KenGen’s Successful Implementation of a Modular Geothermal Wellhead Strategy

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ABSTRACT

Facing a delay in the construction of conventional large-scale geothermal plants after drilling was completed, and the availability of steam was confirmed, Kenya Electricity Generating Company (KenGen) started the evaluation of using wellhead technology for earlier power generation in the mid 1990s.

A feasibility study on Geothermal Wellhead Generation in Kenya was finalized in 2001 by then Sinclair Knight Merz (SKM). The study confirmed the possibility for KenGen to recoup the drilling investment cost and provide much required energy to spur economic growth.

Following a competitive bid, KenGen and Green Energy Group (now Green Energy Geothermal, UK) signed a collaboration agreement on the design, installation and commissioning of a 5 MW geothermal wellhead pilot plant in late 2009. The plant successfully completed an 18-months reliability run in 2013.

In May 2010, a new contract was signed between KenGen and GEG on the delivery of 14 additional modular geothermal wellhead plants. With the experience from the pilot plant, the partners continued to improve the design of the plants and in June 2016, the contract was fulfilled with the successful start of the last of the 15 geothermal wellhead plants built by GEG.

As of today, the overall installed power generation capacity from modular geothermal wellhead power plants of KenGen is 81 MW, representing about 12 percent of overall installed geothermal power generation capacity in Kenya.
With annual revenues from electricity sales of USD37 million (KSh 3.7 billion), the modular geothermal wellhead plants of KenGen represent a significant part in the success for geothermal development in Kenya.

The successful implementation of a strategy utilizing a modular geothermal wellhead approach has been widely recognized internationally. With an increasing demand to speed up geothermal development utilizing smaller and modular geothermal wellhead plants is appealing to developers, investors and governments. Furthermore, this approach allows for a staged development making financing easier to obtain and the projects more attractive to investors.

1. Introduction

In the mid-1990s, KenGen’s Geothermal Development Department prepared an internal report on early power generation using geothermal wellhead technology. Facing delays in the construction of conventional large-scale geothermal power plants after drilling was completed and steam availability was confirmed, KenGen looked at ways to utilize drilled wells and generate power earlier.

KenGen engaged Sinclair Knight Merz (SKM, now Jacobs) to carry out a feasibility study on Geothermal Wellhead Generation in Kenya. The main objective of the study was to establish the technical feasibility, economic and financial viability of wellhead generation for a range of plant configurations and make recommendations for their implementation. The final report was delivered in May 2001.

The scope of the study looked at various types of power plants and economic analysis of each option, considering a nominal net (delivered) power output of 5 MWe and 10 MWe, and turbine inlet pressures of 5 Bar_a and 12 Bar_a. While the initial findings were considered not sufficient to pursue a wellhead approach, KenGen continued facing a delay in financing of conventional plants and decided in 2009 to launch a competitive bidding for a 5 MWe condensing turbine at well OW37A as a research and development project. Overall, this started the implementation of the strategy to utilize geothermal wellhead plants in the development of geothermal power generation capacity by KenGen at Olkaria.

2. Implementation of the KenGen geothermal wellhead plants

With the tender for the 5 MWe pilot plant, the competitive bidding resulted in a collaboration agreement between KenGen and Green Energy Group AS (now Green Energy Geothermal, UK) that was signed on 31st December 2009, under which GEG was to design, install and commission of a 2 x 2.75 MW pilot plant on well-pad OW 37 in Olkaria. The KenGen scope of works included the provision of Civil Works and power evacuation.

Following significant challenges with the first installed turbine, a new turbine manufacturer was chosen and GEG undertook the civil works, while KenGen provided an evacuation line. With continuous issues of unstable power connection, Kenya Power and Light Company (KPLC)
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constructed a stable 30 km long 33 kV line to Naivasha Substation and the plant was successfully commissioned.

After a successful 18 months’ reliability run of the 5 MWe pilot plant by GEG, KenGen decided for an additional 14 geothermal wellhead plants to be built.

