effectively, ensuring continuity even with staff turnover.

In addition, a team of engineers from the technical assurance and quality department visits sites, and works closely with the plant operation and maintenance team to review all work. The team monitors such items as adherence to energy management policy, regulatory compliance, maintenance practices (including preventive and condition based maintenance programs), operating procedures and the material condition of the plant. These audits highlight areas that meet stipulated operation and maintenance standards, as well as determine areas that require attention. The overall goal of the audits is to enhance productivity, profitability and reduce liability. Audits involve operator interviews, observation of normal work practices, inspection of machine history and preventive maintenance records. At the end of each audit, all items are documented in a detailed report, complete with action plans and follow-up action programs towards deficiency corrections.

4.2.2 Overhaul of major equipment and capital improvements in Olkaria power stations

Maintenance and inspection is a matter of utmost importance to any geothermal power plant in order to prevent various problems and to maintain the high availability and longevity of units (KenGen, 2009). The recommended mean time between major overhauls varies depending on the equipment manufacturer and specific challenges of the geothermal field. For instance, it is recommended by the two leading original equipment manufacturers, MHPS and Toshiba, that the first major overhaul should occur after seven years of continuous operation and subsequent overhauls should be done every five years. KenGen's experience in operating the Olkaria I and Olkaria II geothermal power plants for the past 35 years indicates that the mean time between major overhauls depends on the specific challenges and performance parameters arising from the coordination between maintenance and operations on a case by case basis and power purchase agreements considerations. A decision on the scheduling of overhaul inspection is informed by:

- Reliable and actual operating information on functional troubles.
- Age-dependent deterioration that is tied to the potential of failure vs. time curve.
- Changes in operating conditions.
- Abnormal findings arising from routine inspection.

KenGen's experience has demonstrated that the above considerations coupled with condition based maintenance initiatives are indispensable in the formulation of action plans for overhaul maintenance works that have affected restoration and improvement in equipment performance. Olkaria I has undergone a number of major overhaul cycles in all of its three MHPS units whereas Olkaria II has had overhauls in the first two MHPS units and plans are underway to overhaul the third MHPS unit. The 21 Olkaria and Eburru WHPs, on the other hand, have had at least one major overhaul on the mechanical components since 2012. This is mostly linked to the contractual defect liability period requirements during the piloting and the project contract. There have also been a number of infant mortality related failures during the course of the WHP implementation where the failure mode analysis and correction entailed overhauling the affected units. Table 3 outlines notable infant mortality related failures observed in the initial five years of the WHP development in Olkaria, key findings and corrections that were undertaken. Notwithstanding the documented failures, it was deemed imperative to overhaul the major mechanical components in the WHPs due to their compact nature, relative size and vulnerability to operational changes, especially scaling effects and related efficiency drop. A number of functional and technical modifications have been undertaken to restore normalcy and some notable corrective actions to eliminate the re-occurrence of the detected nonconformities.

4.3 Hellisheidi and Nesjavellir (ON Power) geothermal power plants in Iceland

Studies reveal that Icelandic geothermal power plants operate in an efficient manner and the industry has demonstrated systematic and innovative new ways to optimize their operations and maintenance (Atlason et al., 2013). Hellisheidi geothermal power plant is located in the Hengill high-temperature geothermal field in the south western part of Iceland. The plant was built for cogeneration of electricity and hot water through a double flash design process. The plant was commissioned in phases in the following order: 2x45 MW MHPS units (2006), 1x33 MW low pressure Toshiba unit (2007), 2x45 MW MHPS units (2008), 133 MW thermal hot water plant (2010) and the 2x45 MW MHPS Sleggja units (2011) taking the total installed electric capacity to 303 MW electrical capacity and 133 MW thermal capacity (ON Power, 2017). Nesjavellir power plant was commissioned in 1990 as a thermal plant followed by a phased construction of MHPS power plant units in which the initial 2x30 MW was commissioned in 1998, 1x30 MW in 2001 and a further 1x30 MW in 2004 taking the total installed capacity to 120 MW. The hot water system has a thermal capacity of 300 MW.

TABLE 3: Summary of major infant mortality related failures in the first five years of the WHP development in Olkaria

Incident	**Number of counts**	**Root cause(s)**	**Corrective action(s)**
Rotor bends	4	• Reverse power operation. • Fatigue arising from sudden trips. • Inadequate burn-in tests during design.	• Straightened one rotor using off-set machining technique. • Straightened 3 rotors using hot spotting technique (thermal method) and dynamically balanced the rotors.
Erosion of rotor surfaces	2	• Inferior material selection. • Moisture carry over due to poor separation associated with undersized separator.	• Reblading of affected blades. • Installed a more efficient and higher capacity moisture separator.
Fractured 1st stage rotor blades	4	• Material defects. • Stress concentration on root of the blade.	• Reblading of 1st stage of all C-50 rotors by integrating superior blades and eliminating sharp edges on blade root.
Imbalance due to scaling	1	• Scaling on rotor surface leading to uneven build-up of mass on rotor. • Corrosion leading to uneven loss of mass from rotor.	• Cleaning and dynamic balancing. • Regular CBM monitoring of vibration trends.
Corrosion species on diaphragm	10	• Material defects.	• Cleaning by sandblasting. • Ordering replacement spares of superior material with higher resistance to corrosion attack.
Steam gouged casing surface and diaphragms	2	• Material defects.	• Repair of damaged surface with spot welding with superior cladding material. • Ordering replacement spares of superior material that resists erosion.
Steam pipe yielding	1	• Material defect leading to failure by creep. • Inadequate thrust force support in the design.	• Replacement with a higher class piping schedule. • Integration of additional thrust force support. • Intensified NDT thickness checks.
Coupling failures	1	• Material defects.	• Replacement with defect free coupling.

The maintenance management model is an optimised mixed approach that encompasses preventive maintenance, condition based maintenance and a few isolated elements of corrective maintenance, and can arguably be described to have attained reliability centred maintenance. The maintenance workload comprises ten MHPS units, one Toshiba unit and hot thermal plants with a combined installed capacity of 423 MW of power generation and 433 MW thermal capacity. Saemundur Gudlaugsson, technical manager at ON Power, reveals that the Hellisheidi and Nesjavellir geothermal power plants have exhibited very high availability factors, averaging 97.85% as reflected in Figure 10 (personal communication, 5th October 2017). This is attributable to the sustained investment in internal technical capacity, a partnership with established local service providers such as Deilir Technical Services and Mannvit, imparting essential technical skills on the technical staff, continual system review for improvement-based root-cause analysis and improving management models towards reliability centred maintenance.

