RESULT

Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development, Geothermica Project Number 200317

RESULT-D6.3:

Improved field management, lessons learned and guidelines for sustainable use of the Elliðaárdalur field (OR)

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Abstract

This report is part of the RESULT (Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development, Geothermica Project Number 200317) project belonging to Work package 6 Design Study Volcanic Reservoirs – Production Reykjavik and is: D6.3: Improved field management, lessons learned and guidelines for sustainable use of the Elliðaárdalur field (OR). The first two chapters of the report summarize the lessons learned from the production history of the Elliðaárdalur field and the changes in temperature and chemistry that have occurred throughout the utilization history. Based on the lessons learned, improvements in utilization are suggested. Possibilities for alternative drilling paradigms are also discussed. The last two chapters then look at challenges in the utilization of geothermal fields within urban areas in general and introduce results from a RESULT partner workshop held within the project.

Key words	ISBN-number
Elliðaárdalur, RESULT, ÍSOR, OR, geothermal, Iceland, geochemistry, cooling, production, utilization	
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1 Introduction

This report is part of the RESULT (Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development, Geothermica Project Number 200317) project belonging to Work package 6 Design Study Volcanic Reservoirs – Production Reykjavik and is: D6.3: Improved field management, lessons learned and guidelines for sustainable use of the Elliðaárdalur field (OR). The report includes a review of the production history of the Elliðaárdalur field where the changes in temperature and chemistry of produced fluid are illustrated and the processes in play discussed. Following that comes a chapter where improvements in the field management are suggested. The third chapter then zooms out and looks at challenges in the utilization of geothermal fields in urban areas in general based on results from a joint workshop between project partners. The last chapter summarizes the results and presents a roadmap for geothermal exploration and utilization. Note that the names R-xx and RG-xx are used interchangeably for the wells in Elliðaárdalur.

2 A conceptual model of the Elliðaárdalur field and review of production history

The Elliðaárdalur geothermal field (Figure 1) is located along the river Elliðaá which runs through the city of Reykjavík, the capital of Iceland. Between 1967 and 1984, 16 deep exploration/production wells were drilled in the area. Production from the field started in 1968. There are currently eight active production wells in the field and one inactive production well that has not been in use since 2019 due to high levels of oxygen and significant cooling. The remaining seven deep wells that were drilled were not deemed suitable for production due to low productivity or distance from the production site. The Elliðaárdalur field is located just west of the Krýsuvík fissure swarm with a main fracture trend of NNE-SSW. The area is within a zone of Quaternary rocks, characterized by lava flows, intercalated with hyaloclastites (e.g. Sæmundsson et al., 2016).

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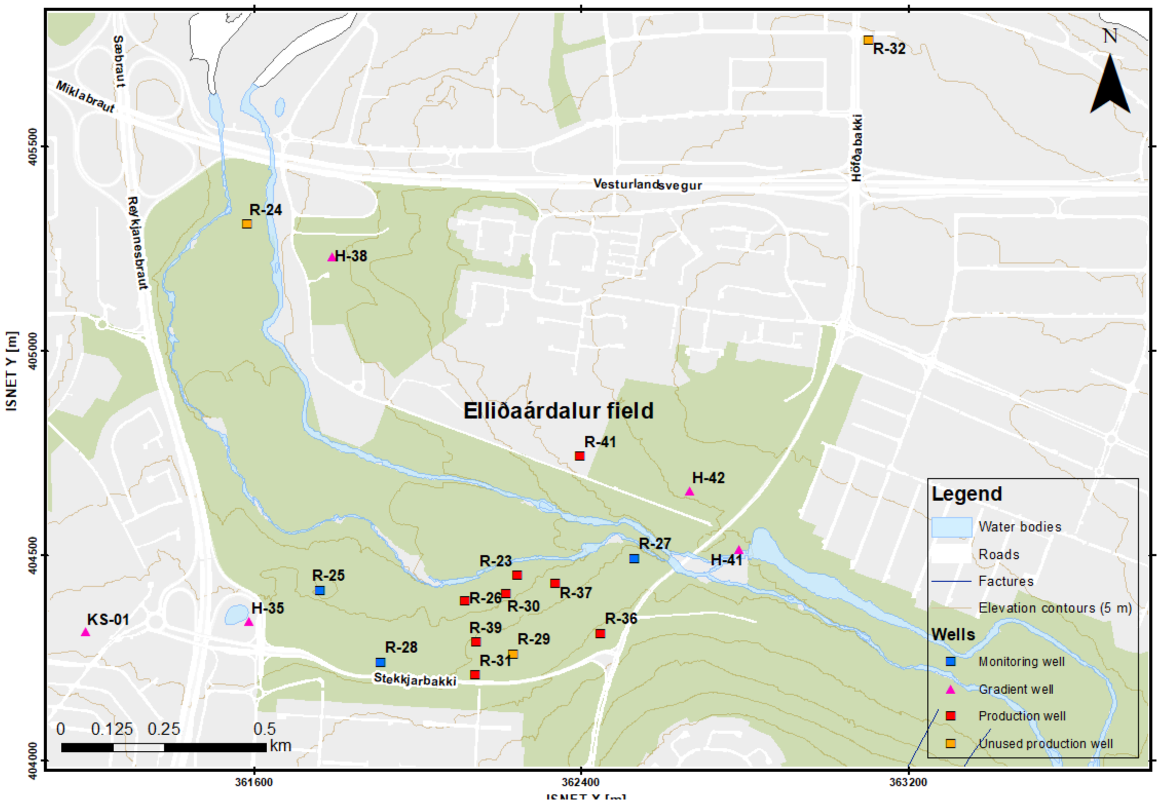

