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Sustainable Development of the Seltjarnarnes Geothermal Field, Iceland, Through Exploration Drilling and Reservoir Modelling

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ABSTRACT

The Seltjarnarnes geothermal field was first harnessed about 50 years ago and has been utilized for a local heating system since 1972. The field is located on a peninsula within the town of Seltjarnarnes, a suburb of Iceland's capital city Reykjavík. About 50 L/s of 95-120 °C hot water is produced from three main feed zones using four production wells. About 40 % of the return water is collected and mixed with the produced water to maintain an optimal temperature for distribution. As the area around the wellfield is densely inhabitated and in close proximity to the coast, conventional reservoir exploration methods are limited. Drilling of shallow exploration wells is therefore the best method to map the geothermal field and nine such wells have been drilled to date. In the last five years, four wells have been drilled providing valuable information on the properties of the geothermal reservoir and on locating possible new production wells. The first three-dimensional reservoir model of the system was constructed in 2002 and was updated in 2016 using the available up-to-date production data. The updated model was used to forecast the reservoir response to several future production scenarios. The results show that a production increase of 10 L/s is sustainable for the next 20 years using the current production wells with unaltered pump depths. It should be possible to increase current production by 20 % through use of the existing production wells, and even further by lowering the production pumps in some wells. The model can be used to calculate additional scenarios with increased production from the reservoir. Evaluation of the feasibility of small scale electricity production is ongoing and preliminary results show that the district heating will benefit from the ORC system with better control of the fluid temperature and lowering or eliminating the electricity bill. As the geothermal field is far from being fully exploited, the possibilities for further sustainable utilization are manifold.

1. INTRODUCTION

The Seltjarnarnes geothermal field is located within the borders of Seltjarnarnes town (Figure 1), a suburb of the capital city Reykjavík with about 4700 inhabitants, (Kristmannsdóttir et al., 2015). The field is a boiling low-temperature geothermal field or a medium enthalpy field (Kristmansdóttir, 2015). Six low-temperature geothermal fields are located within and just outside the capital city region, (Kristmannsdóttir and Tulinius, 2000). All those geothermal fields are located in the same Quaternary rock section within the Kjalarnes caldera, (Fridleifsson, 1990). Within the geothermal fields faults and displacement of the rock formations have been observed, (Fridleifsson, 1990). The heat source of the fields is from the relatively young rock formations and their location is due to active fracturing and subsequent heat mining, (Björnsson et al., 1990). This produces a high geothermal

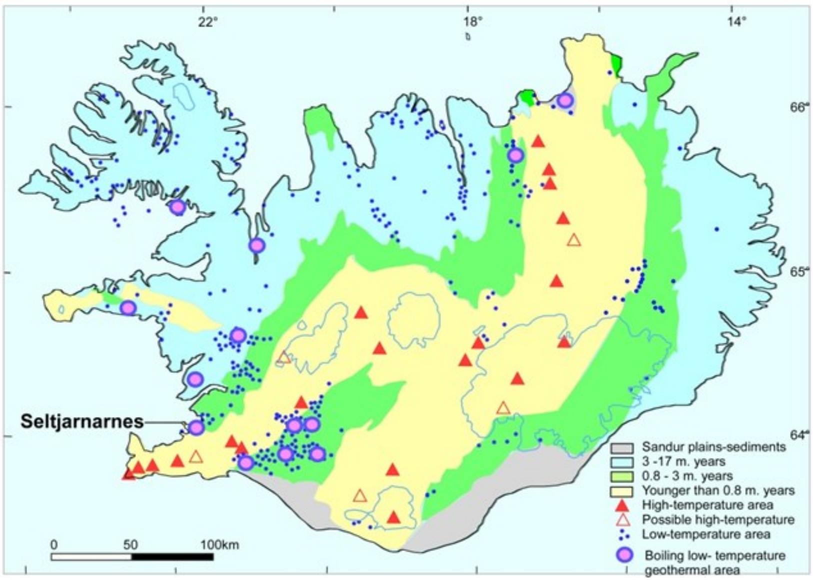


Figure 1. The location of the Seltjarnarnes field is shown on a simplified geological and geothermal map of Iceland based on data from Saemundsson, (1979) and Björnsson et al., (1990).

gradient, which can be used to map the most active area. The fields within the capital city area appear to have a transient pressure connection, but their water recharge comes from separate sources and chemical properties of the geothermal water are quite different (Kristmannsdóttir and Tulinius, 2000).