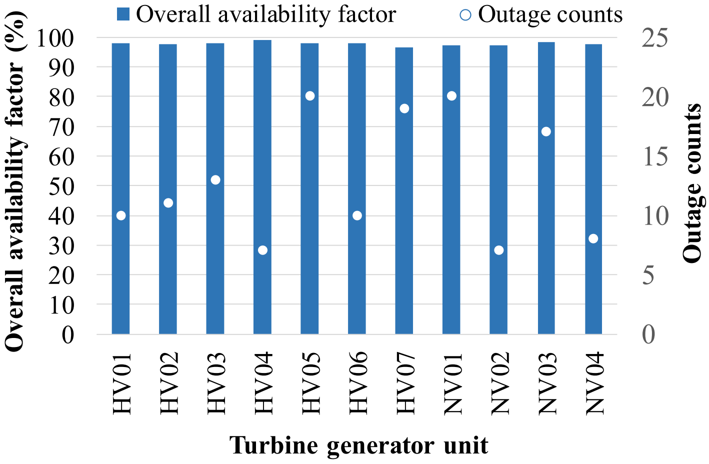


FIGURE 10: Overall availability factor and outage counts for Hellisheidi and Nesjavellir power plants in Iceland

A notable contribution to the success in attaining world-class availability factors is the optimised maintenance plans that have extended the time between maintenance episodes. For instance, Inconel cladding on diaphragms has increased the reliability of turbine elements, hence extending the time between overhauls from 4 to 5 years with the hope to extend it to 6 years in the future. Condition based maintenance has also been optimised by building capacity in oil condition analysis, augmenting predictive monitoring in the SCADA system with portable vibration monitoring and analysis. To mitigate motor rolling element bearings failures, ultrasonic monitoring (listening) of the greasing process has greatly reduced bearing failures by ensuring the control of the process. Non-destructive testing methods are employed in detecting surface and subsurface cracks before they appear or worsen. In addition, significant investment in critical spares and the ability to manufacture at site has mostly eliminated prolonged outages that are tied to long waits for spares from original equipment manufacturers, which has reduced the time of major overhaul duration by up to three days. The company has partnered with local experts in building a strong capacity in Computer Numerical Control (CNC) machining, the advanced welding of rotors and turbine stationary components, post-welding heat treatments, dynamic balancing capacity, and 3-D scanning of parts for repairs and manufacture of components. This investment has paid off by enabling the company to manufacture the right turbine blades at a fraction of the cost compared to original equipment manufacturers.

5. STRATEGIES FOR OPTIMISING MAINTENANCE PRACTICES IN OLKARIA WELLHEADS PLANTS

5.1 Description of strategies and approach

Energy utility firms in the world strive towards continuity in the production of power, market dominance and reduction in operation and maintenance costs through the life cycle of the asset, and these are high on the agenda of plant managers. It is crucial to have minimal machine downtime to minimize further damage. A proper maintenance strategy which is capable of maintaining the performance of the machinery is necessary.

The essence of a strategy is choosing a unique, valuable position rooted in systems of activities that offer a sustainable competitive advantage and go beyond operational effectiveness (Porter, 1996). Porter explains that under pressure to improve productivity, quality, and speed, managers have embraced management tools, benchmarking, and re-engineering in order to attain a competitive advantage. KenGen embraced the unknown field of the wellhead technology with a view to ensure a sustainable bottom line by bridging the gap between initial phases of geothermal development (i.e exploration, appraisal and confirmation drilling) and actual power plant development. In 2016, 21 units scattered in a radius of about 60 km, were operational within the Olkaria and Eburru fields. This brought in new dynamics in terms of operational/takeover preparedness, operational dynamics, maintenance, staffing and logistical challenges. Consequently, the company undertook an optimisation study that analysed the status quo and outlined a sustainable wellheads strategy. The findings revealed that it was more feasible to consider the existing wellhead units as permanent units in order to optimise the return on invested capital as long as they are operated and maintained as per international standards.

A geothermal power plant is basically a typical production line that embraces the common tenets of industrial engineering and manufacturing processes. The exception is the closed loop scientific approach employed in the planning and development of geothermal projects in the world. Owing to limited publications on the operation and maintenance aspect, it was deemed practical to benchmark and borrow a leaf from established research and industrial engineering techniques. These aspects have been customized to suit geothermal utilisation scenarios. A number of industrial improvement philosophies and techniques have been advocated in geothermal power plants as outlined in Chapter 3. It is important to address case study problems and challenges that have been faced in the initial research and development aspects of the wellhead technology in a systematic and comprehensive manner (Shigeo, 1983). This study will borrow heavily from a scientific thinking mechanism for improvement that was advocated by Shigeo Shingo in case studies that he cited in his book: *Key strategies for plant improvement*.

Determining and establishing the best actions to prolong the life span of an asset such as a geothermal installation takes a great deal of knowledge about failure mode analysis. It is important to know specifically how assets fail and the dynamism in operation may not always reveal a clear root-cause. An operation and maintenance strategy will therefore entail a collective effort that includes best practices, and hardware and software that can aid in identifying how and when assets fail. Owing to the strategic importance of these units, established good maintenance practices should be considered a resource (*Operations and maintenance best practices, release 3 2010 by Federal Energy Management Program*).

5.2 Optimizing the preventive maintenance method (a frontline defence against equipment wear)

5.2.1 Failure modes and Pareto analysis on factors impacting on WHP availability

A study on the probability of failure curve (P-F curve) of existing WHPs reveals some unusual infant mortality failures as documented in Figure 11. To mitigate these failures, a number of corrective actions have been implemented in collaboration with Green Energy Geothermal (GEG) during the liability period of defects as summarised in Table 3 The Pareto principle states that for many events, roughly 80% of the effects come from 20% of the causes (Koch, 2001). A Pareto analysis of major failures reveals turbine bows, planned outages, grid forced outages and switchyard faults contribute to 84% of the reduced availability as illustrated in Figure 9. It is worth noting that the generalised preventive maintenance approach common in conventional geothermal power plants cannot be effectively applied to WHPs. It is therefore important to modify the approach to suit WHPs in order to minimise or eliminate the observed infant mortality.