Figure 1. *Map of the Elliðaárdalur area showing wells, roads, elevation contours and water bodies. Active production wells are shown with red squares (Data source: National Land Survey of Iceland, Reykjavík Energy and ÍSOR).*

Tómasson (1988) divided the reservoir in Elliðaárdalur into three different zones, A, B and C. The topmost zone, zone A, lies within a basalt formation and reaches down to 500 m. The temperature in this aquifer zone was 40 – 90°C before production started. Several surface features connected to this zone were catalogued in the southwestern part of the field prior to production (Torfason, 1997). This zone also has a colder groundwater system into which the warm water rises. Below this cold groundwater aquifer is a second zone, zone B, which is a hot water aquifer. This zone is within a series of hyaloclastite formations and reaches between 650 – 800 m in the production area. It is generally thought to contain the highest temperatures in the Elliðaárdalur area, with temperatures that used to reach up to 110°C. Finally, a second hot water aquifer zone, zone C, is found between 1000 – 1250 m. This zone is within a series of basalt layers. The temperature in this zone has, in general, been slightly colder than in zone B, 70 – 115°C. Before production started, pressure was high in the B and C aquifers but lower in the A aquifers. (Tómasson and Thorsteinsson, 1983; Tómasson, 1988). A cross section through a 3D geological model constructed within the RESULT project (Helgadóttir et al., 2021) is shown in Figure 2.

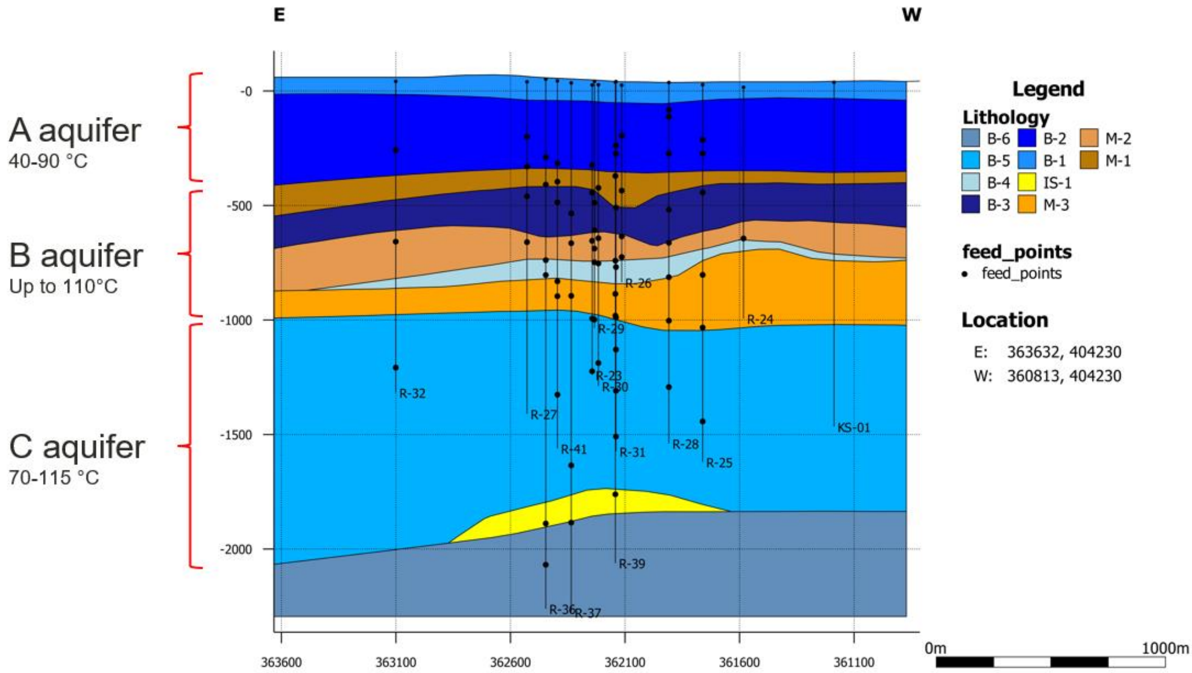

Figure 2. *An E-W cross section through a geological model of the Elliðaárdalur field. B-formations are basalt lava flows and M-formations are hyaloclastite formations. Feed points identified are shown for each well. The division into aquifers and the corresponding temperatures are from Tómasson (1988).*

