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Theistareykir Geothermal Power Plant, Description of the Steam Supply System: Design, Operation and Experience Gained

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ABSTRACT

The steam supply for Theistareykir Geothermal Power Plant is a single flash cycle providing steam for 2x45 MW_e turbine units whereas the separated water is mixed with steam condensate from the units and reinjected. The steam supply has been in operation from end of 2016. This paper describes the design and layout of the steam supply, the characteristics of the steam wells, operation and control strategy of the steam supply and its ability to cope with variable load. Furthermore, the paper will report on the experience gained from mixing steam condensate with the separated water, the effect of condensate mixing on the permeability of the reinjection wells and operational history for the first years of operation.

The steam supply system comprised of the steam wells, steam pipelines, steam gathering pipelines, steam separators, main steam pipelines, steam control valves, mist eliminators, reinjection pipeline, condensate mixing system and reinjection wells. The steam wells are located on five drilling areas from where most of the wells are directionally drilled. The average length of the wells is 2 500 m and their vertical depth ranges from 1 800 – 2 400 meters, each well producing steam in the range equivalent to 5-21 MW_e of electrical power. In the operation of the wells, some of the wells have been shown to have fluctuation in the output and some decline has been noted.

The operation of the steam supply must facilitate the operation of the units at variable load and handle abrupt changes in the power output of the turbine/generator units without any delay in the operation of the units due to instability or transient behavior of the steam supply system. The paper describes some the events that can occur and how the steam supply system is able to robustly negate these events.

The separated water from the steam separators is reinjected into wells at a depth of approximately 400 meters at the boundary of the geothermal field. To increase the permeability of the wells and reduce scaling, the geothermal water from the steam separators is mixed with condensate from the condensers of the turbines to cool and dilute the water. The experience of condensate mixing has shown large increase in the permeability of the reinjection wells without any adverse effects after about 2 years of operation.

1. INTRODUCTION

The geothermal area at Theistareykir in north east of Iceland has great potential for geothermal utilization, with an estimated capacity of up to 200 MW_e. The Theistareykir geothermal field is a part of the north-east highlands of Iceland. The area is located in a rural area, 27 km south of town of Húsavík and some 25 km north of Lake Mývatn, at an elevation of 330 m above sea level, see figure 1. Theistareykir area is a green field area which had mainly been used by local farmers up until this point. The geothermal area at Theistareykir is registered in the Icelandic Nature Conservation Register as the fumaroles located there are very active. Stóravítishraun lava field is approximately 525 km^2 runs through the area. The area is considered to be of historical relevance with over 50 registered heritage sites. Theistareykir area is a green field area which had mainly been used by local farmers up until this point. The area is uninhabited but has a ramblers' hut and is still used as a grazing common for 5,000 sheep every summer.

Exploration of the area started as early as in the nineteen-seventies. Preparation work and research on the sustainable utilization of geothermal energy at Theistareykir began in 1999 by an association founded by local municipalities and regional utility companies, later merged into the National Power Company of Iceland, Landsvirkjun. In addition to planning, licensing and environmental impact assessment, the first 15 years were used for explorational drilling to confirm potential steam availability, stakeholder management, with consultation to land owners and users of the planned construction area as well as a definition of vegetation reclamation program. In 2010 the Environmental Impact Assessment was published and preparation works in the area started 2012.

Exploration drilling started in 2002 and by the year 2008, six exploration wells had been drilled at the Theistareykir area. The first phase of exploration drilling in the Theistareykir area confirmed that the area has great potential for electrical production using conventional methods (Gautason et al 2010). The results provided confidence for decision of starting construction of 90 MW_e power plant at the Theistareykir site. Research drilling and planning continued over the next years and in the beginning of 2013 nine exploration wells had been drilled. At project launching in April 2015 the nine steam wells had been confirmed with total of 58 MW_e capacity for electrical production. From spring 2016 until fall 2017 eight additional boreholes were drilled at Theistareykir, raising the total capacity of electrical production to estimated 105 MW_e. Theistareykir Geothermal Power Plant was taken in full operation in April 2018. The power plant has two 45 MW_e turbine/generator units and utilizes steam from single flashed geothermal fluid. The construction of the power plant was carried out from spring 2015 and late 2017 the first 45 MW_e production started followed by additional 45 MW_e in spring of 2018.