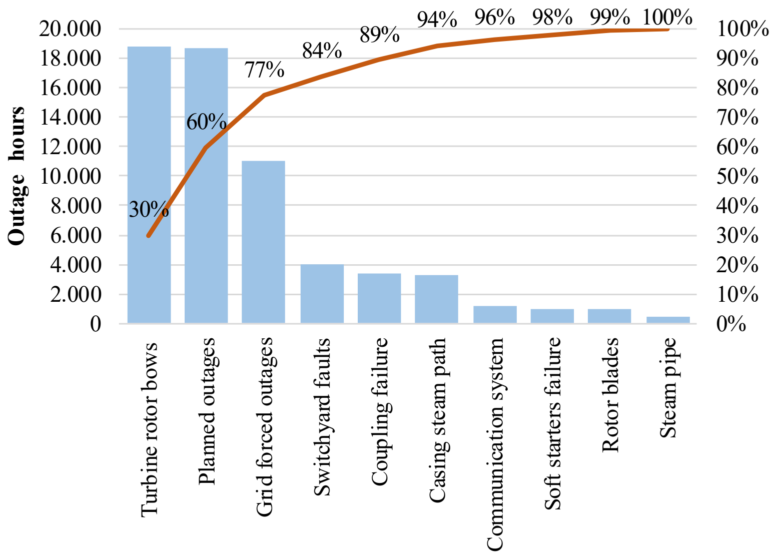
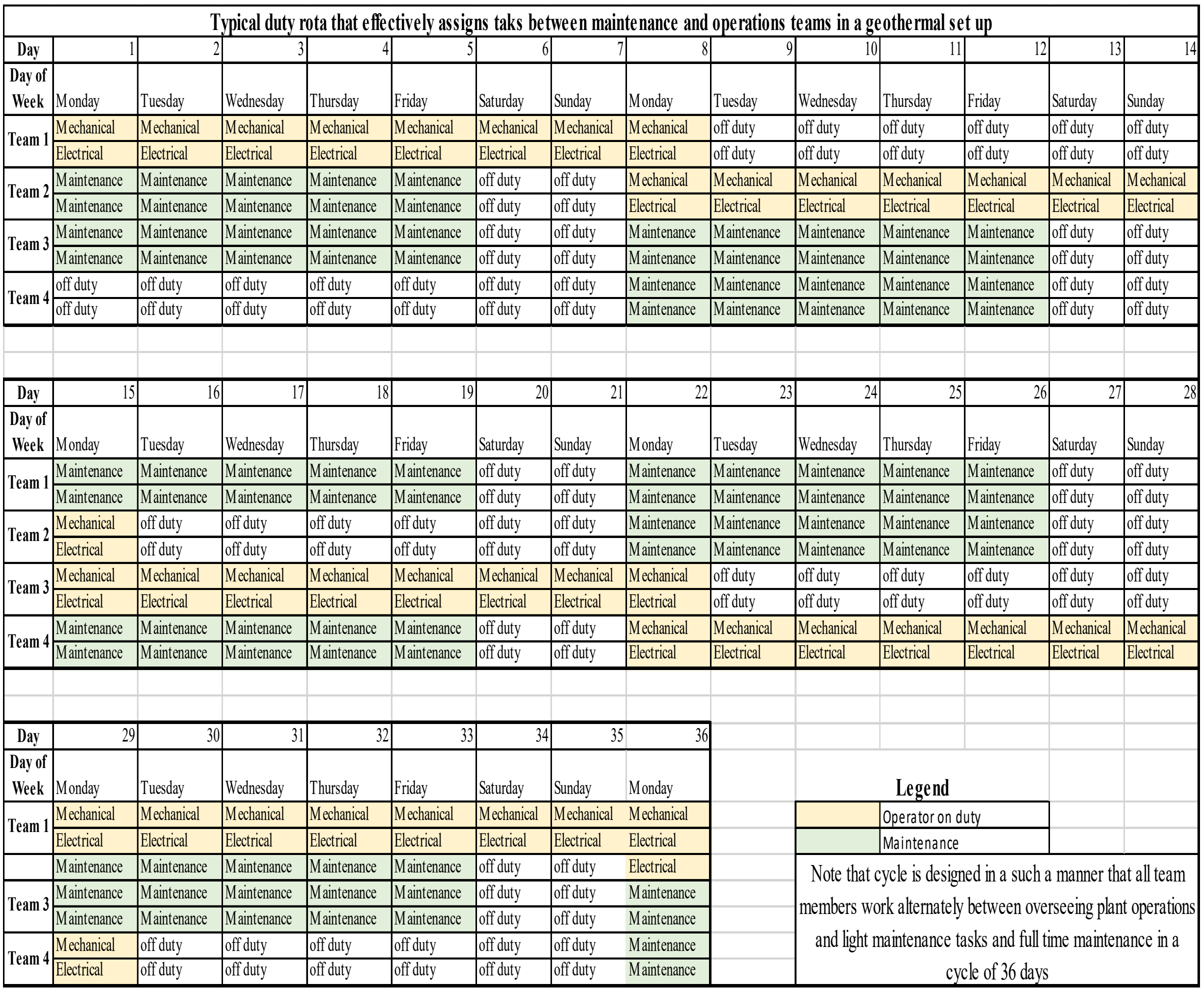


FIGURE 11: Pareto Chart illustrating the 80/20 principle in factors impacting on existing WHP outage hours on left axis and cumulative % of total outage hours on right axis

ReliabilityWeb.com in its maintenance benchmarking study recommends the adoption of an appropriate strategy that entails effective testing methods on electrical and mechanical plant equipment during preventive maintenance. This includes motor testing and non-destructive testing (NDT) techniques on critical mechanical components, including the steam pipeline, to enable early detection of failures (O'Hanlon, 2017). Information from tests forms a basis for establishing an asset condition database that will be useful in data analysis and maintenance decisions. A benchmarking study of ON Power in Iceland reveals that the company has managed to effectively sustain the high availability of its power plants by assigning tasks between the maintenance and operations teams by adopting a rotational shift programme where both teams work in operations and maintenance alternately. Further, two operators of electrical and mechanical backgrounds man the centralised control room at Hellisheidi with remote control capabilities of the Nesjavellir power plant on daytime duty. During normal operations the two operators perform light autonomous maintenance duties and routine tasks in the plants as they observe the critical plant parameters. After that they retreat to a nearby guest wing in the evening where they remain on standby. This cycle repeats for eight days after which they are off-duty. In order to ensure all plant parameters are under watch, there is a remote monitoring and control system in Reykjavík where operators watch over the ON power plants around the clock and are in constant communication with the operators on duty in case of alarms that require attention. An example of a shift programme is indicated in Figure 12.