No geothermal activity was known in the Seltjarnarnes area before drilling. The field was detected by drilling of two gradient wells on the north and south coastline of the peninsula between 1965-1967, both showing a high geothermal gradient. The main upflow zone of the field was assumed to be located towards the west and probably connected with the Álftanes geothermal field to the south (Tulinius et al, 1987). Later development of the field and drilling of further gradient wells have changed previous knowledge considerably (Kristmannsdóttir et al., 2015). Four exploration wells have been drilled in the last five years to define better the location and properties of the field. The heating system was established in 1972 and was almost fully expanded by 1996, when the last production well was connected. Since then the energy demand has not increased substantially, but recently there have been new residential and institutional developments with more planned in the next few years. This requires more energy for heating and the possibilities to increase the energy production in the most sustainable and beneficial way have been considered (Kristmannsdóttir and Björnsson, 2014, Kristmannsdóttir et al., 2015). The field has been continuously monitored through its production history and research has been ongoing (Kristmannsdóttir et al., 2015, Kristmannsdóttir and Vatnaskil, 2019). Reservoir models of the field have been constructed and updated several times (Tulinius et al., 1987, Vatnaskil, 1994 and 2002) and the last update was done in 2016 (Vatnaskil, 2016). Possibilities of binary electricity generation on a small scale are being considered.

2. PRODUCTION OF THE GEOTHERMAL FIELD

In total there have been 16 wells drilled in the Seltjarnarnes field as listed in Table 1 and shown in Figure 2. Four wells are producing at present, SN-04, SN-05, SN-06 and SN-12. The others are exploration wells or former production wells now used for monitoring or reinjection. The depths of the production wells range from 2025-2714 m and the main production zones are at 400-600 m, 1000-1500 m, 1800-2100 m and about 2400 m depth. The production from each well has been variable through the years depending on several factors. Well SN-12 has proven to be the best production well, sustaining high production for long periods of time and recovering quickly when rested. The temperature of the produced water depends on the rate of production as well as the average long-term production. As shown in Table 1, the temperature of the produced water from well SN-04 was very low in 2018 due to very low production rate of about 1.2 L/s (Kristmannsdottir and Vatnaskil, 2019). In well SN-05, the temperature of produced water is inversely proportional to the average production. In wells SN-06 and SN-12 the temperatures of produced water is more stable as they have much deeper production casing. Well SN-06 is the only well producing from the deepest sections of the reservoir at about 2400 m.

Table 1. Wells drilled in the Seltjarnarnes geothermal field.

Well no.	Drilled in year	Depth in m	Depth of prod. casing m	Width (") of casing/well	Type of well	Maximum yield in L/s	Range of temperature in °C of produced water	Average temperature in °C of production water in 2018
SN-01	1967	1282	18.5	7 ”	Monitoring			
SN-02	1965	856	81.5	8 ”	Monitoring			
SN-03	1970	1715	99	$9^{5/8}$ ”	Monitoring	15	100-105	
SN-04	1972	2025	172	$9^{5/8}$ ”	Production	35	85-114	88
SN-05	1981	2207	168	$13^{5/8}$”	Production	25	98-109	99
SN-06	1985	2701	414	$13^{5/8}$ ”	Production	25	118-121	121
SN-07	1993	154	none	3”	Exploration			
SN-08	1993	153	none	$6^{1/2}$”	Exploration			
SN-09	1994	132	none	$6^{1/2}$”	Exploration			
SN-10	1994	132	none	$6^{1/2}$”	Exploration			
SN-11	1994	145	none	3”	Exploration			
SN-12	1994	2714	791	$10^{3/4}$ ”	Production	35	105-111	107
SN-13	2014	153	none	$6^{1/2}$”	Exploration			
SN-14	2014	157	none	$6^{1/2}$”	Exploration			
SN-15	2018	150	none	$5^{1/2}$”	Exploration			
SN-16	2018	150	none	$5^{1/2}$”	Exploration			

Due to the high temperature of production water, return water is needed to cool down the produced water before entering the district heating system. As the town is mostly a residential area with few multistory buildings, it is rather costly to gather enough return water for this purpose after expansion of the residential areas. In all newly constructed buildings however systems are put in place for collection of return water. The water temperature from the wells is also variable so the need for return water is subject to change by seasons and demand. As it is quite costly to dispose of any unused return water into the sewage system it is reinjected into the reservoir through well SN-03. This reinjection has been determined to be the best disposal method with regard to minimizing environment effects.

No cooling of the reservoir has been detected through the 47 years of production, but there have been changes in production characteristics of the wells as well as in the production water. The pressure in the wells has declined, both temporarily and permanently in some wells. This has changed the temperature of the production water in some of the wells.

The salinity of the production water was high at the start of production from the fields and increased rapidly during the first years of production (Kristmannsdóttir, 1983, 1986, Kristmannsdóttir at al., 2015). Increased salinity enhances the danger of corrosion and scaling and is carefully monitored. Substantial supersaturation of calcium carbonate has been observed at times (Kristmannsdóttir and Vatnaskil, 2019) even though scaling at the wellhead has yet to be observed. The reason for supersaturation is probably mixing of water from different aquifers of different temperatures and salinity. There may occur some scaling in the distribution net at areas of sub-optimal mixing conditions, but for the most part it occurs due to accidental inflow of cold water (Kristmannsdóttir, 2009). Due to shallow casing in the older wells, sand debris has been a problem, but has almost been eradicated by the installation of sedimentation traps.