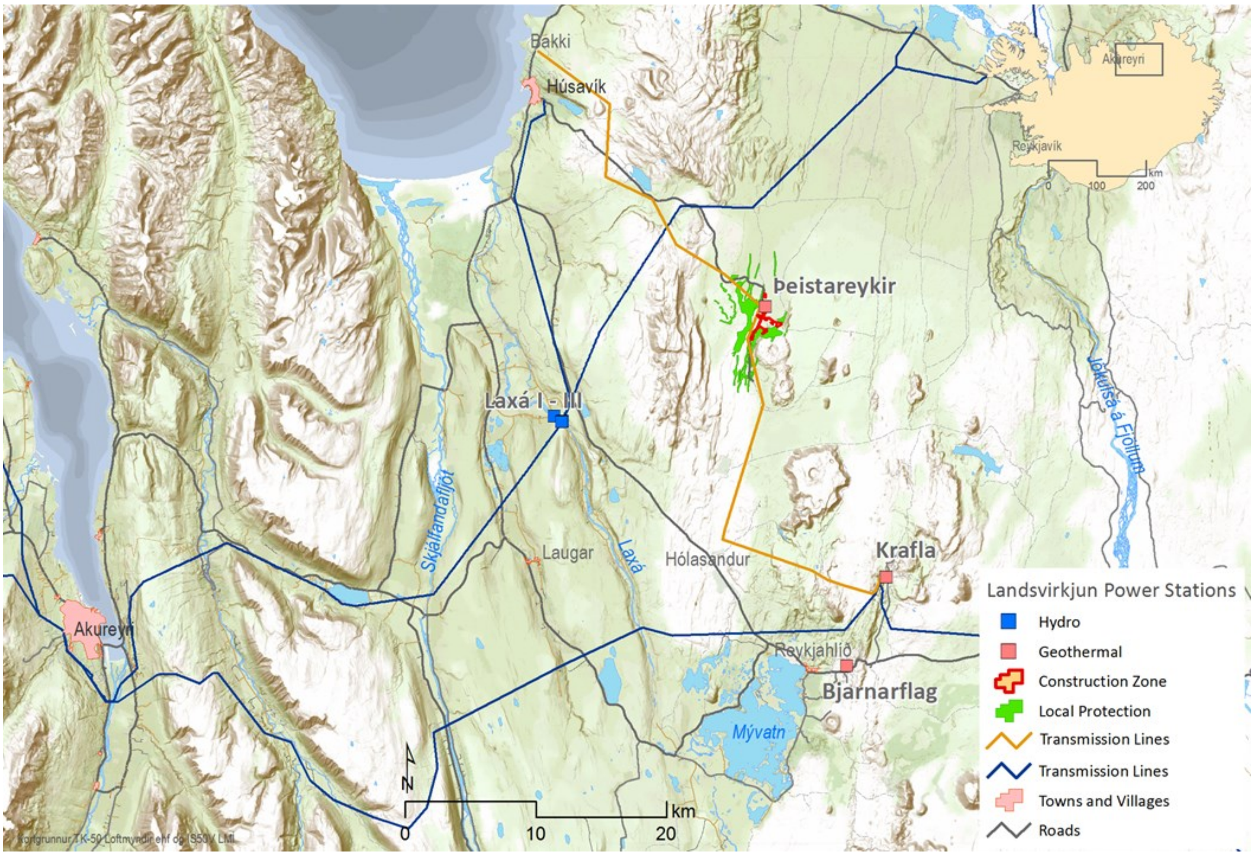


Figure 1: Overview of the NE Iceland, showing the location of the Theistareykir Geothermal Power Plant.

This paper will provide an overview of Theistareykir Power Plant and describe in detail the design of the steam supply. The paper will also describe tests that have been done, the response of the plant to various incidents and results of first inspection of the steam supply system.

2. PLANT OVERVIEW

Theistareykir Geothermal Power Plant is comprised of following main systems: steam supply, turbine/generator units including the cold end (i.e. condenser, gas extraction systems, cooling water circuit), cold water supply and instrument air supply, see Figure 2. All main equipment is located indoors due to local weather conditions as heavy snow and winds can be expected. The power house contains the turbine/generator units, the cold end equipment, transformers, along with electrical distribution, and instrument air supply, as well as a workshop and other facilities for operation and maintenance of the plant. There are two buildings in the steam supply to house equipment, the steam valve house and the reinjection house. Finally, there are two buildings for the water supply.

The turbine/generator units consist of single flow turbine of the axial exhaust type, generator and terminal equipment, condenser, gas extraction system and cooling water circuit with wet cooling tower. The design, manufacturing, installation and commissioning was done by the consortium of Fuji Electric and Balcke-Dürr. All equipment of the turbine/generator unit, except for the cooling tower, are located within the turbine hall of the powerhouse, see Figure 3.

The turbine design is single cylinder condensing with twelve reaction type stages. The turbines have a rated output of 45 MW_e each and maximum output of 47.25 MW_e. The design inlet pressure of the turbine is 9.0 bar_a and condensing pressure 0.08 bar_a, allowable inlet pressure range is 6.5 to 10.5 bar_a. The generator is directly shaft coupled to the turbine. The generator is rated 50 MVA, at 11 kV and 50 Hz. The excitation system is a brushless type.

The condenser is of shell and tube type. The steam condensate in the condenser is pumped out to the condensate circuit from where the condensate is led to booster pumps that pump the condensate to the reinjection pipeline in the steam supply where it is mixed with the geothermal water. The condensate can also be used as make-up water in the cooling water circuit

The cooling water circuit is used for the condenser, oil and generator coolers, the intercondenser of the gas extraction system and the gland steam condenser. The cooling tower is of the mechanical induced draught wet type and counter flow. The cooling towers consists of three cells, each with two-speed fan. The make-up water for the cooling water circuit is mainly with cold water from the water supply but condensate from the condenser is also being used.

The gas extraction system extracts the non-condensable gases from the condensers and consist of four identical systems. The system is hybrid, where the first step is by steam ejector with intercondenser and the second step is with a liquid ring vacuum pump. The total capacity of the gas extraction system is for gas content 0.6% by mass of the steam.