Typical duty rota that effectively assigns taks between maintenance and operations teams in a geothermal set up

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Day of Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Team 1	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	off duty	off duty	off duty	off duty	off duty	off duty
	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	off duty	off duty	off duty	off duty	off duty	off duty
Team 2	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical
Team 3	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
Team 4	off duty	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
	off duty	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty

Day	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Day of Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Team 1	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
Team 2	Mechanical	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
	Electrical	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty
Team 3	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	off duty	off duty	off duty	off duty	off duty	off duty
	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	off duty	off duty	off duty	off duty	off duty	off duty
Team 4	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical

Day	29	30	31	32	33	34	35	36
Day of Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday
Team 1	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Electrical
Team 3	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance
	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	off duty	off duty	Maintenance
Team 4	Mechanical	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance
	Electrical	off duty	off duty	off duty	off duty	off duty	off duty	Maintenance

Legend

🟨	Operator on duty
🟩	Maintenance

Note that cycle is designed in a such a manner that all team members work alternately between overseeing plant operations and light maintenance tasks and full time maintenance in a cycle of 36 days

FIGURE 12: Typical work cycle illustrating assignment of maintenance and operation tasks being implemented at ON Power, Iceland

Owing to a relatively large number of WHPs under operation at Olkaria (21 units), it is imperative that the operators are directly involved in the autonomous maintenance. Following the automation of the monitoring system of the WHPs, operations have been rationalised to enable remote monitoring at four clusters: at the OW914 well pad where 11 units are monitored, at the OW37 well pad where five units are monitored, at the OW43 well pad where four units are monitored and at Eburru where a single unit is monitored. A back up team of six operators is on standby during the daytime at the OW914 and OW37 well pads to respond to alarms arising from nearby plants. Plans are underway to ensure the full automation of WHPs to ensure the effective remote monitoring of existing WHPs and integrating them into KenGen's SCADA system (Apiyo, 2016). In addition, the current WHP workforce comprises 45 operators (about 70% of section workforce) which has been viewed as a disadvantage due to the labour intensity. However, this can be leveraged as an opportunity to utilise this multidisciplinary and diverse workforce in undertaking the autonomous maintenance of the facilities without a need to hire additional maintenance personnel if duties are shared strategically as exemplified in Figure 12. There is much to gain by involving the operators in the drive for improved reliability as a step towards operational excellence: Regular "machine health checks" by operators who are working closest to the equipment around the clock can be converted to a maintenance frontline as the ears and eyes at the site. In addition, closer relations between maintenance and operations increases motivation and understanding as a result of clearer roles, cooperation, joint objectives and relieves maintenance resources in favour of more preventive and optimized special maintenance tasks which require specific and higher skills.

A study of the WHP preventive maintenance schedule reveals that a number of scheduled maintenance tasks conducted during annual inspections can be eliminated and minimised by adopting operator driven maintenance as the units run. This includes the cleaning of oil coolers, cleaning oil filters, turbine oil replenishment, cooling tower gearbox oil replenishment, valve stem freedom checks and instrument air compressor preventive maintenance, which are largely time dependent. This can be made possible by incorporating redundancy in the existing set-up by installing standby and safe change over equipment to avoid interrupting the operation of the plant. Areas that critically require redundancy include the oil coolers, emergency oil pumps, auxiliary cooling water pumps and brine control valves. In addition, the safe isolation of individual cooling tower cells should be made possible by integrating manual isolation valves on each cell. This approach will aid in cutting down the current duration for a planned annual inspection from seven days to five days.

Furthermore, a more effective utilisation of predictive technologies in the WHPs will help in early detection and just in time scheduling of preventive maintenance. Incorporating a monitoring system in the motors and gearboxes in the existing cooling towers will help eliminate the occasional failures in the existing WHPs. Trending of cooling tower drive system oil level and vibrations will enable the timely intervention of failures by offering an early warning system. At the moment, walk about inspections are being employed which in most cases necessitates switching off the cells and taking toxic gas safety measures to enable physical inspections, an approach that is costly and unsafe to personnel.

To shorten planned annual maintenance time, some calendar based tasks such as the inspection of bearings, alignment measurements, generator air cooler cleaning and oil change, can be shifted to on the run maintenance and condition based maintenance programs, hence enabling focus on critical preventive maintenance tasks and saving on preventive maintenance outage duration. It is important to ensure the 100% execution of preventive maintenance without more than 10% variation of the scheduled time since it is effective when done in a regular and consistent manner as shown in the *Digital report on maintenance strategies* (Jardine and Tsang, 2016).

The effectiveness of preventive maintenance overhaul needs focus to ensure that the performance of units that have exhibited major failures is evaluated and trended to determine an appropriate mean time between major overhauls.

The mean time between major overhauls for the C-64 units and Eburru has been set to two years to enable the evaluation of the condition of the units following the repair works, whereas the time for C-50 units has been proposed as four years. This is informed by the fact that a lot of the design improvement in the reliability of the C-50 units has been implemented by GEG and thus the units have exhibited consistently higher availability factors in comparison to the C-64 units and Eburru. Figure 13 illustrates the proposed major overhaul program for the WHPs for a period of 18 years.

Proposed WHP major overhaul plan for 18 years lifespan																				
Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
EBURRU		1			1		1			1				1				1		1
	C-64 units																			
KWG 01 UNIT 1				1				1			1		1		1		1		1	
KWG 01 UNIT 2	1	1	1	1			1		1		1		1		1		1		1	
KWG 02 UNIT 1					1	1		1		1		1		1		1		1		1
KWG 02 UNIT 2					1	1			1		1		1		1		1		1	
KWG 03 UNIT 1					1		1		1	1			1		1		1		1	
KWG 03 UNIT 2				1	1		1		1		1		1		1		1		1	
KWG 04 UNIT 1					1			1		1		1		1		1		1		1
KWG 04 UNIT 2							1		1		1		1		1		1		1	
KWG 05 UNIT 1				1				1		1		1		1		1		1		1
KWG 05 UNIT 2							1		1		1		1		1		1		1	
	C-50 units																			
KWG 06				1			1			1				1				1		
KWG 07					1			1				1				1				1
KWG 08				1			1				1				1				1	
KWG 09					1			1				1				1				1
KWG 10					1			1				1				1				1
KWG 11						1		1				1				1				1
KWG 12					1				1				1				1			1
KWG 13					1			1				1				1				
KWG 14					1				1				1				1			
KWG 15					1				1				1				1			
Overhauls per year	1	2	1	6	13	3	8	8	9	6	7	7	10	5	8	8	11	6	8	8
Cumulative overhaul duration in days	0	0	0	42	91	21	56	56	63	42	49	49	70	35	56	56	77	42	56	56