The production zone itself is around ~1 km^2 and lies within a larger geothermal system that covers 8 – 10 km^2 (Tómasson, 1988). The production wells in Elliðaárdalur are located at the edge of a thin body of warm water that rises into the area from the north or north-east. Because of the system´s location by the margin of the thin body of warm water, the system is very sensitive to cold water recharge in response to production. Hence, cooling of wells in Elliðaárdalur was observed almost immediately after production started. This cooling results from various processes; pressure decrease in the hottest aquifer causing a greater portion of produced water to come from cooler aquifers, downflow of colder water to the deeper reservoirs through unused wells and fractures, and inflow of cooler water from the edges of the system. Due to its connection to an extensive colder groundwater system, the pressure in aquifer zone A has remained relatively constant over time (Tómasson and Thorsteinsson, 1983).

Figures 3 to 7 show a timeline review of the production history in Elliðaárdalur and corresponding changes in produced temperature and chemistry. The figures show that the production temperature has declined since the start of production, although the rate of decline has varied over time, due to well re-casing and drilling of new wells. Along with the temperature decline, the chemistry in the production wells has changed over time. This is most notable with the rise of the concentration of O_2 in produced fluid. These temperature and chemical changes indicate that the pressure decline in the hottest part of the system, aquifer zone B, has resulted in the infiltration of cooler water from the groundwater aquifer zone A into the lower, hotter zones. However, temperature measurements in sealed wells R-25 and R-28 in the SW part of the field show that, despite the inflow of cooler water, the formation temperature of the rock has not decreased noticeably (Figure 8).