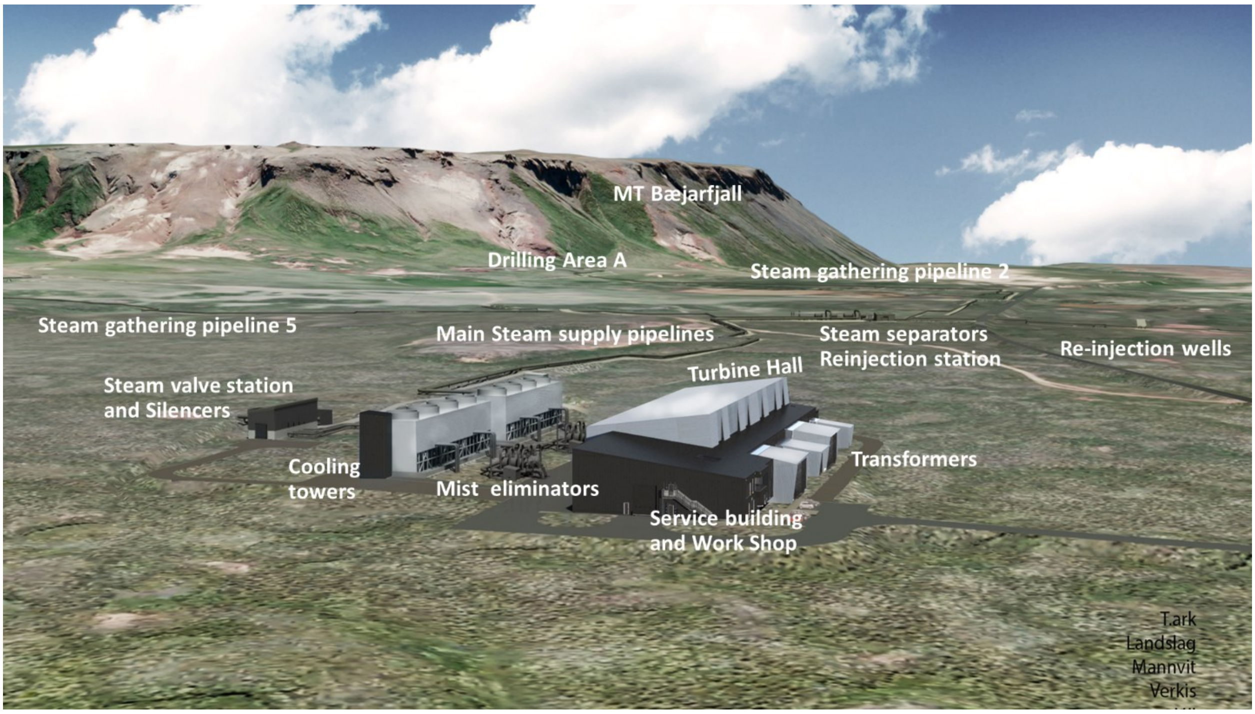


Figure 2: Overview of the power plant, showing the powerhouse, consisting of turbine hall, service building and workshop, cooling towers and buildings and equipment of the steam supply.

Figure 3: Turbine/generator units. Unit 2 in the foreground and unit 1 in the background.

The plant has its own ground water supply, located approximately 5 km from the power house, providing 8°C water. The current capacity of the water supply is 240 l/s but the pipeline allows for increase up to 370 l/s with additional pumps. The main usage of the water is make-up water for the cooling water circuits of turbine/generator units, but it also provides direct cooling water for the transformers, compressors for instrument air and seal water of the liquid ring vacuum pumps in the gas extraction system, as well as HVAC systems.

As a backup, a secondary water supply is located close by the powerhouse. The water supply was used during construction period, mainly to provide drilling water. The close vicinity to the geothermal field results in that the water temperature is around 26°C which limits its use as cooling water for direct cooling, but tests have shown that the units are able to operate with the backup water.

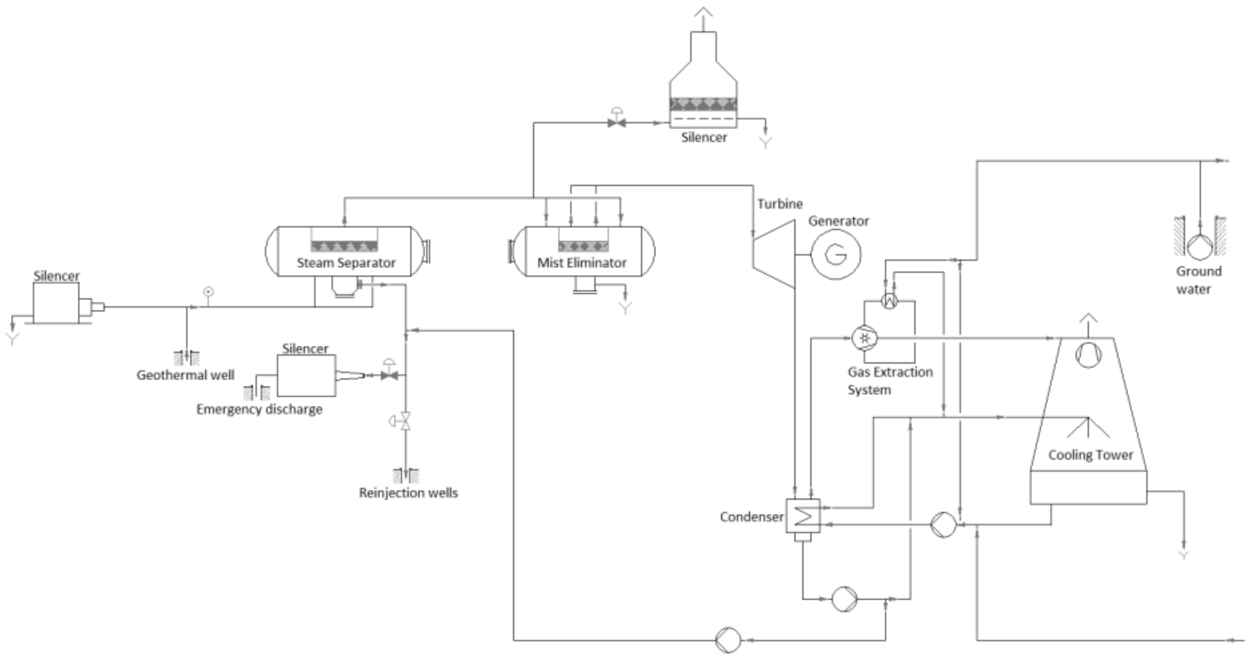


Figure 4: Simplified Process Flow Diagram of the plant.