FIGURE 13: Proposed WHP major overhaul program for a lifespan of 18 years

5.3 Road map for the application of Single Minute Exchange of Die to WHPs in optimising preventive and condition based maintenance

Shigeo indicates that benchmark Single Minute Exchange of Die (SMED) programs were developed over long periods as a result of examining the theoretical and practical aspects of setup improvement closely, hence emphasising analysis and implementation (Shigeo, 1985). There are two types of setups, internal and external. The conceptual road map for improvement entails distinguishing these two types of set up and converting internal set up to external setup. Once this is done, all aspects of the setup can be streamlined and at every stage the setup can be improved. In order to reduce waste, KenGen rolled out SMED at relevant levels to enable relevant decisions on improvement initiatives at all functional levels.

5.3.1 Identification of pilot area

Pareto charts reveal the percentage distribution of downtime and can be summarised as follows:

- 30% of outage hours were due to turbine bows in a period of 36 months under study;
- 30% of outage time was spent on planned outage works;
- 17% of outage time was lost as a result of grid forced outages; and
- 7% of outage time was due to switchyard related faults.

The above factors collectively contribute to 84% of time lost. Hence, they present multiple opportunities for piloting a SMED program in the WHP operations.

5.3.2 Applying SMED to planned outage works

30% of WHP outage time was spent on planned outage hours compared to a target of 6% which is 5 times more than what is generally acceptable in the operation and maintenance policy. This is largely attributable to the numerous counts of pre-emptive measures to forestall failures, addressing of deficiencies identified during contractual defects liability periods and scheduled annual inspections. The current practice in undertaking overhauls or major inspections entails that all the elements are executed simultaneously in specialised groups i.e. mechanical, electrical, instrumentation, civil and steam field works. These tasks are undertaken in parallel and the critical path is usually the turbine works which in general lasts for up to seven days for an annual inspection if there is no major problem.

5.3.3 Optimisation scenario: Separation, conversion of internal to external elements and streamlining planned outage duration elements

This step focuses on the identification and separation of elements to ensure that maintenance work is undertaken when the machine is in operation as much as possible by determining work elements that can be undertaken before or after the planned outage work. The question in this phase is "Can this element as currently performed or with minimal change, be completed while the equipment is running" (Shigeo, 1983) and the answer forms a basis to categorise the element as external and move it before or after shutdown as appropriate. A description of candidates for this treatment is shown below:

- Oil condition and replenishment can be shifted to condition based maintenance and on the run programs.
- Cleaning of oil coolers and filters can be undertaken on the run by a modification of the existing setup to enable changeover without tripping the plant, a task which operators can undertake.
- Cleaning of generator air coolers can be shifted to the condition based maintenance program.
- Visual and condition monitoring of pumps can be shifted to the condition based maintenance program.
- The inspection and cleaning of distribution piping and nozzles in cooling towers can be converted to condition based maintenance programs by installing manual isolation valves to each cell to enable on the run maintenance. WHPs have experienced a de-rating by up to 10% due to a lack of a suitable isolation valves resulting in ineffective cooling.
- Inspection of cooling tower drives can be shifted to condition based maintenance programs and on the run programs involving the plant operators by enabling remote monitoring and trending of critical parameters such as vibrations, noise level and oil level through a modification of the current setup. Oil checks and on the run oil replenishment can be made through a modification of the draining system and topping system to allow the use of an oil transfer pump during replenishment. Often there has been a de-rating of units by up to 60% of output whenever a component of the cooling drive system is lost, such as a gearbox and a motor.
- The inspection of the cold end piping system and components can be converted to become a condition based maintenance program.
- HVAC and fire suppression system maintenance can be undertaken by operators on the run.
- Air compressor servicing can be streamlined by the installation of redundant connection points in each well pad to hook up a portable instrument air compressor during breakdowns or preventive maintenance, in order to avert the shut down of the units during scheduled maintenance of air compressors.
- Moisture separator preventive maintenance inspection can be shifted to condition based maintenance since experience indicates that the condition of the existing separators has been stable since commissioning, hence it is needless to open them during annual inspections except for the drain valves, still well, instrumentation and impulse line on the lower side that tend to

block. However, these units are equipped with adequate instrumentation systems that send the real-time status of the separators, thus enabling prompt action since any extreme alarm is configured to trip the units. Inspection can be done after three years or when operating parameters change.

- Hot end piping and valve component checks can be converted to external elements by employing non-destructive testing (NDT) techniques such as ultrasonic thickness measurements, hence necessitating on the run and condition based maintenance programs.
- Brine control valve maintenance can be external through a modification of the existing set up to enhance redundancy by integrating a spare valve or flange connection that will enable a quick change over during maintenance. This can be undertaken as condition based maintenance and on the run maintenance.
- Silencer checks can be shifted to condition based maintenance owing to an adequate existing monitoring system. The pressure control transmitters and sensors will detect chokes in the system that often lead to build up of pressure that is indicative of a blockage of the diffuser or A-plate (sieve plate).

In this pilot area, it is clear that 40% of planned outage tasks can be converted to condition based maintenance and on the run maintenance, hence cutting down significantly on what has to be undertaken when the unit is shut down. These modifications require an initial investment and a cost-benefit analysis which, as discussed in Chapter 6, justifies the benefits that will be accrued when planned outage duration is reduced by 40%.

The streamlining phase entails reviewing the remaining internal elements with a view of simplification to shorten the outage work duration. The question in this phase is “How can this element be completed in less time and how can this be simplified?” (Shigeo, 1985; LeanProduction, 2017). Specialised requirements to support WHP maintenance in Chapter 3 indicate the infrastructure necessary to optimise maintenance.