Initial challenges with the pilot plant and its limited mobility provided some valuable lessons. The overall design builds upon a standardized design of the plant and its components, while the design of three inlet pressure ranges with turbines possessing flat efficiency curves provides the possibility for a customization of the plants to specific well characteristics. This resulted in a planned increased installed capacity to 75.6 MWe.

The main contract was amended in September 2012, which provided an installation of 4x 6.4 MWe (C64) model and 10x 5 MWe (C50) model units. The project was to be implemented in three (3) packages: Package I – four (4) C64 plants of each 2x 3.2 MWe units, Package II – five (5) C50 plants of each 5 MWe, and Package III – five (5) C50 plants of each 5 MWe.

Today, the 5 MWe pilot plant and the additional 14 wellhead plants built by GEG prove the strategic value of wellhead power plant technology on speeding up development and early revenue generation from drilled geothermal wells.

The last of the wellhead plants went online in September 2016 and was officially inaugurated by Kenya’s President Uhuru Kenyatta in a ceremony in May 2017.

Table 1. Overview of Geothermal Wellhead Plants of KenGen at Olkaria

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location/ wellpad</th>
<th>Nameplate capacity (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLK01</td>
<td>WH-37A</td>
<td>5.0</td>
</tr>
<tr>
<td>OLK02</td>
<td>WH-37A</td>
<td>6.4</td>
</tr>
<tr>
<td>OLK03</td>
<td>WH-43A</td>
<td>6.4</td>
</tr>
<tr>
<td>OLK04</td>
<td>WH-914A</td>
<td>6.4</td>
</tr>
<tr>
<td>OLK05</td>
<td>WH-914B</td>
<td>6.4</td>
</tr>
<tr>
<td>OLK06</td>
<td>WH-914</td>
<td>5.0</td>
</tr>
<tr>
<td>OLK07</td>
<td>WH-914</td>
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<td>OLK12</td>
<td>WH-37</td>
<td>5.0</td>
</tr>
<tr>
<td>OLK13</td>
<td>WH-37B</td>
<td>5.0</td>
</tr>
<tr>
<td>OLK14</td>
<td>WH-905</td>
<td>5.0</td>
</tr>
<tr>
<td>OLK15</td>
<td>WH-39</td>
<td>5.0</td>
</tr>
</tbody>
</table>
3. The Technology of the GEG Wellhead Plants

The geothermal wellhead power plants designed, delivered and built by GEG for KenGen at Olkaria in Kenya, are modular-type single flash condensing power plants. The plants, delivered on a turn-key basis, consist of four main systems:

1. Steam System (Hot End)
2. Turbine & Generator System
3. Condensing System (Cold End)
4. Electrical & Control System
The sequence of the plant key processes is as follows:

Well fluid is discharged from the well and supplied into the steam separator/demister system (2), the system separates liquid, droplets or mist from the steam to a certain dryness fraction before it is led via short pipeline to the turbine (3) where it expands resulting in rotation of the turbine rotor which is connected to the generator (8) via gearbox.

A crossover carries the spent steam from the turbine exhaust to a direct contact condenser (4) where the steam is condensed by spraying cooling water from the cooling towers into the steam. Non-condensable gases are cooled down in the condenser before being extracted with a two-stage steam ejection system.

The condensed steam/cooling water mixture is then pumped from the condenser (4) in to the cooling towers (5) where it is cooled down and recycled through the cooling circuit.

![Figure 3. The Main Components of the Wellhead Condensing Power Plant](image)

The plant is semi-automatic in the sense that it requires manual start-up after a cold or hot/restart. Shut-down is automatic through a stop command in the governor system or due to any pre-programmed trip parameter/function.

The plant is controlled and monitored via PLC (Process Logic Controller) systems, made visible to the operator through a SCADA (Supervisory Control and Data Acquisition) interface screen located in the Electrical Control Unit (ECU) (6).