3. STEAM SUPPLY

The steam supply is comprised of the steam wells, steam gathering pipelines, steam separators, steam pipelines, steam control valves, mist eliminators, reinjection pipeline and reinjection wells. Figure 4 shows a simplified process flow diagram of the plant. The two-phase fluid from the wells is piped to two steam separators, one for each turbine, where the steam is separated from the water. The steam is piped to the powerhouse area and through mist eliminators to the turbines. Steam control valves, located in the steam valve station, are connected to the steam pipelines and vent the steam to steam silencers. The water from the steam separators is reinjected into wells at a depth of approximately 400 meters at the boundary of the geothermal field. To increase the permeability of the wells and reduce scaling, the geothermal water from the steam separators is mixed with condensate from the condensers of the turbines to cool and dilute the water. An emergency discharge for the separated water is connected to the reinjection line next to the reinjection wells.

3.1. Steam wells

The steam wells are located on five drilling areas from where most of the wells are directionally drilled, a total of 17 wells (excluding well ThG-08). Each drilling area has a set of silencers that connect to the wells with underground pipelines for direct exhaust from the wells, see Figure 6. The average length of the wells is 2 500 m and their vertical depth ranges from 1 800 – 2 400 meters. The estimated power capacity of all drilled wells is 105 MW_e. There are currently 13 geothermal wells connected to the steam supply and 10 in use, each well producing steam equivalent to 5-21 MW_e of electrical power. The gas content of the steam is 0.21% by mass.

Exploration drilling started in 2002 with the completion of well ThG-01, a vertical well reaching 1953 m below the surface. By the year 2008 six exploration wells had been drilled at the Theistareykir area. The exploration wells provided data from a ~4 to 5 km3 volume of the geothermal reservoir. To date the highest bedrock temperatures recorded in the area close to 380°C. This is one of the highest temperatures recorded in a production well in Iceland so far. Research drilling and planning continued over the next years. In the beginning of 2013 nine exploration wells had been drilled. At project launching in April 2015 nine steam wells with total of 58 MW_e confirmed capacity had been drilled.

From spring 2016 until fall 2017 eight additional wells were drilled at Theistareykir, ThG-11 to Thg-18. These new wells are all directionally drilled. They are around 2500 m long and reach around 2000 m in depth. The wells have steel casing down two 800-1000 m and the production zone is drilled with 8 ½” drill. Figure 5 show location of all wells and direction of wells at Theistareykir area. Table 1 show the result of drilling exploration/production wells at Theistareykir area. The biggest wells at the site ThG-04 is around 21 MW_e. As of now the estimated power capacity from the connected wells at Theistareykir equals around 105 MW_e.