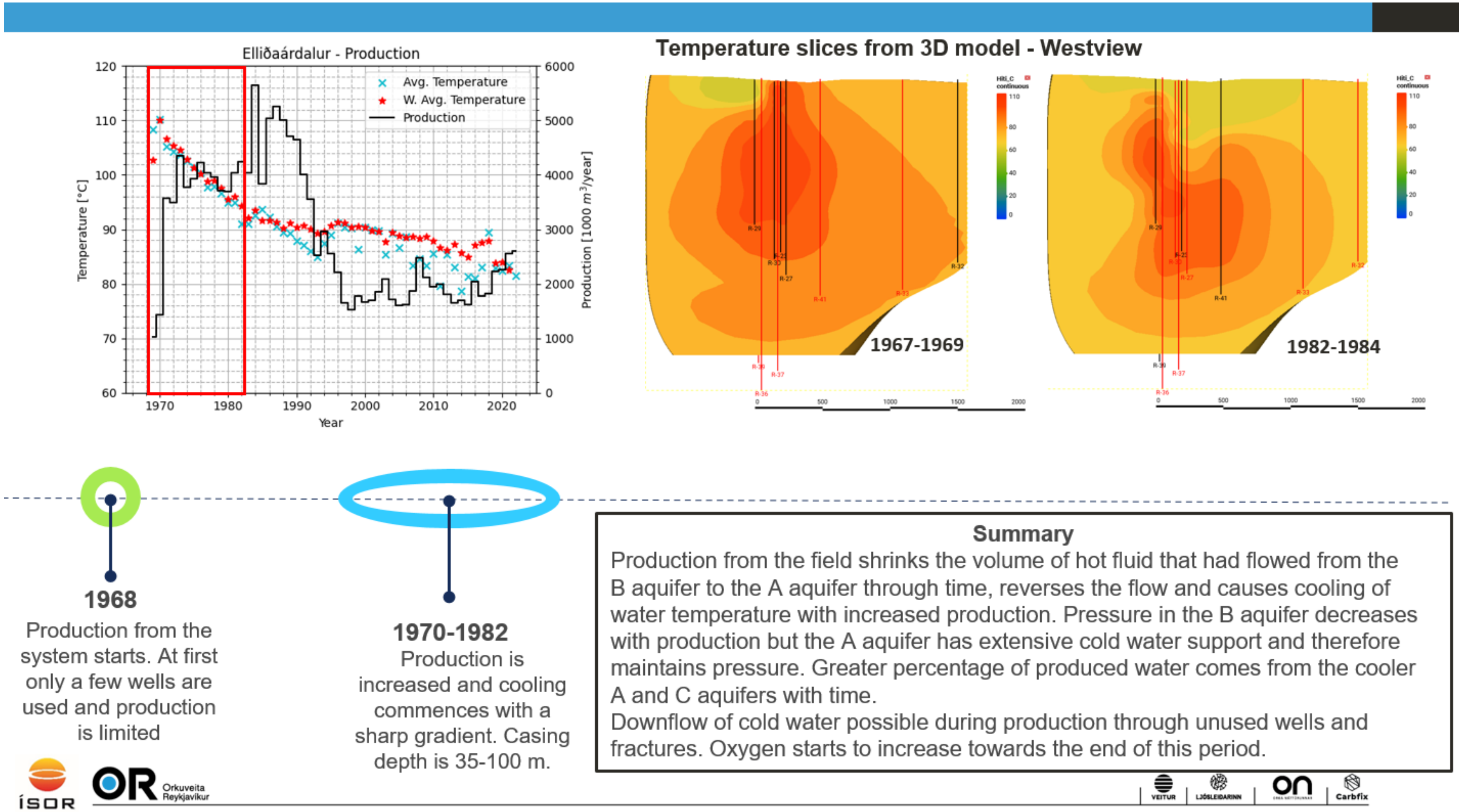

Figure 3. *Review of the production history between 1968 and 1982 and corresponding changes in produced temperature.*

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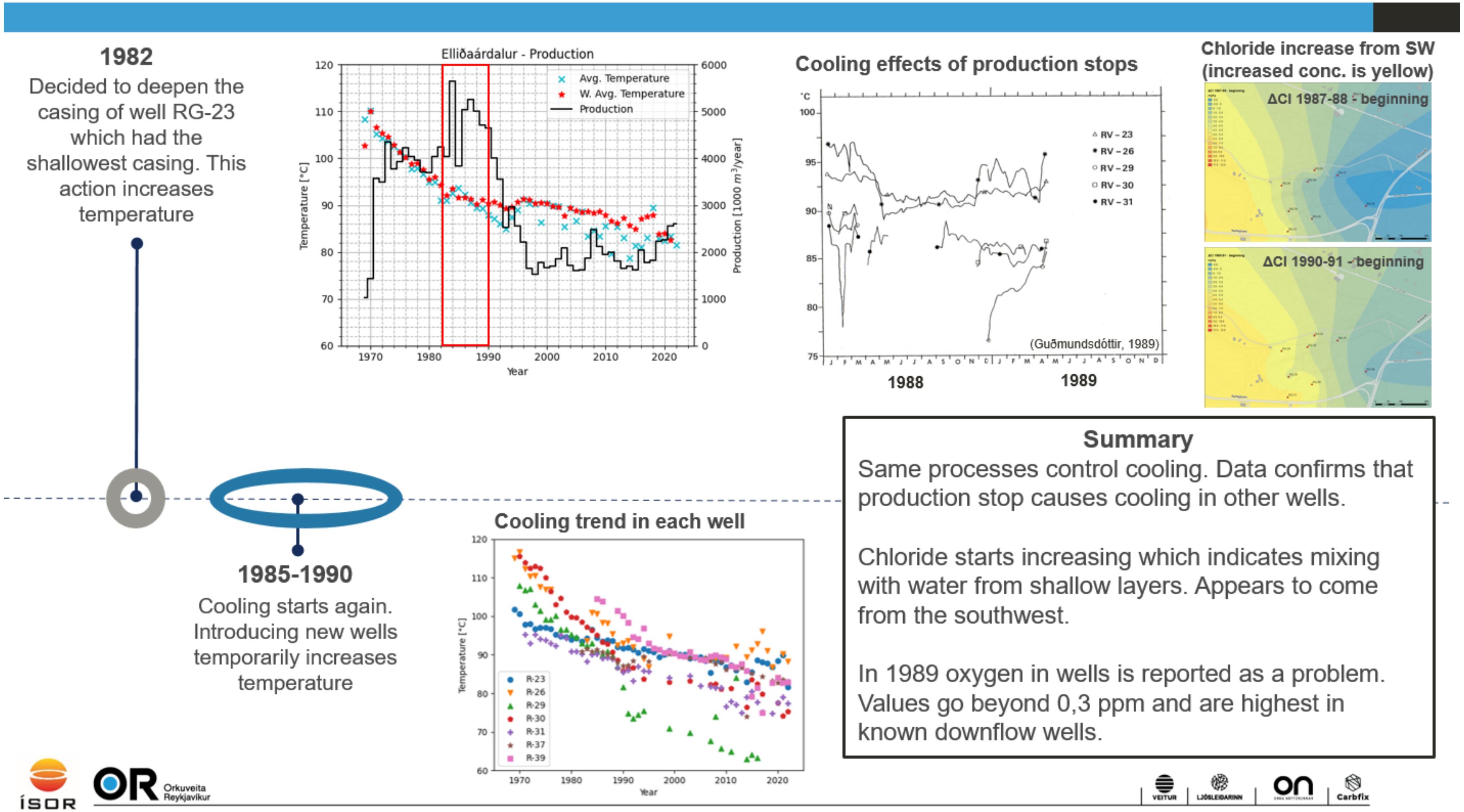