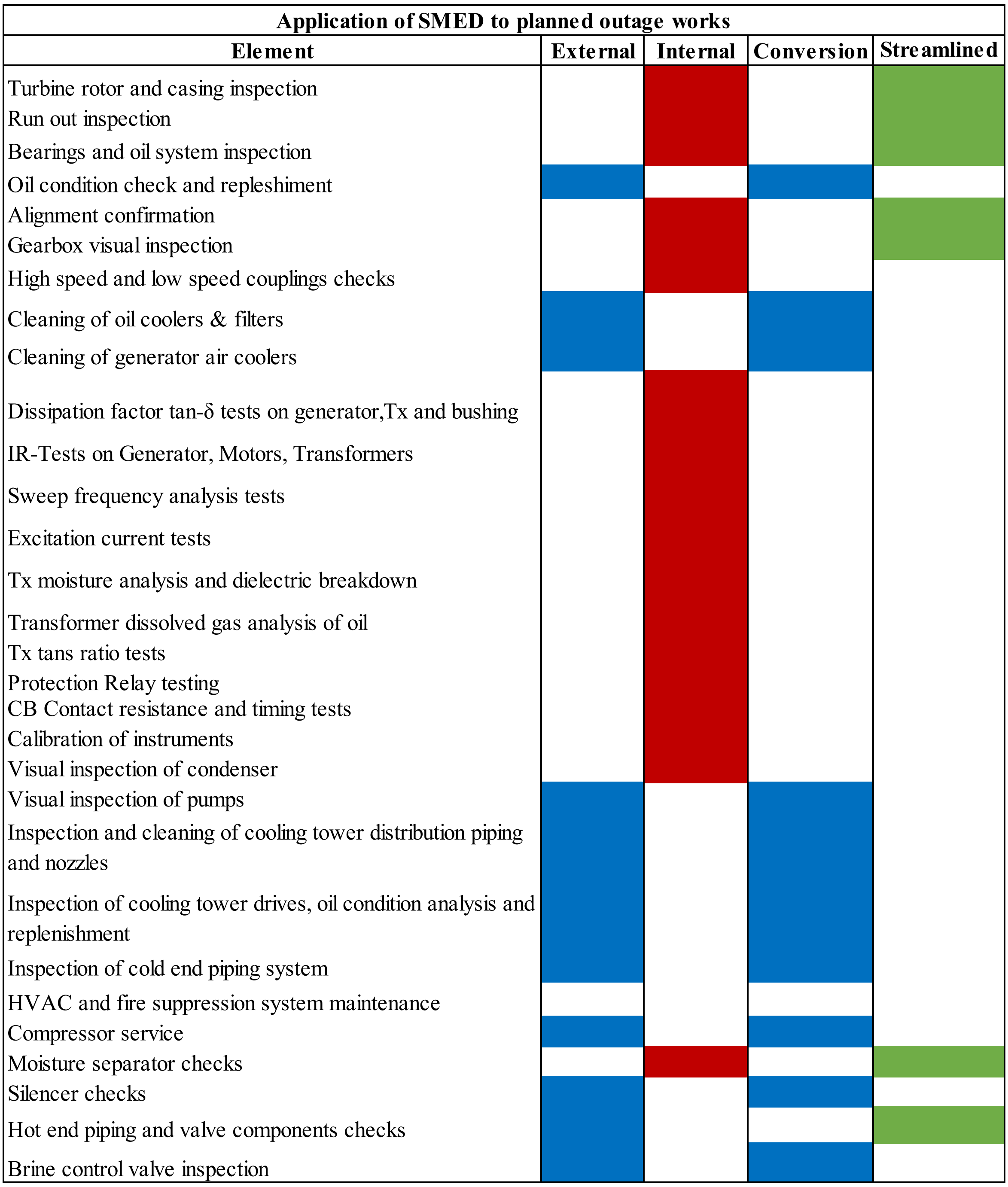
Figure 14 shows that seven out of the 18 remaining internal elements in planned outage can be streamlined to reduce the outage duration by up to 24%. For instance, turbine rotor and casing inspections and correction works can be simplified by investing in in-situ repairs such as jigs, fixtures, a welding machine, a horizontal boring machine, a heat treatment apparatus and adequate strategic spares such as spare rotors and diaphragms to ensure quick replacement and repairs. This will considerably reduce the overhaul duration from the current average of three months to two weeks. This, coupled with multiple parallel operations and well-coordinated project management practices, will go a long way to reduce the time spent on planned annual inspections.

5.4 Optimising the corrective maintenance method

The corrective maintenance method can be optimised through an investment in a mobile workshop, optimising the existing infrastructure to support in-situ repairs, investment in a remote monitoring and control system to aid in fault identification and enhancing technical skills. This can also be enhanced through the rationalising of operations by promoting operator driven maintenance since operators are the first line of defence in case a maintenance need arises.

5.5 Enhancing technical capabilities through training and development

The strategic significance of key operation and maintenance persons cannot be overemphasised in the development of power plants. In the conventional approach, KenGen has always ensured that key persons are brought on board early enough to ensure they operate and maintain new and existing plants with an adequate theoretical background. Throughout the construction and functional commissioning tests, key persons are involved in witnessing and benchmarking with the experts from leading players such as the MHPS Corporation, Toshiba Corporation, Toyota Tsusho Corporation, Hyundai Engineering Co. Ltd., Sinopec, KEC, ABB and Siemens. This approach is designed and executed by the project consultant, i.e. Jacobs SKM who has acted as KenGen's representative in all phases of major geothermal projects in Olkaria, including attending Factory Acceptance Tests (FAT). This approach has ensured that the operational preparedness and subsequent takeover was smooth, with the main Olkaria plants registering consistently high availability factors in the region of 97% over the years as discussed in previous chapters.



Application of SMED to planned outage works				
Element	**External**	**Internal**	**Conversion**	**Streamlined**
Turbine rotor and casing inspection		🟥		🟩
Run out inspection		🟥		🟩
Bearings and oil system inspection		🟥		🟩
Oil condition check and repleshiment	🟦		🟦	
Alignment confirmation		🟥		🟩
Gearbox visual inspection		🟥		🟩
High speed and low speed couplings checks		🟥		
Cleaning of oil coolers & filters	🟦		🟦	
Cleaning of generator air coolers	🟦		🟦	
Dissipation factor tan-δ tests on generator,Tx and bushing		🟥		
IR-Tests on Generator, Motors, Transformers		🟥		
Sweep frequency analysis tests		🟥		
Excitation current tests		🟥		
Tx moisture analysis and dielectric breakdown		🟥		
Transformer dissolved gas analysis of oil		🟥		
Tx tans ratio tests		🟥		
Protection Relay testing		🟥		
CB Contact resistance and timing tests		🟥		
Calibration of instruments		🟥		
Visual inspection of condenser		🟥		
Visual inspection of pumps	🟦		🟦	
Inspection and cleaning of cooling tower distribution piping and nozzles	🟦		🟦	
Inspection of cooling tower drives, oil condition analysis and replenishment	🟦		🟦	
Inspection of cold end piping system	🟦		🟦	
HVAC and fire suppression system maintenance				
Compressor service	🟦		🟦	
Moisture separator checks		🟥		🟩
Silencer checks	🟦		🟦	
Hot end piping and valve components checks	🟦			🟩
Brine control valve inspection	🟦		🟦	