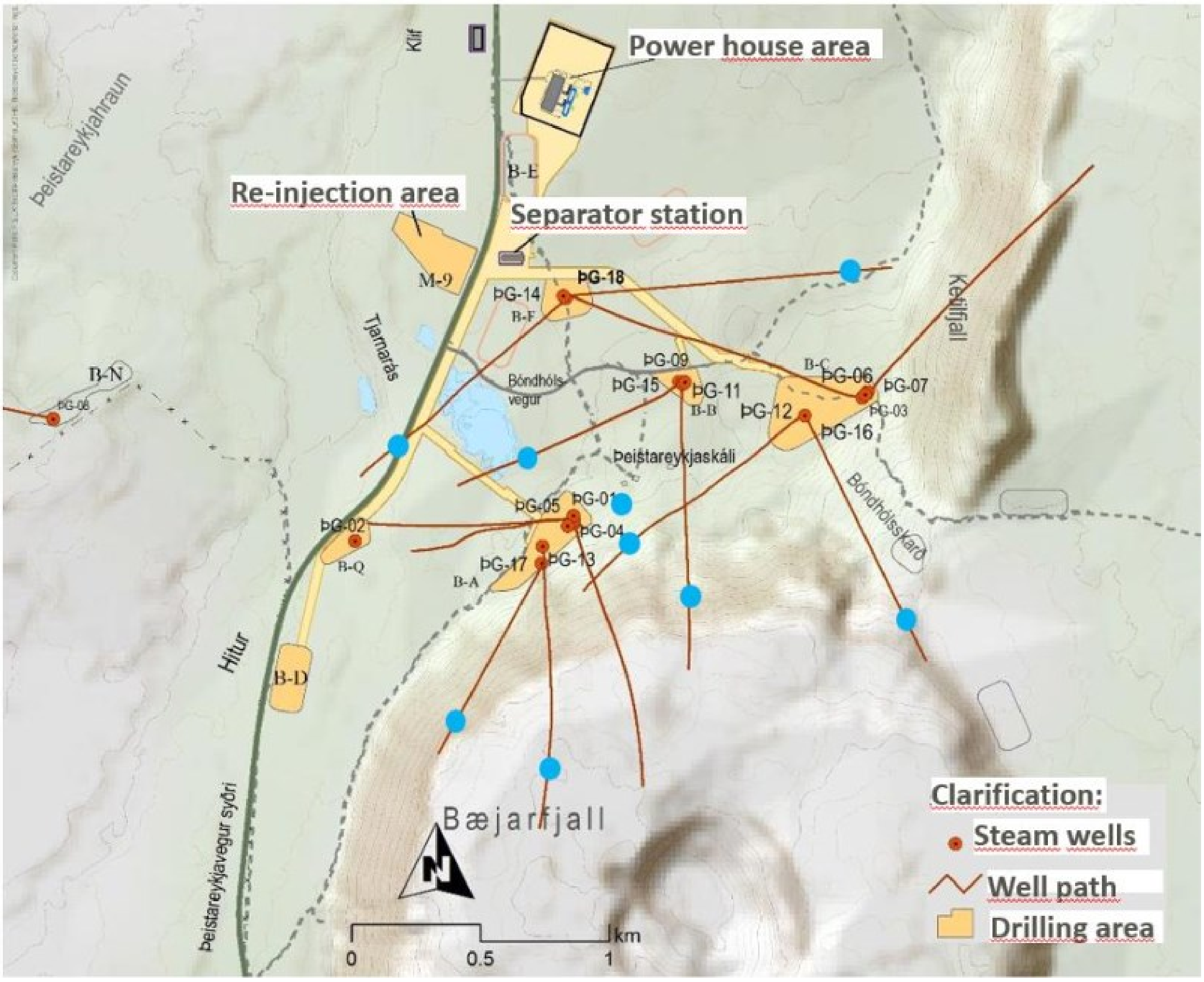


Figure 5: Operational wells at Theistareykir area (blue dot marks mean drilled 2016 and 2017).

Table 1: Information about wells at Theistareykir

Well no	Power estimate (MWe)	Remarks
ThG-01	6,9	Confirmed/ In use
ThG-02	-	Not to be used
ThG-03	7,0	Confirmed/ In use
ThG-04	21,3	Confirmed/ In use
ThG-05	8,4	Confirmed/ In use
ThG-06	7,3	Confirmed/ In use
ThG-07	4,7	Confirmed/ In use
ThG-08	-	Not to be used
ThG-09	3,6	Confirmed/ In use
ThG-10	-	Failure in early stage of drilling
ThG-11	14,4	Confirmed/ In use
ThG-12	5,7	Confirmed/ In use
ThG-13	7,3	Confirmed/ In use
ThG-14	0	To be tested for re-injection
ThG-15	2,0	Estimated / Not in use
ThG-16	1,9	Confirmed/ In use
ThG-17	14,8	Confirmed/ In use
ThG-18	2,0	Estimated/ Not connected
Total	107,3	Total 105,3 for connected wells

Figure 6: Drilling area C with wells ThG-12 and 16 in the foreground and wells ThG-03, 06 and 07 in the background. The joint silencer for ThG-12 and 16 can be seen at the edge of the drilling area.

Figure 7: Overview of the steam field. The geothermal fluid is collected from the drilling areas and piped to the steam separators (bottom left). The steam pipelines continue to the powerhouse (left) and the separated water is sent to reinjection (bottom).

Figure 8: Steam separator.

3.2. Steam separators

The two-phase fluid from the wells is piped to two steam separators, one for each turbine, where the steam is separated from the water, see Figure 7 and Figure 8. The length of each separator is 15,7 m and have a diameter of 3,2 m. The separator has two inlets at the bottom and the fluid is directed through diffusers to both ends of the separator. There are two outlets at the center of the separator, one at the bottom for separated water and one at the top with chevrons for the steam.

3.3. Steam system

The steam is piped to the powerhouse area and through mist eliminators to the turbines. There are two mist eliminators for each unit, of length 8,5 m and diameter of 2,8 m. Steam control valves, located in the steam valve station, are connected to the steam pipelines and vent the steam to steam silencers. Each unit has a set of two steam control valves, with capacity of 67% and 33% respectively of the total steam flow for each unit.

3.4. Reinjection system

The water from the steam separators is reinjected into three wells at a depth of approximately 400 meters at the boundary of the geothermal field. The wells are still within the hot zone and will build up pressure if they are closed off. An emergency exhaust for the water is connected to the reinjection line next to the reinjection wells, see Figure 9. To increase the permeability of the wells and reduce scaling, the geothermal water from the steam separators is mixed with condensate from the condensers of the turbines to cool and dilute the water, see Sigfússon and Gunnarsson (2011) and Gunnarsson (2011). When the condensate is not being mixed with separated water, the reinjected water is about 120 l/s at appr. 175°C and the pressure in the wells is about the same as the steam supply pressure (8-8,5 bar) as the water flashes. The condensate is at about 36°C and lowers the temperature down to 90-120°C, depending on the amount of condensate taken from the units, increasing the flow up to 200 l/s to reinjection. Despite the increase in reinjected water, the permeability of the wells in notably increased and the pressure in the wells can drop down to 0 bar as there is no flashing of the water. During inspection of the steam supply, insignificant amount of scaling where found in the control valves on the reinjection wells.

Figure 9: Reinjection wells, the emergency discharge is being installed in the background.

3.5. Control design

The operation of the steam supply must facilitate the operation of the units at variable load and handle abrupt changes in the power output of the turbine/generator units without any delay in the operation of the units due to instability or transient behavior of the steam supply system. The requirements focus on functions to maintain stability of the steam supply to minimize disruption in the operation of the units and minimize down time. The two main control functions, thereby the main potential sources of instability, are the control of the steam pressure and the control of the level in the steam separators. The systems are coupled in the way that changes in steam pressure will affect the level in the separators.