Figure 4. *Review of the production history between 1982 and 1990 and corresponding changes in produced temperature and chloride concentration in produced fluid.*

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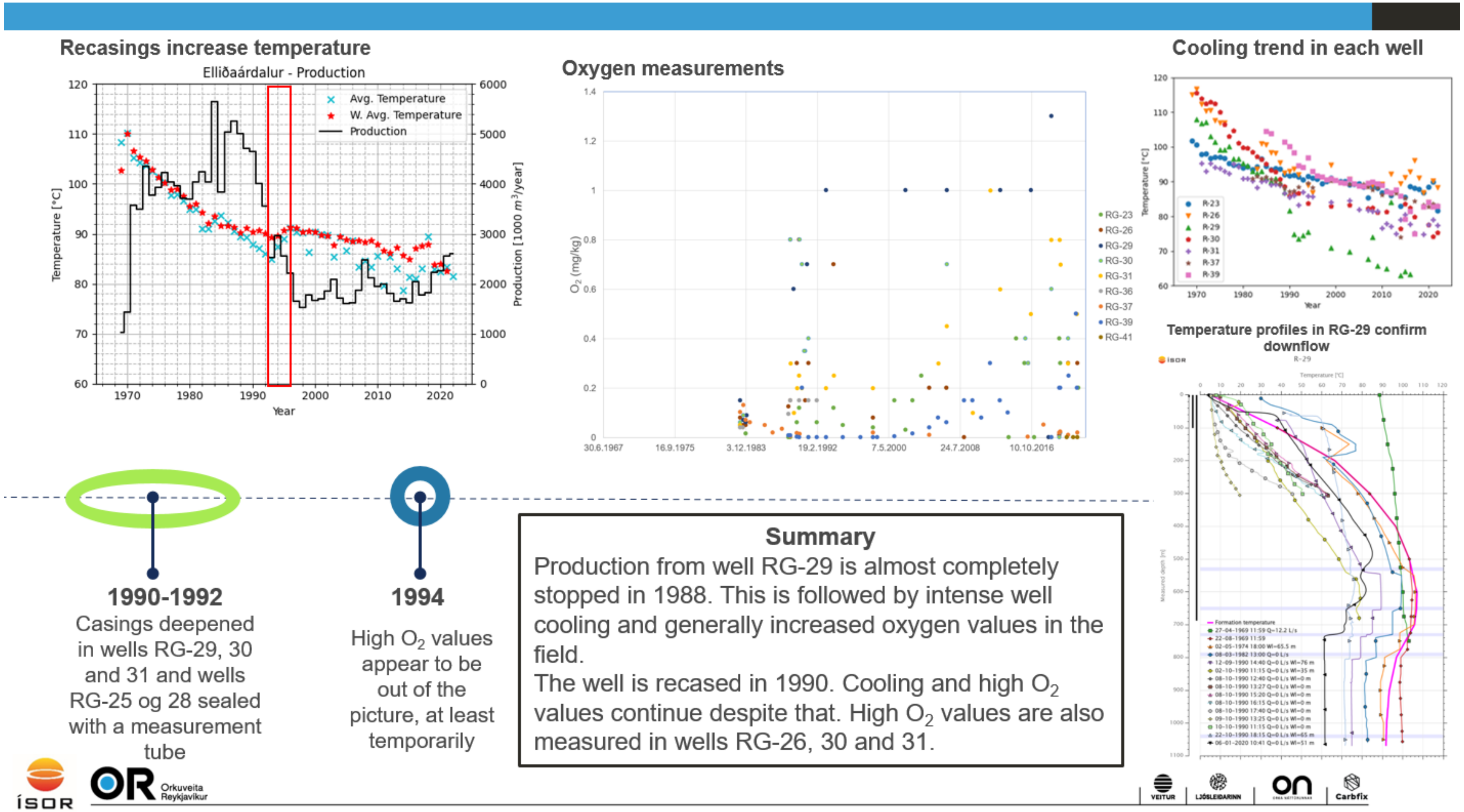

Figure 5. *Review of the production history between 1990 and 1994 and corresponding changes in produced temperature and O_2 concentration in produced fluid.*