FIGURE 14: Summary of the application of SMED to planned overhauls and annual inspections in WHPs

When the WHP development was conceived in 2010, a similar approach was adopted, except for some variation in the structural approach. In the beginning, only a few key persons were brought on board and trained as required between 2011 and 2014, owing to the smaller size of the initial WHP project under development. As the number of units grew, more staff, both new and experienced, were taken on board and the total number has since grown to over 60 persons under the direct operation and maintenance of the Olkaria WHPs. In 2015, 21 WHP operators were trained by GEG in a geothermal course that entailed basic physics of geothermal, existing configurations and operational considerations to ensure they are able to operate the WHPs with the right theoretical background. This training aided in inducting the new operations team members into the team and went a long way to stabilize the operations challenges emanating from human error.

The maintenance team, on the other hand, has not built sufficient capability to take full control of the existing WHPs. This can be attributable to a lack of a structured training plan in the contract, the unique unprecedented challenges faced and the relatively frequent breakdowns experienced, which on some occasions present challenges in steering proactive maintenance. In fact, usually an annual inspection or corrective maintenance scenario ends up in a major overhaul which stretches the existing resources. This led the company to enter into a framework contract with GEG for technical support as a leverage to continuously build the human capacity.

5.5.1 Key training needs for effective maintenance

This investment will present an important step in building the internal capacity for executing in situ maintenance which will transform into large savings in repair costs and enhanced availability as outlined in Chapter 6 of this report. The key maintenance training needs include the following:

- Steam turbine rotor straightening and balancing, i.e. hot spotting and offset machining techniques.
- Stress relieving and heat treatment.
- Laser alignment methods.
- Maintenance planning and management.
- Rotor repairs (rebuilding of journals and surfaces, reblading), casing repairs through specialized welding, stress relieving and heat treatment.
- Advanced machining and welding methods.
- AutoCAD, finite element modelling, a solid works modelling system, 3-D modelling.
- ISO 18436-2:2003 vibration analysis training and certification level 1 and 2.
- Certified infrared thermography.
- Certified Siemens mechatronics engineer, training simulators for PLC, SCADA and DCS.
- Power systems/ protection.
- Programming and troubleshooting of the Woodward digital governing system.
- Heating, ventilation and air conditioning systems maintenance.
- Maintenance planning, work order generation and analysis.

5.6 Implementation plan

The recommended approach can be phased in a three year interval as illustrated in Figure 15. Priority can be given on peer review of the proposal, approval and rationalisation of simple maintenance processes that do not require resources. This will be followed by the acquisition of critical infrastructure,

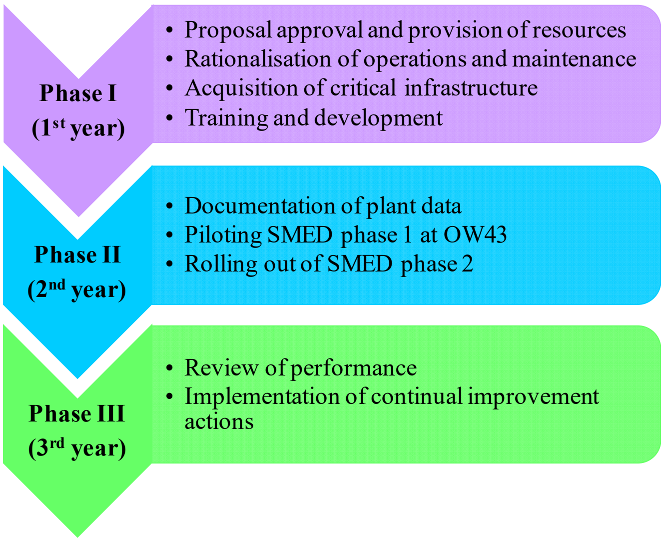


FIGURE 15: Proposed three year initial implementation plan

training and development. The second phase will entail the documentation of plant data, piloting of SMED initiatives in one WHP and the subsequent rollout of SMED in the rest of the WHPs depending on resource availability. Phase III will entail a review of performance and the implementation of continual improvement action plans.

6. COST BENEFIT ANALYSIS OF MAINTENANCE MANAGEMENT MODELS

6.1 Cost of proposed infrastructure and a pilot SMED project

Table 4 below summarises the proposed cost structure of the infrastructure, training and development needs necessary to increase the WHP uptime.

TABLE 4: Cost of proposed investment continuation

Cost analysis				
Item	**Unit of measure**	**Quantity**	**Estimated cost per unit (USD)**	**Total cost estimate (USD)**
A 3 tonne dynamic balancing machine supply, installation and training.	Lot	1	250,000	250,000
Jigs, fixtures and specialised lifting equipment.	Lot	1	100,000	100,000
Heat treatment/stress relief equipment supply, installation and training.	Lot	1	300,000	300,000
A 20 tonne mobile workshop complete with suitable machine tools and lifting equipment. Preferable set up is a containerised truck mounted workshop on a side loader complete with HIAB crane.	Lot	1	500,000	500,000
Emergency lighting tower.	Lot	1	30,000	30,000
250 kVA standby diesel generator set complete with a changeover switch.	Lot	1	70,000	70,000
Pneumatic wrenches, power tools and a portable air compressor.	Lot	1	150,000	150,000
Vibration analyser and a two year ISO level 1 training framework.	Lot	1	100,000	100,000
Portable multifunctional welding machine.	Lot	1	100,000	100,000
Ultrasonic inspection, testing equipment and training framework.	Lot	1	50,000	50,000
Thermal imaging camera and training.	Lot	1	60,000	60,000
Video Borescope Camera and training.	Lot	1	30,000	30,000
Sandblasting apparatus.	Lot	1	40,000	40,000
Special tools for maintenance.	Lot	1	150,000	150,000
General tools for maintenance.	Lot	1	100,000	100,000
A portable horizontal line boring machine and automatic welder.	Lot	1	150,000	150,000
3-D scanner, CAD modelling software and work station.	Lot	1	300,000	300,000
Dedicated emergency response pickups to support corrective maintenance.	PC	2	70,000	140,000
Portable oil purifiers.	Set	4	70,000	280,000
Training package on the mechanical, electrical and instrumentation system framework contract for the initial three years.	Lot	1	150,000	150,000
Leasing of specialised equipment, simulators and services in the initial period of knowledge harvesting and transfer framework.	Lot	1	100,000	100,000
Piloting of SMED at cooling towers through the installation of manual isolation valves on risers at the OW43 well pad.	Lot	1	150,000	150,000