The steam supply is operated with the wells at fixed opening. Controlled throttling of the wells is not deemed practical as rapid changes would strain the casing that will lead to failure and slower adaption to steam usage would limit the ability of the plant to rapidly adjust to load conditions. The pressure of the steam supply is controlled by the steam control valves by venting the steam to steam silencers. When the turbines are running at full or partial load, excess steam is vented to the steam silencers. If the turbines trip or are not in operation, all steam is vented to the steam silencers. In case there is not enough steam for operation at full capacity, one of the turbines will switch over to steam pressure control to maintain pressure in the steam supply. In addition, the governors of the turbines have been implemented with steam pressure controllers and switch automatically if there is not sufficient steam to maintain set power output.

The level in the steam separators is controlled by control valves on the reinjection wells that control the flow in the reinjection line. In addition to the flow of water from the geothermal wells, the level control in the steam separators is affected by the amount of condensate from the condenser being mixed in the reinjection line. The flow of condensate to the reinjection is controlled by the temperature of the mixed fluid, which is equivalent with control of mixing ratio of the fluids, currently the mixing ratio is 50/50. Control function in the condensate system of each unit prevents that the steam supply is not trying take too much condensate. In case the turbines trip, mixing of condensate will abruptly stop and disturb the level in the separators.

4. PERFORMANCE OF THE STEAM SUPPLY

Landsvirkjun and Landsnet (the grid operator) have performed various system tests to verify the response and the resilience of the power plant (Hardarson et al, 2018). Although the tests are primarily for evaluating the grid stability and protection functions, they also provide valuable tests for the steam supply. The performance of the steam supply systems has been proven reliable and the response to disturbance events have not hindered the operation of the plant. Following are two examples of the operation of the steam supply.

4.1. Load rejection

During the commissioning of the industrial area, an event occurred where both substation breakers opened due to overcurrent when both units were at full capacity, see Figure 10. The response of the units resulted in load shedding of unit 1 and it went to house load, producing 3.4 MW_e for the plant's parasitical load, whereas unit 2 went to no load, maintaining 3000 rpm and ready to synchronize. Both units were therefore immediately ready to resynchronize to the grid as soon as grid conditions would permit. In this event, down time of the units was 35 minutes while the causes for the mishap were investigated, however, in other disturbance events, a unit has been resynchronized within 15 minutes after the trip of the unit.

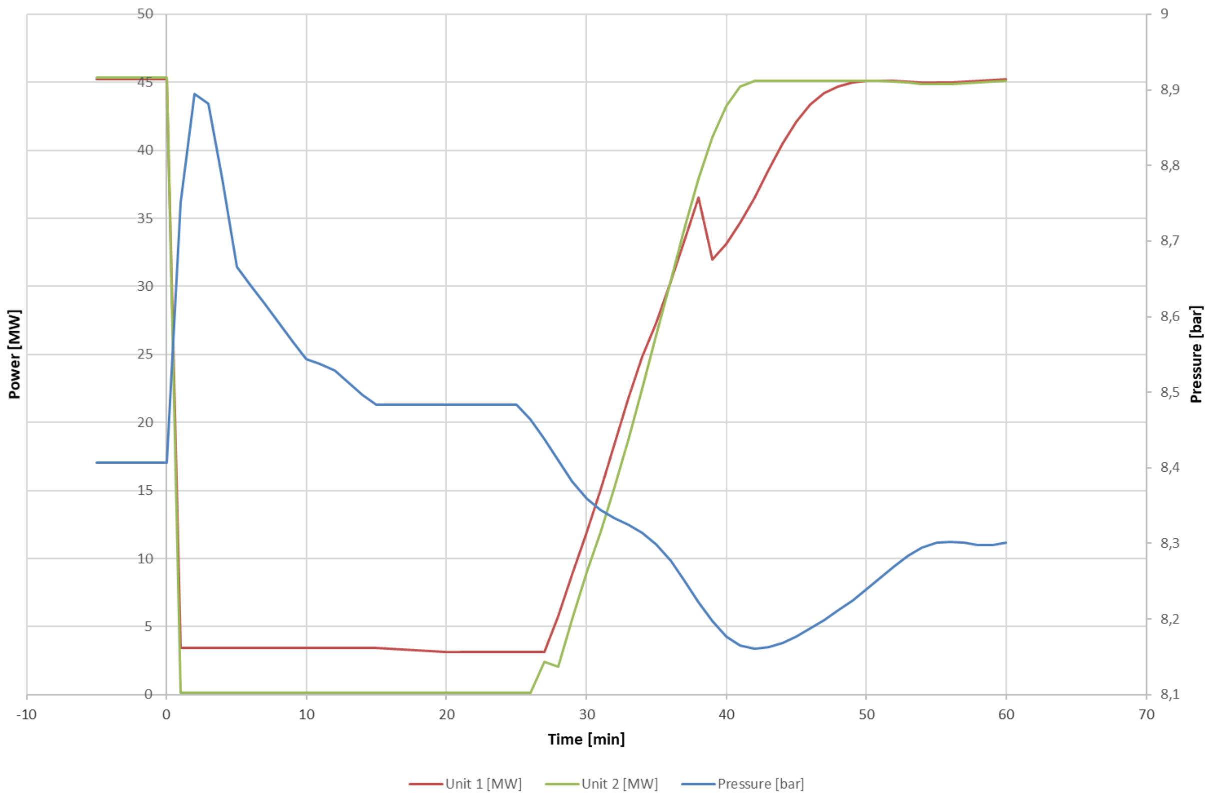


Figure 10: Load rejection with both units at full load. Unit 1 switches to house load, producing 3.4 MW_e (left axis), whereas unit 2 is in no load until the units are resynchronized and set to full load again. Steam pressure is initially 8.4 bar and peaks at 8.9 bar following the load rejection (right axis)