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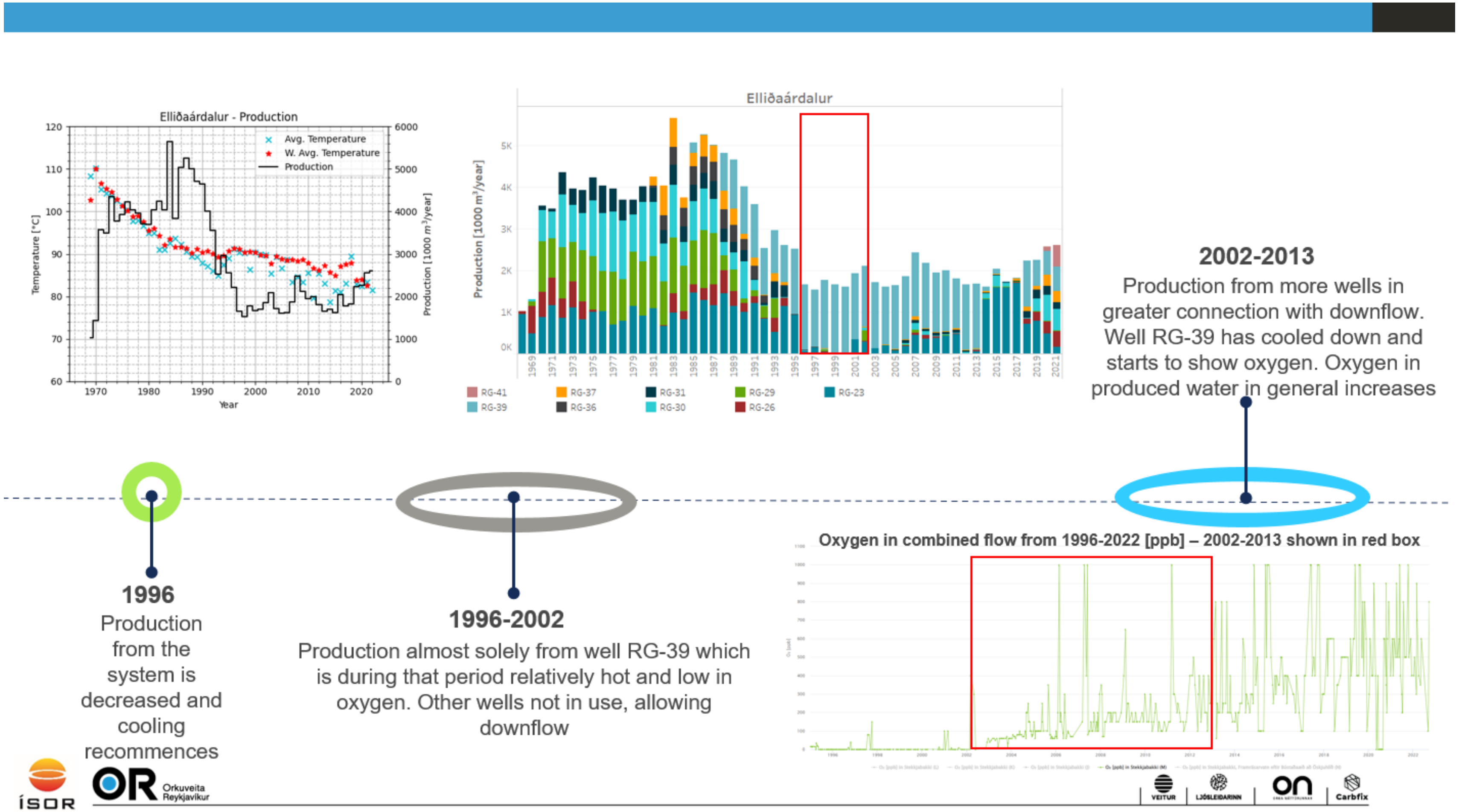

Figure 6. *Review of the production history between 1996 – 2013 and corresponding changes in produced temperature and O_2 concentration in produced fluid.*