The SCADA/PLC systems, besides monitoring current plant condition, also provides data logging and plant process controls and reactions/alarms when measurements deviate from set-points.
3.1 Steam System

The plant’s steam system is a three-stage separation system split up in four principal component categories:

- The two-phase pipelines
- Integrated separator/demister.
- Brine pipelines.
- Controls and emergency pressure relief devices including a silencer/stack.

The system separates brine, droplets and mist from the process fluid providing saturated steam to the turbine at required dryness fraction.

The steam pipeline carries steam from the steam separation system to the turbine and the gas extraction system. The brine pipeline carries the brine (which has been separated from the steam in the steam separation system) from the steam separation system to a re-injection system or to the stack/silencer where it is flashed to atmospheric pressure.

The system is provided with a silencer/stack which has the main function of reducing noise levels during brine discharge and during the emergency bypass of steam supply. Its secondary function is to serve as a sump to cool the brine and reduce its pressure to atmospheric pressure prior to discharge to drains.

3.2 Turbine Generator

The geothermal steam turbine is supplied complete on a skid with a gland sealing system, steam drain system, lubrication system, control valves, emergency stop valves, and both mechanical and electrical protection systems. The GEG scope also includes a mechanical transfer gearbox on
an integrated skid/oil reservoir for turbine to generator transfer, complete with a shared lubrication system, protection system and barring gear assembly with motor. The turbine design is adapted to geothermal conditions with efficient condensate drainage and industry proven material selection. The standard turbine models provide for three inlet pressure ranges, covering inlet pressure to turbine from 4 bar to 15 bar. The rated output range of the turbine models is from 3 MWe up to 10 MWe.

The generator comes complete and suited for use in a geothermal environment with an AVR system, synchronising system, excitation system and protection system.

3.3 Condensing System

The GEG scope includes a direct contact condenser which produces vacuum by two effects, the gas extraction system and the cooling water. As cold water condenses the hot steam, the steam reduces in volume and by that effect a vacuum is sustained within the condenser.

A two-stage steam ejector system extracts non-condensable gases (NCG) from the geothermal steam entering the condenser. The extraction system consists of two steam ejectors, inter-condenser, a silencer and related piping and supports.

The cooling water is pumped to the forced draft cooling towers where it is distributed evenly and cooled. After passing through the cooling towers, the water is collected in a large sump from which the condenser draws cooling water via pressure difference. This circulation is maintained by a hot-well pump which pumps the heated cooling water & condensate from the condenser hot well to the cooling tower for cooling. The condensed steam provides for the make-up water for the cooling circuit, thus chemical dosing to maintain pH levels is required.

The sump also provides cooling water for the auxiliary pump which pumps water to cool the generator and the oil coolers for the turbine. It also supplies cooling water to the inter-condenser in the gas extraction system.

3.4 Electrical Control System

The main parts of the control system are designed to fit into a 40ft container, that serves as the Electrical Control Unit (ECU) for the plant. The electrical control system design is based on IEC and European standardisation using harmonized standards for relevant directives where applicable. An auxiliary transformer for the plant own electrical appliances is installed in the open end of the ECU.

The ECU is fitted with two (2) separate active carbon filter systems for H2S filtration and as well with a dedicated fire alarm system including sensors, manual release provisions and alarm annunciation.

The ECU contains an AC Distribution system consisting of a Main AC distribution panel and a Motor Control Centre (MCC).

The ECU is fitted with a compact medium voltage gas insulated switchgear, including generator breakers, feeder breaker and transformer breaker. Both the generator breakers and the feeder
breaker are suitable for synchronization to the power grid. The feeder breaker is controlled by a line protection relay.

**Plant Control System**

The plant is controlled by the means of Programmable Logic Controller (PLC) and has a human machine interface (HMI) via touch panel. All control, monitoring and historical logging of the plant can be accessed through the HMI. All supplied equipment including a plant control system, protection relays, governor, excitation system, vibration monitoring system and metering devices are supplied configured and programmed as a standard turn-key solution.