Simultaneous load rejection of both units is one of the most severe tests for the stability of the steam supply, after full trip of both units. As both units are at full load, all steam control valves are closed, except one that is bleeding off excess steam. The steam control valves must open and exhaust almost all the steam to the silencers to maintain steam pressure within limits. The reinjection system must react to the disturbance in the level of the steam separators due to the rise of steam pressure and an abrupt change in the amount of water to the reinjection wells as the loss of condensate from the units reduces the flow in the reinjection line by more than a half.

Figure 10 shows the steam pressure in the steam supply and how the steam control valves limit the pressure rise within 8.9 bar peak rise from initial 8.4 bar and stabilize the pressure at 8.5 bar. The reinjection was further able to stabilize the level in the separators in a smooth manner without any destabilizing effects on the steam supply. It can be further noted in Figure 6 that as both units are resynchronized and start to load up, the steam pressure drops while the steam control valves are closing. That triggers unit 1 to switch briefly to steam pressure control and assist in maintaining steam pressure. As the pressure stabilizes, the unit switches back to load control and goes to full load.

4.2. Steam supply bursts

Well ThG-05 has periodical bursts when connected to steam supply. When the well was initially drilled the resulting capacity was low. In an attempt to improve the capacity and provide further information on the area, another path was directionally drilled out of the original well. Well tests to silencer showed that the measured power is 8,4 MW_e and no fluctuations were noted during the tests. However, when the well is connected to the steam supply the well starts to show instable behavior where the pressure measured on the wellhead pressure fluctuates from 11,5-23 bar in period of 54 hours, see Figure 11. This results in steam bursts where there is a steam increase equivalent to approximately 5 MW_e which lasts for about 3 hours.

Figure 12 shows the power output of the units, the steam supply pressure and the amount of separated water to reinjection during a steam burst. Prior to the burst, unit 2 is at set 45 MW whereas unit 1 is in steam pressure control at 8,2 bar at 42 MW_e as there is insufficient steam for full 45 MW_e load at the time as not all wells were being used. When the steam burst starts, there is an increase in steam pressure up to 8,6 bar which causes unit 1 to switch to load control at 45 MW_e and the steam exhausts take over steam pressure control at a setpoint of 8,4 bar. At the same time there is an increase in separated water to reinjection, probably caused by the increased steam is pushing the water from steam gathering pipelines into the steam separators, i.e. there is increase in the speed of the water but probably not an increase in the amount of water. The increase in steam lasts for about 3 hours where it stops abruptly, steam exhaust close and unit 2 takes over pressure control.