3. DRILLING OF EXPLORATION WELLS

In the last five years, four shallow gradient wells have been drilled (Figure 2) providing valuable information on the properties of the geothermal reservoir and on locating possible new production wells. From existing data, a geothermal gradient map of the area has been produced, indicating that the field is connected to a NNW-SSE fault zone crossing the peninsula. This is a rather uncommon trend for faults in southwest Iceland where NE-SW and N-S trending faults are dominant. The highest gradient appeared to be in the northern part of the field corresponding to production experience which indicated that the highest permeability within the reservoir is also in the northern part of the field. From reevaluation of the data by Kristmannsdóttir and Björnsson (2014) it was obvious that the limited number of gradient wells give a poor basis for drawing a detailed gradient map. Some of the estimated gradients are based on data from the production wells which may have a high uncertainty. The conclusion was that it was hardly justifiable to close the temperature gradient contour lines towards the south. Looking at the data, it seemed that the geothermal gradients could indicate several parallel faults with different directions, most probably N-S. The drilling of the two first gradient wells in 2014, wells SN-13 and SN-14 showed that the high gradients extended further south than shown in the older maps and gradients were also higher further towards the west than estimated before (Kristmannsdóttir and Björnsson, 2014). Well SN-13 may be affected by local cooling and the estimate thus may give a low estimate. The third well (SN-15) drilled in 2018 was a diagonal well inclining 30° towards the north from a landfill just north of well SN-12, the main production well and at the area of highest estimated geothermal gradient (Kristmannsdóttir and Björnsson, 2019). The estimated gradient there was 350 °C/km and there was indication of hydrothermal alteration high up in the rock section. This is also the only well showing connection to the geothermal water level, even though it yields no water. The fourth well (SN-16) drilled also in late 2018 was drilled about 800 m SW of well SN-15, giving also a very high gradient of about 360 °C/km. In Figure 2, the gradient contour lines from the reevaluation from 2014 are shown, except for the > 300°C/km contour, which is replaced by a section enclosing the area believed to be the main part of the field. The drilling of the last exploration wells has thus changed partly the model of the geothermal area, showing that there is a very high gradient further towards the south and west. The main upflow in the field still seems to be in the northern part, which is in accordance to experience from production of the field.

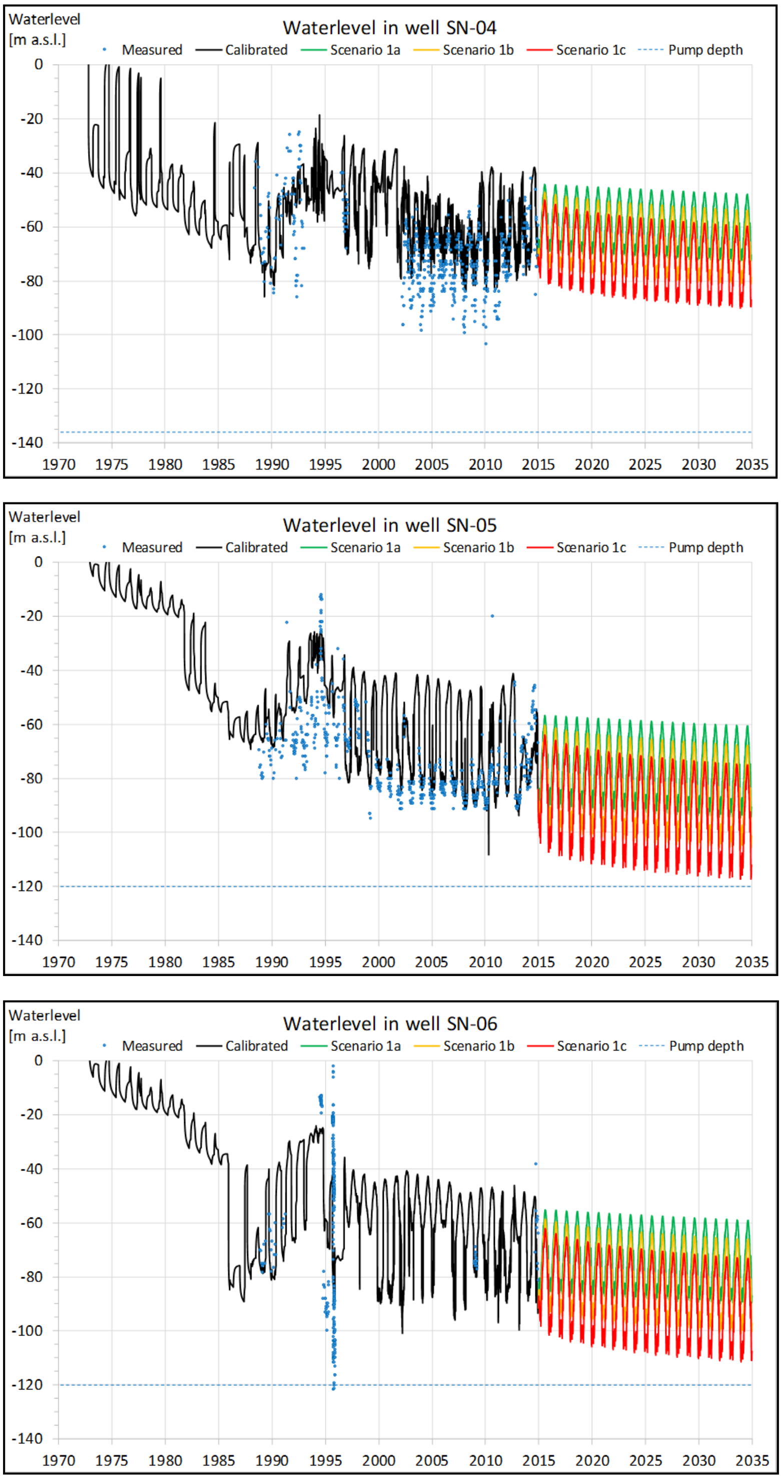
Figure 2: Location of the wells in Seltjarnarnes town. The last four exploration wells are marked by red dots with blue circles outlining them (Kristmannsdóttir and Björnsson, 2019).