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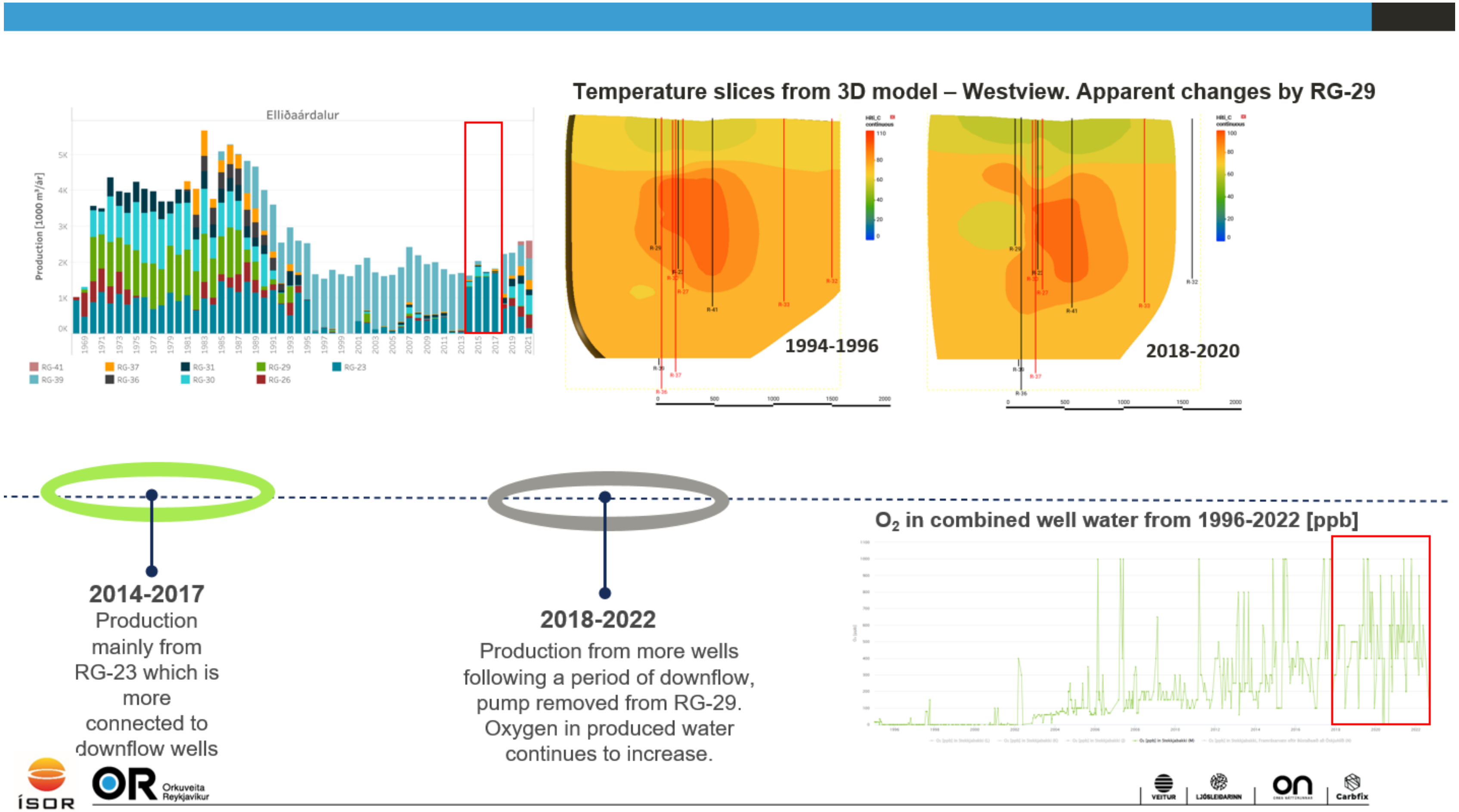

Figure 7. *Review of the production history between 2014 and 2021 and corresponding changes in produced temperature and O_2 concentration in produced fluid.*

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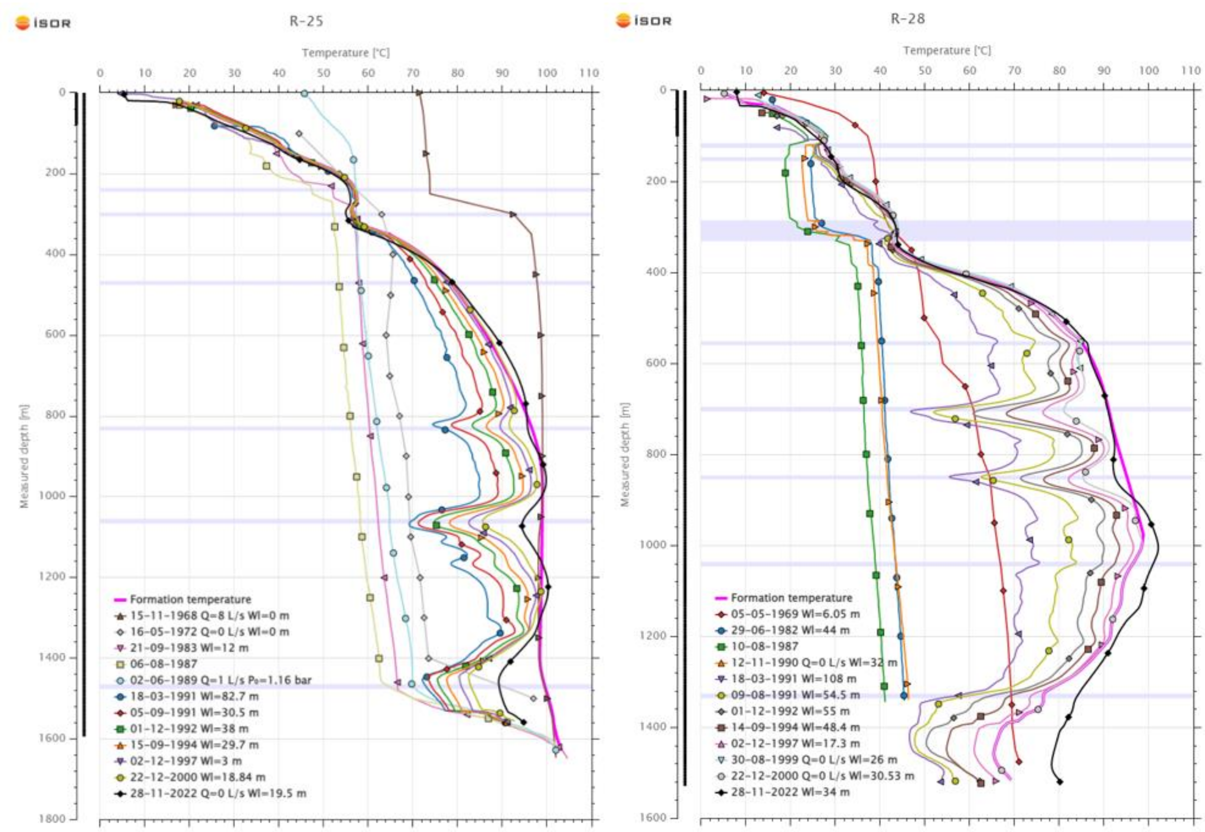