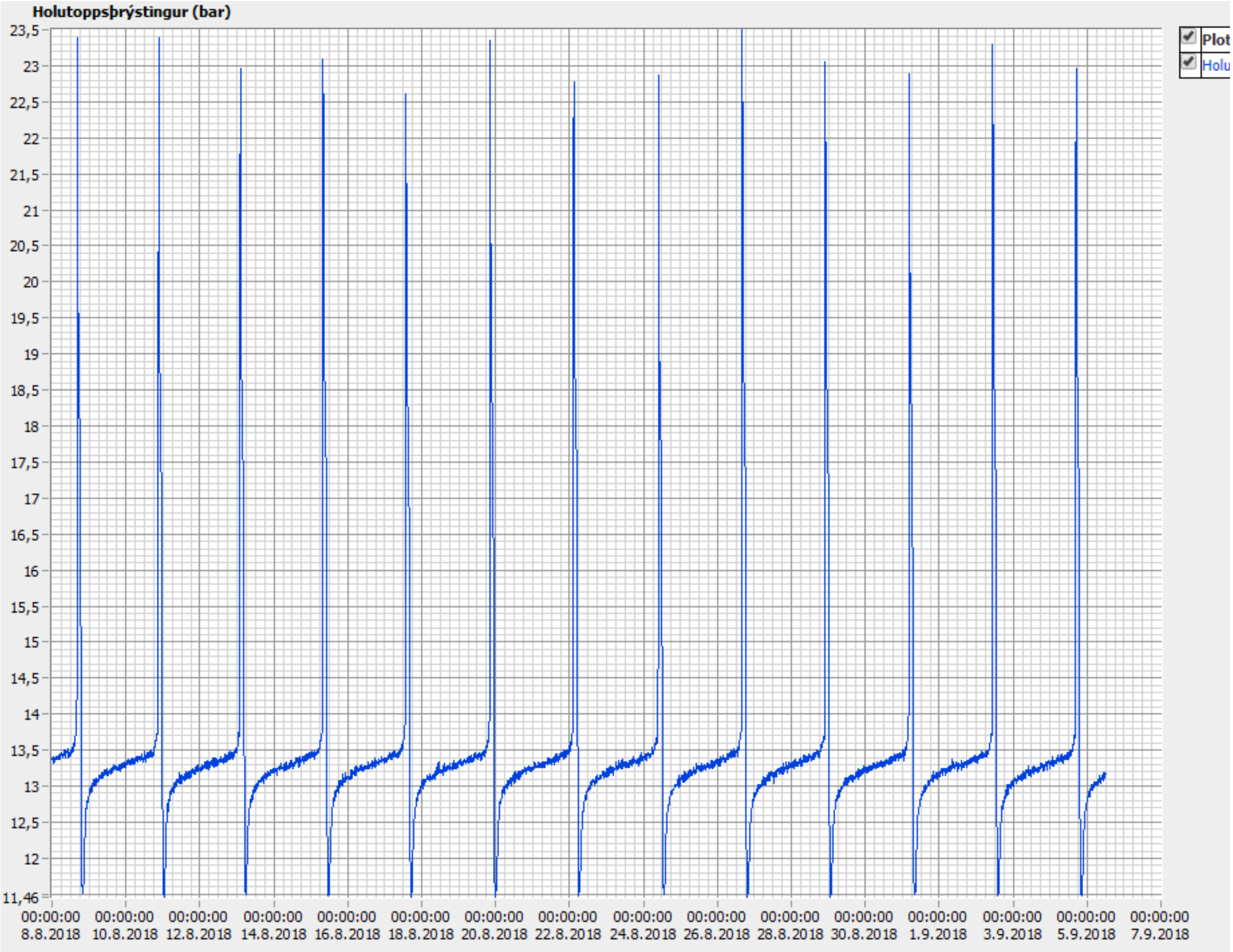
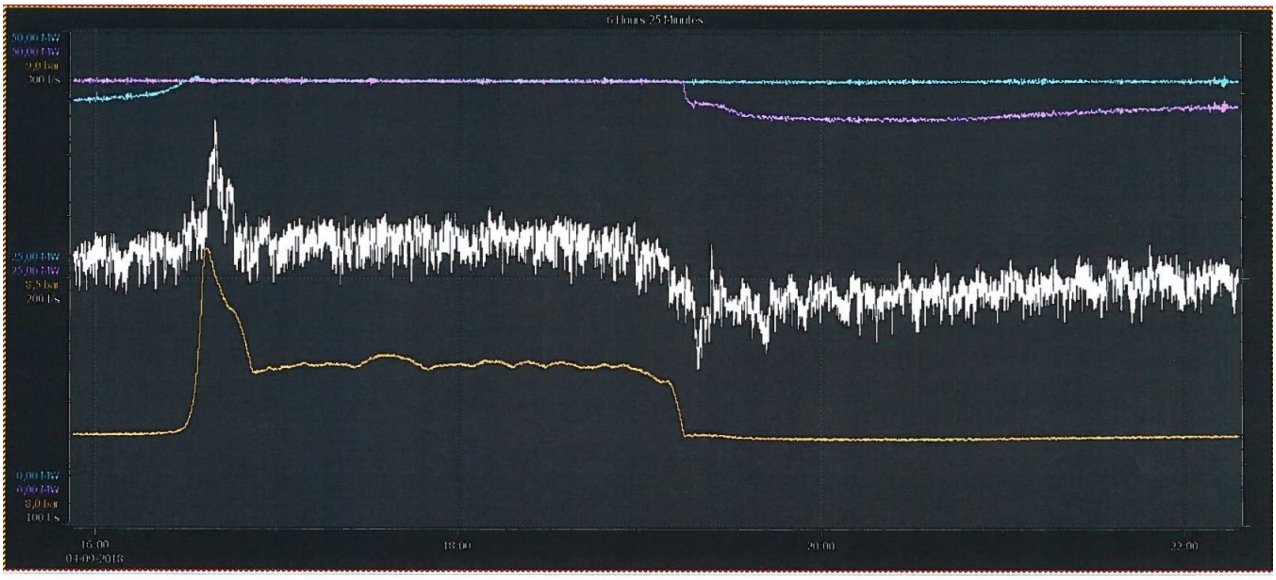


Figure 11: Measurement of pressure on the wellhead of ThG-05 when connected to the steam supply. The wellhead pressure fluctuates from 11,5-23 bar in period of 54 hours.



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1		X		1MKC10CE900_XJ57	Segulmögnun-Raunafl	Status.Out.Value	44,97 MW			Stepped	0,00 MW	50,00 MW	42,67 MW	45,61 MW	ExtMomentary	SEAMLESS	0	00:00:00 00:00:00
2		X		2MKC10CE900_XJ57	Segulmögnun-Raunafl	Status.Out.Value	42,61 MW			Stepped	0,00 MW	50,00 MW	40,78 MW	45,31 MW	ExtMomentary	SEAMLESS	0	00:00:00 00:00:00
3		X		1LBB10CP921	Gufuaðveita 1-Þrýstingur rakaskiljur	Xmtr1.Forward.Value	8,2 bar			Stepped	8,0 bar	9,0 bar	8,2 bar	8,6 bar	ExtMomentary	SEAMLESS	0	00:00:00 00:00:00
4		X		0LBU10CF301_XJ11	Niðurrennsli-Flæði	Status.BaseStatus.Out.Value	197 l/s			Stepped	100 l/s	300 l/s	163 l/s	264 l/s	ExtMomentary	SEAMLESS	0	00:00:00 00:00:00

Figure 12: Printout from the control system during steam burst. The cyan and magenta lines are the power output of units 1 and 2, respectively, the orange is the steam supply pressure and the white line is the amount of separated water to reinjection.

5. CONCLUSIONS

Landsvirkjun's Theistareykir Power Plant has been successfully put in operation with set objectives achieved in good cooperation with Landsnet (transmission system operator) and the consortium of Fuji Electric and Balcke-Dürr (contractor for the units). The performance of the units and the steam supply systems in handling unexpected events during testing has shown to be reliable and robust.

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