4. RESERVOIR MODELLING

A three-dimensional numerical reservoir model of the Seltjarnarnes geothermal reservoir has been developed by Vatnaskil Consulting Engineers. Modelling work began in 1994 with the development of an initial conceptual model of the reservoir using available geological and geophysical data. A previously constructed two-dimensional regional model of the Greater Reykjavik Area, which encompassed the Laugarnes, Elliðaár, Reykir and Reykjahlíð geothermal fields, was expanded to include the Seltjarnarnes field (Vatnaskil, 1994).

Model development continued as more data became available, and significant improvements were made to the numerical model between 1999-2002 when it was made three-dimensional (Vatnaskil, 2002). Vertical discretization of the model allowed for a much more detailed representation of the geothermal reservoir and made it possible to model important factors such as horizontal flow through preferred feed zones within the reservoir and vertical flow through fractures. The numerical model was utilized in 2011 to simulate a proposed tracer test in well SN-03, with the goal of determining the volume of tracer necessary to ensure a successful test and the approximate return time in surrounding monitoring wells.

The latest modelling work was performed in 2015-2016 when the model was updated and recalibrated with all available data. The updated model was utilized to simulate proposed future production scenarios in order to predict the effects of increased production and assist in sustainable management of the reservoir. At the time of the modelling, average production from the field was approximately 46 L/s from four production wells. This production rate was simulated 20 years into the future (Scenario 1a) and compared with scenarios simulating an increase in production of 5 L/s (Scenario 1b) and 10 L/s (Scenario 1c). Results from the simulations showed that a production increase of 10 L/s (total production 56 L/s) is sustainable for the next 20 years using the current production wells with unaltered pump depths (Figure 2). Additional scenarios were performed, simulating the use of a combination of only two of the current production wells. The results of those simulations indicated that a total production of 56 L/s is not sustainable unless the pumps are lowered considerably in either one or both wells.



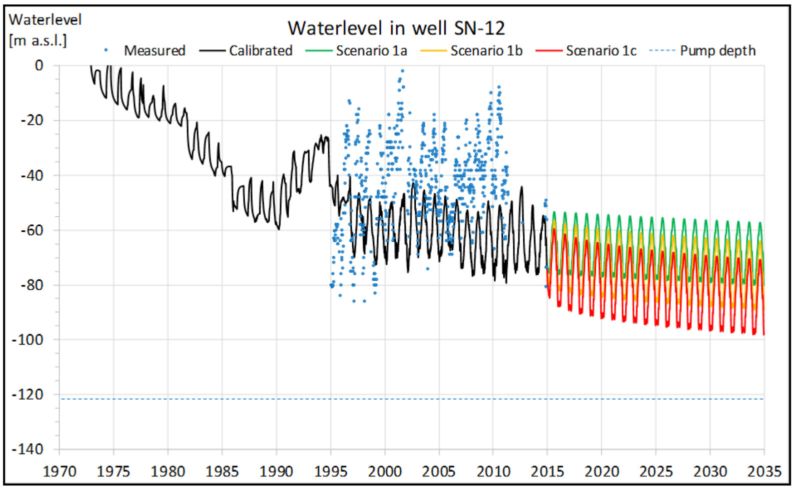


Figure 3. Measured and calibrated water levels in the current production wells. Simulated water levels are shown 20 years into the future for Scenario 1a (2014 production), Scenario 1b (5 L/s increase in production from 2014) and Scenario 1c (10 L/s increase in production from 2014).

5. ELECTRICITY PRODUCTION

The possibility of building an ORC system in Seltjarnarnes to optimize the production has been considered for a long time (Kristmannsdóttir et al., 2015). District heating systems are generally designed for 70-90°C fluid temperature. The fluid temperatures can vary significantly between resources and even between wells in the same resource. In medium temperature resources (100-150°C @ 0-1.000m depth) as in Seltjarnarnes the produced water needs to be cooled down either by mixing with return water, industrial utilization or electricity generation with a binary power plant. The possibility of installing a small binary plant has recently been considered and a feasibility study has been made (Thorbergsson and Magnússon, (2019).