**Turbine Control and Protection System**

The control and protection equipment for the turbine is installed in a dedicated panel including a vibration monitoring system and the turbine governor. Both systems are connected to the PLC system by a communication bus for monitoring and control. All signals used for tripping the turbine under ab-normal operating conditions are hardwired to the system.

**Generator Control and Protection System**

The control and protection equipment for the generator is installed in its dedicated panel including the generator protection relay, synchronizer, metering and excitation control system. All the systems are connected to the PLC system by a communication bus for monitoring and control purposes. Signals used for tripping the generator circuit breaker and/or excitation system under ab-normal operating conditions are hardwired to the systems. Provisions for testing of the instrumentation transformers are located in the generator control & protection panel.

![Figure 5. Two of GEG’s C64 geothermal wellhead plants, Olkaria, Kenya](image-url)
4. Challenges, solutions and lessons learned

The implementation of a wellhead power plant approach has not been without challenges. Here below challenges and the approach to solve them are described, as well as some specific lessons learnt.

4.1 General Challenges

The pilot plant did not deliver on the expected mobility, which required improvements on the overall design and a redesign of specific components of the wellhead plants. To allow for mobility, most of the plant’s systems have been containerized. This included the electronic control system, and the step-up substations with an 8 MVA transformer. The cooling tower was divided into individual cells which were placed on movable pre-cast foundations. The turbine-generator foundation was cast in two sections and most of the wiring of the plant is above ground.

KenGen did not have sufficient capacity to implement the required civil works, which affected the delivery schedule for the plant. In the end GEG, as contractor, carried out the required civil works pushing responsibility on schedule and quality on the contractor.

With the small-scale geothermal wellhead plants, each of them required 33/11 kV step-up transformers with associated switchgear. The Plant Control System required an integration of the substations. In the end, KenGen signed a substation works supply contract with GEG on the delivery of 14 substation units. Due to an inadequate 33 kV evacuation system, only four were supplied and the contract amended to supply a 220/11 kV substation and a 132/11 kV substation.

Another challenge were the evacuation lines and the connection to the nearest national grid via a 33 kV network, which turned out not to be adequate in absorbing the power generated by the wellhead plants. This required an update of the 33 kV line to a 220 kV line to the Olkaria IV 220 kV substation and a 132 kV line to the 132 kV substation at Olkaria I.

The allocation of wells to the wellhead plants was delayed due to a prioritization of the 280 MWe plant development by KenGen. But due to the standardization of the plants, several well options became available and plants were concentrated around high voltage step-up substation with short 11 kV evacuation lines.

Initially a re-injection system was not incorporated into the design, given the scattered location of plants in the Olkaria East and Domes fields. But with more plants having been installed on one well pad, e.g. five (5) plants on well pad OW914, three (3) plants on pad OW37, two (2) plants on pad OW915 and two (2) plants on pad OW43, this allowed for a connection to the nearest re-injection system.

4.2 Power Evacuation Challenges

Due to the constraint on the 33 kV network, only 17 MWe of the 80 MWe could be evacuated by existing transmission lines. This required construction of new high voltage substations and transmission lines. Most of the initial plants were ready to go to commercial operation while step-up substations were under construction.
To evacuate the completed plants, more than 20 km of existing 33 kV lines were up-rated to allow temporary evacuation. This enabled 6 months of partial evacuation of the five (5) plants on well pad OW914. The long lead time to supply the substation transformers was a major hindrance and a solution was required.

**OW914 220/11 kV 80 MVA Substation**

The total installed capacity at OW914 is 47.6 MWe with plants situated as follows; five (5) plants at OW914, two (2) plants at OW915, one (1) plant at OW919 and one (1) plant OW905. This is more than power generated from Olkaria I power station. In order to evacuate this power, a 220/11 kV substation was designed and constructed by GEG and 4 km of 220 kV transmission line constructed by KEC International of India to Olkaria IV 220 kV substation.