TABLE 4 cont'd: Cost of proposed investment continuation

Cost analysis				
Item	**Unit of measure**	**Quantity**	**Estimated cost per unit (USD)**	**Total cost estimate (USD)**
Piloting of SMED for cooling tower drives at the OW43 well pad.	Lot	2	100,000	200,000
Piloting of SMED at oil coolers and filters at the OW43 well pad.	Lot	2	20,000	40,000
Piloting of SMED at brine control valves at the OW43 well pad.	Lot	2	100,000	200,000
Piloting of SMED modification of oil level and monitoring of cooling tower drives at the OW43 well pad.	Lot	2	100,000	200,000
Miscellaneous cost.	Lot	1	200,000	200,000
Subtotal:				**4,140,000**
Taxes (16%)			662,400	662,400
Grand total				**4,802,400**

For the economic viability analysis a number of assumptions have been made based on data applicable to Kenya and the projected period of 15 years of operation. These assumptions are summarised in Table 5.

TABLE 5: Basic assumptions

Basic assumptions	Value	Unit
Discounted interest rate based on LCOE	8	%
Operating period	15	Years
Constant load factor with other factors held constant	72	%
Increase in availability at a constant load factor of 72%	14.1	%
Feed in tariff energy charge rate	8.5	US¢/kWh
Annual O&M cost of additional infrastructure	2.4	% of initial capital cost

6.2 Net present value (NPV) determination

Considering that the availability factor (capacity) and the actual load factor are held constant, the net cost is determined as shown in Table 6.

TABLE 6: Net cost calculation

Description	Period 1	Period 2
Capacity (%)	77.7	77.7
Load factor (%)	68	58
Net Annual electrical output (GWh)	460.40	391.34
Feed in tariff energy charge rate (USD)	0.085	0.085
Net Annual Revenues (Million USD)	39.13	33.26
Increase cost per unit (US¢)	5.87	
Cost (US¢)	0.10	
Net Cost per kWh(US¢)	**5.97**	

6.3 Net Present Value (NPV) and payback period

The Net Present Value and payback period are used widely in economic decision making. When the NPV is greater than zero a decision to proceed with the investment can be arrived at informatively and the reverse is true when the NPV value is less than zero. Similarly, a sound investment has a short payback period, as the investment cost should be recouped within the service life of the project or within set targets depending on the investment objectives. NPV can be defined as the future worth of cash flow subtracted by the present worth of the investment cost (Present Value). NPV is calculated using the following formula (Jónsson, 2017).

$$Po = \frac{(Ai - Ac)}{i} \times ((1 - \left(\frac{1}{(1+i)^n}\right)) \tag{1}$$

where Po = Present value;
Ai = Annual income;
Ac = Annual cost;
i = Discounting interest rate; and
n = Operating period of equipment.

Therefore,

$$NPV = Po - IC \tag{2}$$

where Po = Present value; and
IC = Investment cost.

The payback period is defined as the length of time required to recoup the cost of an investment. It is an economic decision rule that determines whether to undertake the investment project as prolonged payback periods are typically undesirable from an investment perspective. Unlike other methods such as NPV, internal rate of return or discounted cash flow, payback period disregards the time value of money, hence it is seldom used as a final economic decision tool in isolation.

$$\text{Payback} = \frac{\text{Investment capital}}{\text{Gain in revenue}} \tag{3}$$

6.3.1 Discounted NPV calculation

The results from the NPV and payback analysis indicate that the proposed investment cost of 4.8 Million USD is viable and will be recouped in about 16 months. Table 7 shows the discounted NPV calculation for a period of 15 years while applying depreciation and applicable interest rate.

6.4 Opportunities and benefits

This investment presents benefits that can be classified as technical, economic and people-centred. Technical benefits include a direct improvement in equipment reliability, the enhanced residual life of the WHP equipment and enhanced internal capacity for leveraging. From the economic perspective, the proposed investment will inject an estimated additional revenue stream of about 5.5 million USD into the balance sheet that will enable a more stable revenue forecast for financial planning with a positive NPV. The greatest benefit will be on people by bringing more internal expertise, enhanced workplace safety, enhanced motivation, professional development and numerous opportunities for consultancy locally and regionally, which fits well with KenGen's revamped Good to Great (G2G) transformation journey.

TABLE 7: NPV and payback calculation

Period (year)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Revenues (Million USD)	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87	5.87
O&M Cost (Million USD)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)	(0.24)
Depreciation (at 32% rate)	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Revenues (Million USD)	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95
Interest	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Revenues (Million USD)	5.35	5.39	5.43	5.47	5.51	5.55	5.59	5.63	5.67	5.71	5.75	5.79	5.83	5.87	5.87
Revenues (Million USD)	3.74	3.77	3.80	3.83	3.86	3.88	3.91	3.94	3.97	4.00	4.03	4.05	4.08	4.11	4.14
Revenues (Million USD)	3.74	1.06													
Net Revenues (Million USD)															(4.80)
Payback period in years															1.28
NPV															$26.48

7. CONCLUSION AND RECOMMENDATIONS

An assessment of the current WHP operation and maintenance practices presents numerous opportunities for improvement with regards to bridging the technical skills gap, and improving equipment, software and infrastructure to support classical and modern maintenance methods. The management of these methods is crucial since the WHPs are unique in design and technological maturity and are vulnerable to increased probability of failure in comparison to conventional geothermal power plants. A benchmark study of ON Power geothermal plants in Iceland reveals that the world class performance attained over the years has been realised through sustained efforts in continually improving management approaches, a prudent investment in internal in-situ repairs, a collaborative partnership with local and international players to ensure professionalism and expert input, bringing in skilled personnel tapped from the marine engineering market into the operation and maintenance team and adequate spares planning and stocking. Additionally an effective root-cause analysis has catapulted Icelandic geothermal power plants to an elite group that has strived towards the elusive league of reliability centred maintenance. The study, therefore, puts impetus on the benefits of the proposed strategies to ensure optimal machine uptime. It is therefore recommended that the proposed infrastructure and training be implemented in order to create the necessary resources to support the WHP maintenance.

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