If the temperature of the produced water is decreased by mixing with return water, as is done in Seltjarnarnes, the amount of return water needed increases as the resource temperature increases. However, the attractiveness of a binary power plant also increases with higher resource temperatures. An ORC system utilizes the high temperature fluid down to approximately 80°C for electricity generation (Spadacini and Xodo, 2016). The electricity can be used to power e.g. auxiliary equipment, such as pumps, control equipment, etc. and the surplus can be sold to the electricity distribution grid.

The produced water from the four Seltjarnarnes production wells is pumped into a buffer tank and then mixed with return water before it is distributed to the network. A simplified diagram of the district heating system is shown in Figure 4.

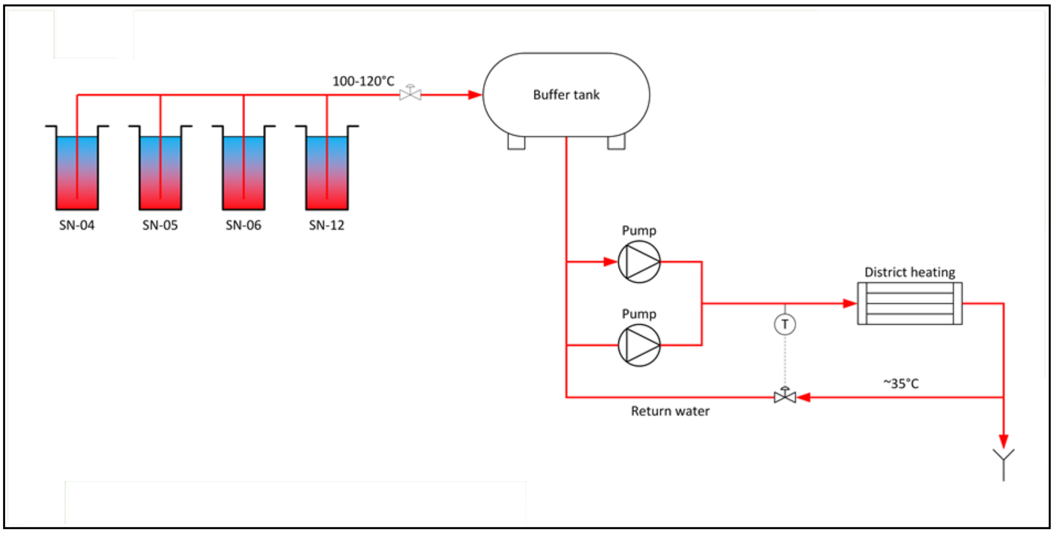


Figure 4: Simplified diagram of the Seltjarnarnes district heating system.

The four production wells currently in use are are listed in Table 1. Well SN-06 has the highest production water temperature of about 120°C and well SN-12 is the most productive well overall. Wells SN-06 and SN-12 are considered the most suitable for utilization in an ORC system due to location, yield and temperature of produced water.

The demand for hot water for the district heating system varies with seasonal weather changes. A case study was conducted with data that is representative of the seasonal distribution of flow in the district heating system and an analysis was conducted using a thermodynamic model of the district heating system along with an ORC system. The average flow to the network was 66 l/s with 46 l/s flow from the wells and the remaining 20 L/s return water (Figure 5). Usage is variable from 29-112 L/s (23-78 L/s from the production wells). With decreased temperature of the fluid after an ORC cycle, there is no need for mixing of return water. In that case the pumped fluid from the wells needs to be increased to the same level as the total usage. That means that the wells will be at maximum capacity at peak hours. At peak hours, the ORC system could be bypassed as needed and well fluid mixed with the return water to increase the total flow and decrease extraction from the reservoir.

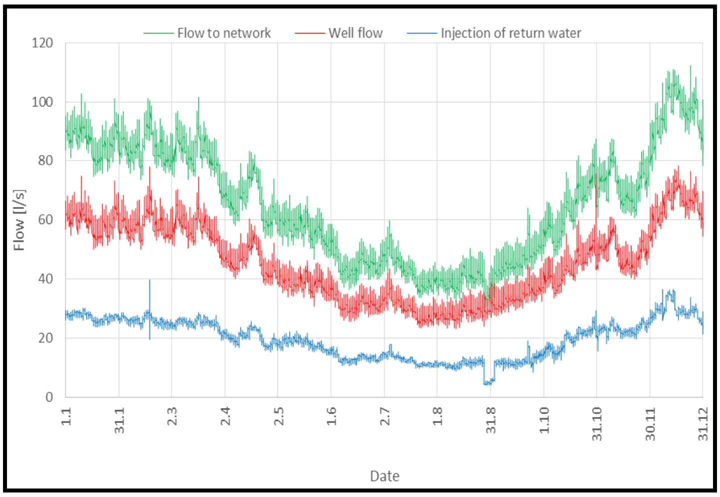


Figure 5: Flow measurements from the Seltjarnarnes district heating system for the case study.