KenGen in house Technical Services provided and installed a refurbished 87 MVA old transformer from Kiambere Power Station. This allowed full power evacuation of all the plants installed at Olkaria Domes. The substation is capable of evacuating remaining 15 MWe of wellheads.

**OW37 132/11kV Substation**

All the wells in Olkaria Domes were prioritized for the 140 MWe Olkaria V power plant, thus requiring the last three plants to be re-allocated to newly drilled wells at OW37 and OW39. This required a new substation and transmission line. The total installed capacity at OW37 well pad is 15.5 MWe, including the pilot plant and 5 MWe at well pad OW39. In order to evacuate this power, an 132/11 kV was designed and constructed by GEG and 2km 132 kV transmission line constructed by Telco MacNaught JV to Olkaria I 132 kV substation.

KenGen’s in-house Technical Services provided and installed a new 45 MVA transformer, which had been procured for Olkaria I power station. This allowed full power evacuation of all the plants installed at Olkaria North East. Only 12.6 MWe of Wellhead generation is evacuated via 33 kV line to Naivasha KPLC substation.

**4.3 Lessons learned**

The challenges faced in the development of the first and corresponding further development of geothermal wellhead plants, provided an opportunity to learn.

Among the lessons learned were that new innovations should be embraced, despite challenges and initial failures. Most of the time, the first attempt might not work, as the pilot project showed when the first turbine failed.

Another crucial lesson learnt for KenGen was the required teamwork, with each team player playing his or her role effectively, teamwork is key to success.

GEG provided KenGen with comprehensive training of operational and maintenance staff and provided technical support during the initial operation period. The importance of these services can’t be overemphasized as they have proven to be extremely valuable for consistent operation of the plants.
Throughout the years, KenGen has built up sufficient capacity to carry out the supervision of the construction of geothermal power plants.

Planning development based on available power lines for temporary evacuation helped KenGen to improve revenue from power generated by wellhead plants during the construction of the step-up stations.

Through its development activities, KenGen gained extensive geothermal knowledge, and this should be utilized to realize more innovative projects. If early wellhead generation would have been implemented in the 1990s, idle steam would have been a thing of the past.

Figure 6. Inside of GEG’s containerized Electronic Control Unit
5. Operational performance/ project cost vs revenue

In its financial overview, KenGen gives the total project cost, excluding the cost for drilling the wells used, at KSh 13 billion, at an exchange rate of 1 USD = 100 KSh.

The initially planned capacity foresaw an additional 5.6 MWe installed capacity. With less steam available for the plants KWG8 (OLK08) and KWG15 (OLK15), plans had to be adapted. The feed-in-tariff for the plants is USD 0.088/ kWh and the steam charge rate is USD 0.030/ kWh.

Under these assumption, the projected annual revenue from the 14 geothermal wellhead plants is approximately KSh 2.6 billion, and around KSh 907 million will cover payments to Geothermal Development Company (GDC) and cover drilling costs.

Based on the projected revenues, as outlined in above, KenGen will be able to recoup KSh 13 billion of the project cost for the wellhead plants, including the costs for the pilot plant within five (5) years of the start of operation.

6. The role of wellhead power plants and an outlook

With the positive experience of implementing a modular geothermal wellhead strategy by KenGen, the question is if and how this will affect further development in Kenya and beyond.

The approach for small-scale wellhead plants always compares to conventional large-scale development and one of the key assumption has been “that larger equipment is less expensive
(per MW) and more efficient.” (Gudmundsson, et al.) The experience in the KenGen context has though shown that wellhead power plants are being offered at a similar capital cost per MW, as traditional large-scale geothermal power plants.

While there are arguments of lower efficiency and more steam consumption from small-scale wellhead plants compared to conventional large-scale installations, wellhead power plants provide the option to utilize each individual well, at its own specific optimal pressure and “none will be unusable due to low closing pressure.” This allows a better output for the geothermal field being tapped and “counter act to the lower efficiency resulting from using smaller equipment.” (Gudmundsson, et al.).

Furthermore, losses in SAGS and throttling down of high pressure wells to a common lower pressure system of the large-scale installations, benefits the comparative feasibility of the well head approach.