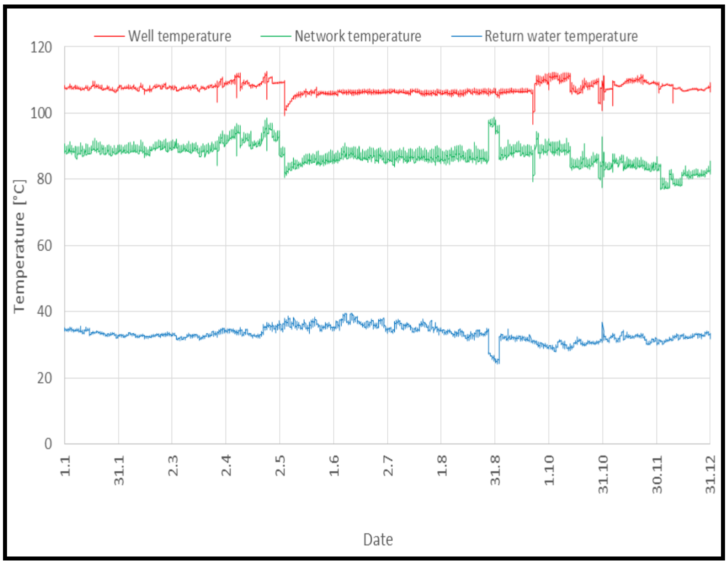


Figure 6: Temperature measurements from the Seltjarnarnes district heating system for the case study.

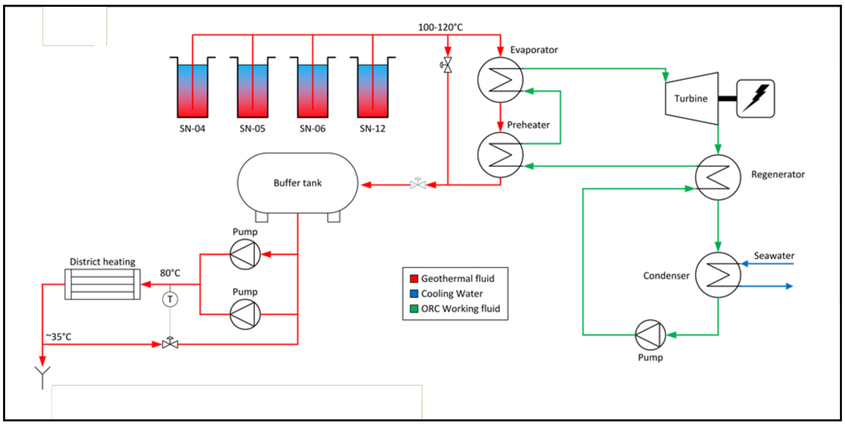


Figure 7: A simplified diagram of the thermodynamic model of the Seltjarnarnes district heating system with added ORC cycle.

The flow and temperature measurements used in the case study are shown in Figures 5 and 6. The data series have 1 hour interval between measuerments of flow and fluid temperature from wells, return water and fluid to the network. The power production capacity of the ORC system needs to be chosen carefully because of seasonal variations in heat demand. An optimal size should be around 50-70% of the maximum usage for more efficient use of the installed capacity. A simplified diagram of the thermodynamic model can be seen in Figure 7. The maximum installed capacity of the ORC cycle was set to 100 kW to 1200 kW with 100 kW interval in each step. The well flow was increased to meet the same heat demand as supplied to the network according to logged data from 2014 but now with a lowered network temperature of 80°C. The maximum potential production for the case study was 1.191 kW with increased well flow of 53 l/s. The results from the thermodynamic calculations are shown in Figure 8.

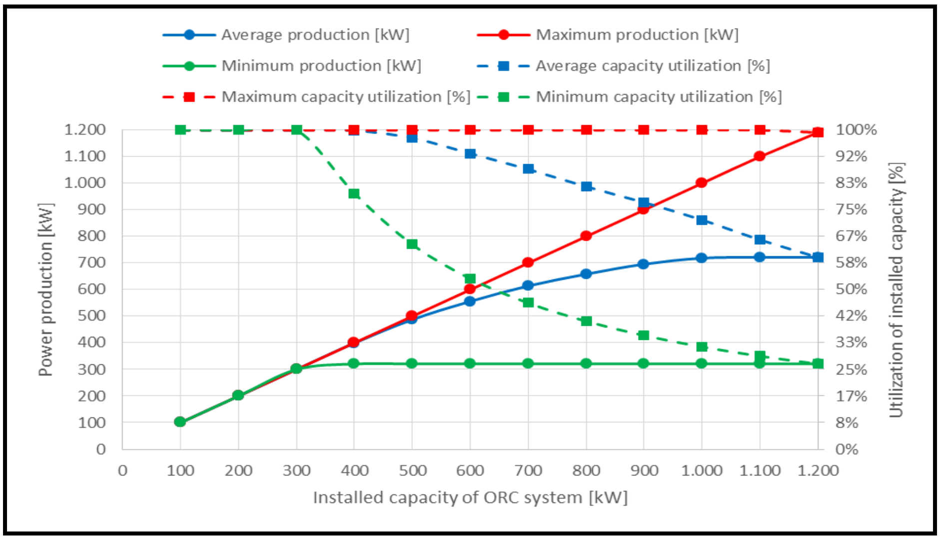


Figure 8: Power production and utilization of installed capacity versus installed capacity of the ORC system.

The optimal size of the ORC cycle should be around 700 kW where the average utilization of the ORC system is 88% or 614 kW. If the installed capacity is increased to 800 kW the utilization drops to 82% and average power production increases only to 658 kW. The thermodynamic calculations need to be evaluated with a financial feasibility model before making a final decision.

The increased flow from the wells needed to supply the existing and increasing heat demand from the district heating system with an added ORC cycle needs further consideration, as the geothermal resource at Seltjarnarnes is limited. A determination needs to be made as how much water can be sustainable produced from of existing wells and weather there is a need for a new well in order to operate the ORC cycle. The average increased flow versus installed ORC capacity can be seen in Figure 9.

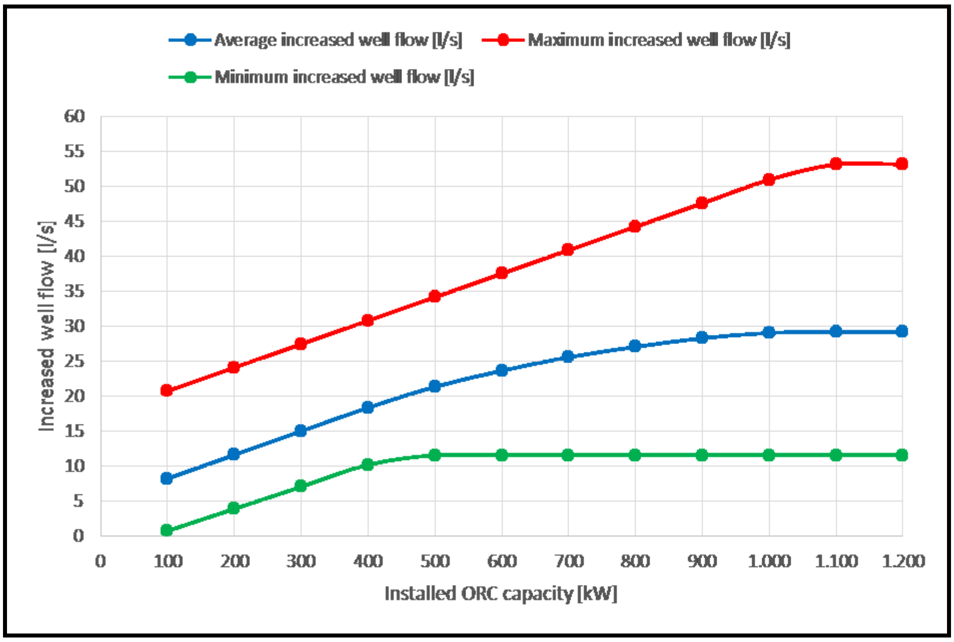


Figure 9: Increased flow from wells needed to supply the heat demand versus installed ORC capacity.

The district heating system utilizes different production ratios from the four production wells over the course of a year and overall produce more from the lower temperature wells than the high temperature wells. By prioritizing the wells for maximizing the temperature of the combined production water for utilization in an ORC cycle, the power production can be increased significantly and lower temperature wells could be bypassed to minimize extraction from the wells.

The Seltjarnarnes district heating system will benefit from the ORC system with better control of the fluid temperature and lowering the electricity bill. Lowering the amount of low temperature and return water and cooling water/seawater needed by the district heating system opens opportunities for other uses of that water, including spa, swimming pools or a thermal beach.

6. CONCLUSION

During the almost 50 years of production in the Seltjarnarnes geothermal field, monitoring and research have been continously ongoing to ensure the most economical and environmental beneficial production. In total there have been 16 wells drilled in the Seltjarnarnes field whereof four are produced at present. The other wells are exploration wells or former production wells. The depths of the production wells range from 2025-2714 m and the main production zones are at 400-600 m, 1000-1500 m, 1800-2100 m and about 2400 m depth. Four new exploration wells have been drilled in the field during the last five years. The drilling of the new exploration wells has changed the model of the geothermal area, showing that there is a very high gradient further towards the south and west than previously assumed. The main upflow zone still seems to be in the northern part of the peninsula, which is in accordance with the experience from production from the field.

A three-dimensional numerical reservoir model of the Seltjarnarnes geothermal reservoir has been developed by Vatnaskil Consulting Engineers and the latest update was concluded in 2016. Results from the simulations show that a production increase of 10 L/s is sustainable for the next 20 years using the current production wells with unaltered pump depths. Additional scenarios were calculated, simulating the use of a combination of only two of the current production wells indicating that a total production of 56 L/s is not sustainable unless the pumps are lowered considerably in either one or both wells.