Well characteristics of a field thus dictates the feasibility of a wellhead power plant solution compared to a conventional large-scale set-up.

The other question on wellhead plants is, if they should be set up as a permanent or a mobile solution. This has been discussed in the context of the KenGen wellhead strategy, and while a mobile solution was preferred in the design and set-up, the plants could also remain permanently on the position, with a certain flexibility should well output change, or the well to be used for a larger-scale plant in the future. The opinion is that permanent wellhead power plants should be considered in the overall feasibility of a larger conventional plant and not as stand-alone projects. (Gudmundsson, et al.) In the end this is an economic decision after an evaluation of the feasibility of either a stand-alone solution, or a combination of a conventional plant and one or more wellhead plants.

With the experience of the Olkaria wellhead plants by GEG, a certain mobility of the plants provides an option to dismantle and relocate the plants to another well, but does not exclude a permanent operation on the original well pad.

By far the largest argument though for the deployment of geothermal wellhead power plants is the speed of development offered over conventional large-scale development. While in a traditional large-scale project, a large number of wells need to be drilled before a power plant can be designed and built. This requires an extensive up-front investment, which also takes time and effort to secure. The high-cost of drilling and the long-time from when the first well is drilled until a power plant is commissioned and provides revenues from electricity sales, is therefore a large burden on developers. Smaller-scale wellhead power plants, built immediately after a well has been drilled, can start power production and generate revenues much earlier. For investors, this represents a strong incentive and helps the developer to secure funding for the further build-out of the geothermal field.

In a feasibility study for Kenya’s Geothermal Development Company, it was evaluated if portable wellhead power plants could accelerate the development of green field geothermal projects in Kenya, based on a case study of the Menengai geothermal field. The study “demonstrated that the use of wellhead power plants early in the development of geothermal resources was economical.” (Kiptanui, et al.) The deployment of a 5 MW wellhead power plant,
in this case study, increases the net present value (NPV). Furthermore, the time difference of more than 24 months between the drilling of production wells and the construction of the conventional large-scale and central power plant make the application of wellhead power plants a very attractive option. With annual net revenue of around USD 7 million, the plant can be help pay off investment much faster. (Kiptanui, et al.)

But in the context of development with wellhead plants, the option of a staged approach by smaller-sized plants provides the opportunity to reduce development uncertainty and risk by allowing time to confirm the performance of the reservoir before increasing the production demand on the reservoir. The second stage then becomes a “brownfield” development, as distinct to the “greenfield” nature of the first stage. (ARUP)

The investment risk is further reduced by packaging investment into smaller bundles as opposed to a single large investment to complete the installation of the entire well field and plant construction. (ARUP)

The overall capital expenditure associated with the steamfield above ground system (SAGS) can also be significantly reduced (ARUP)

In countries, such as Indonesia, there are also a rather large number of wells drilled that were initially planned to feed conventional large-scale development that though never happened and are therefore idle. A small-scale wellhead power plant application would allow to utilise these idle wells for power generation, benefiting the local population, businesses and feed overall energy demand.

In the context of national energy policy level, geothermal wellhead power plants help to feed electricity into the national grid and to the general public much earlier, thereby helping to meet an increasing demand for power and lower electricity prices.

Wellhead power plants have though yet another important advantage. The overall impact on the environment is much less than for the large-scale projects, due to less infrastructure requirement and less land use. Smaller plants simply allow for a better fit into the natural environment, than large-scale plants with their extensive infrastructure elements, such as steam gathering systems, roads etc.

The successful implementation of a modular geothermal wellhead power plant strategy in Kenya has created a strong interest in wellhead power generation. The authors are seeing an increased interest in wellhead power plant technology for speeding up development of geothermal resources, e.g. in Southeast Asia, Latin America and further development in Africa. So, while wellhead power plants are not going to replace conventional development, they help to speed up development and provide a rather attractive modular approach to developing geothermal resources.
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