Optimizing the production from the field by installing an ORC system has long been discussed and an analysis was conducted using a thermodynamic model of the district heating system along with an ORC system. The optimal size of the ORC cycle in Seltjarnarnes should according to the present study be around 700 kW where the average utilization of the ORC system is 88% or 614 kW. By prioritizing the wells for maximizing the produced water temperature, the power production can be increased significantly, and lower temperature wells could be bypassed to minimize extraction from the wells. The increased flow from the wells to supply the existing and increasing heat demand from the district heating system with an added ORC cycle needs further consideration. The next step is to calculate several scenarios using the three-dimensional numerical reservoir model and determine if this is a viable option for future production from the field. The Seltjarnarnes district heating system will benefit from the addition of an ORC system by allowing for better control of the fluid temperature of the district heating system and lowering the electricity bill. Lowering the amount of low temperature return water and cooling water/seawater needed by the district heating system opens opportunities for other uses of that water, including a spa, swimming pools or a thermal beach.

REFERENCES

Björnsson. A. Axelsson G. and Flóvenz Ó. G.: „The origin and nature of geothermal fields in Iceland" (in Icelandic) *Náttúrufræðingurinn* **60**. (1990), 15-38.

Fridleifsson, G.Ó.: The geology of the Laugarnes geothermal area in Reykjavík (in Icelandic) *Report* Orkustofnun, **OS-90035/JHD-07**, (1990), 63pp.

Kristmannsdóttir, H. "Analysis of possible scales in the distribution net of Seltjarnarnes heating company" (In Icelandic). *Report* University of Akureyri, Department of science, **TS09:03**, (2009). 23pp.

Kristmannsdóttir, H. "Changes in chemical composition of geothermal water during the years 1970-1983" (in Icelandic). *Report* Orkustofnun **OS-83106/JHD-19**, (1983), 27 pp.

Kristmannsdóttir, H.. Exploitation-Induced Infiltration of Seawater into the Seltjarnarnes Geothermal Field, Iceland Geothermal Resources Council, *Transactions* **19**, (1986), 389-393.

Kristmannsdóttir, H. and Björnsson, A. "Energy acquisition for Seltjarnarnes heating system. Increased production of water and improved utilization" (In Icelandic). Geological consulting company, HK/AB, *technical report* **14:01**, (2014) 49pp.

Kristmannsdóttir, H. and Björnsson, A. "Drilling of exploration wells in Seltjarnarnes 2014" (In Icelandic). Geological consulting company, HK/AB, *technical report* **14:02**, (2014), 14pp

Kristmannsdóttir, H. and Björnsson, A. "Drilling of exploration wells in Seltjarnarnes the autumn 2018" (In Icelandic). Geological consulting company, HK/AB, *technical report* **19:02**, (2019), 14pp

Kristmannsdóttir, H. and Tulinius, H.. The development of the Seltjarnarnes geothermal field, SW Iceland during thirty years production. *Proceedings* World Geothermal Congress 2000, Japan (2000) 3465-3470.

Kristmannsdóttir, H. and Vatnaskil: "Seltjarnarnes heating system. Production monitoring 2018-2019" (In Icelandic). Vatnaskil engineering company, *report* **19/03**, (2019), 42pp.

Kristmannsdóttir, H., Stefánsson S. E. and Björnsson, A.: Geothermal Field, SW-Iceland. *Proceedings* World Geothermal Congress 2015, Melbourne, Australia, (2015). Sustainable Geothermal Production of the Seltjarnarnes

Saemundsson. K.: Outline of the geology of Iceland. *Jökull* **29**, (1979). 11-28.

Spadacini, C.. and Xodo, L.G. : Geothermal energy exploitation with Organic Rankin Cycle technologies. In *Organic rankine cycle (ORC) power systems: technologies and applications.* Eds.Macchi, E., and Marco A., Woodhead Publishing, (2016), 473-524.

Thorbergsson, E. M: and Magnússon, R.: "Evaluation of the possibilities of building a small binary power plant in the Seltjarnarnes geothermal field" (in Icelandic). Efla consulting engineers, *report* no. **001-V01**, (2019). 14 pp.

Tulinius, H.,. Spencer, A.L, Böðvarsson, G. S., Kristmannsdóttir, H., Thorsteinsson, Th. and Sveinbjörnsdóttir, Á. E.: Reservoir Studies of the Seltjarnarnes Geothermal Field, Iceland. *Proceedings* 12th Annual Workshop, Geothermal Reservoir Engineering, Stanford University, California, January 20-21, (1987), 67-76.

Vatnaskil Consulting Engineers: Numerical model of the Seltjarnarnes geothermal reservoir (in Icelandic). Performed for Seltjarnarnes heating company. Vatnaskil *report* no**. 06.94**. (1994), 39 pp.

Vatnaskil Consulting Engineers: Seltjarnarnes. Three-dimensional numerical reservoir model (in Icelandic). Performed for Seltjarnarnes heating company. Vatnaskil *report* no. **02.02.** (2002), 134 pp.

Vatnaskil Consulting Engineers: Seltjarnarnes: Three-dimensional numerical reservoir model of the geothermal field. Update of the model and simulation of future production possibilities (in Icelandic). Performed for Seltjarnarnes heating company. Vatnaskil *report* no. **16.01**, (2016), 68 pp.