Figure 8. *Downhole temperature logs and estimated formation temperature for wells R-25 (left) and R-28 (right). The estimated feed zones in the wells are shown as blue shading, and the well casings are indicated as black vertical lines on the left. Both wells were sealed with monitoring pipes in 1991.*

3 Improving field management for optimal use

This chapter presents lessons learned throughout the project from the utilization history of the Elliðaárdalur field, suggests actions or changes in utilization based on the lessons and discusses current monitoring in the field and suggestions for increased monitoring in the future. Finally, the chapter contains a discussion on advances in geothermal drilling and potential methods that could be considered for future drilling and completion of wells in Elliðaárdalur.

3.1 Lessons learned

The characterization and survey (Jónsson et al., 2021; Helgadóttir et al., 2021; Helgadóttir, 2021; Tómasdóttir et al., 2022) of the Elliðaár system done as a part of the RESULT project has greatly increased stakeholder understanding of the system. The survey has highlighted the fact that the complex interaction between different reservoirs, or aquifer zones, in geothermal systems can have a big impact on the quality of produced fluid. Fluid removal from the deeper, hotter system has resulted in pressure decline of the system and allowed cooler fluid to infiltrate it. This intrusion of cooler fluid is not only through natural pathways, such as fractures and fissures, but also from idle production boreholes. Such idle wells can function as high permeability flow paths, and in the case of the Elliðaárdalur field, connect the cooler groundwater aquifer zone to the hotter part of the system. In Elliðaárdalur it has been shown

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that deepening casing in, and sealing of, such wells can help mitigate the effects of pressure driven cooling. Historical production data from the field also seems to indicate that maintaining a more stable production scheme across all wells, rather than allowing individual wells to idle over prolonged periods, can help to mitigate idle well downflow.

The cooling of the Elliðaárdalur system has also resulted in chemical changes in the produced fluid in the system. Of particular concern is the increase in the concentration of O_2, as that can make the fluid highly corrosive, and has resulted in damage to equipment and infrastructure in the field. The concentration of O_2 decreased temporarily following a re-casing campaign in the field between 1990 and 1992 but started increasing again around 2002 and has been increasing steadily since then. Cold groundwater is known to have higher concentrations of oxygen compared to geothermal waters in basaltic hosted systems as oxygen has generally been effectively removed by reactions with Fe^{2+} bearing minerals in the rock, at temperatures well below the temperature of produced water in Elliðaárdalur. This indicates that mixing of cooler water with the hotter, deeper waters is the reason for the increased oxygen. The fact that O_2 in substantial concentrations is found in produced water above 70°C in Elliðaárdalur is in addition a strong indication that this process must include rapid flow through short-cuts into the aquifers that feed the production wells. Whether this oxygen bearing water solely originates from shallower layers or also from cooler peripheral waters is, however, not completely understood.

Summarizing, the main lessons learned from the Elliðaárdalur field are:

- Idle production wells can function as highly permeable flow paths, funnelling colder water into hotter regions as the pressure in those regions decreases with production. This can then lead to a global cooling of the system. Casing and consistent production schemes can help to minimize these effects.
- Production from a geothermal field, like Elliðaárdalur, can lead to unwanted chemical changes in the produced fluid. Trends in chemical concentrations in the production fluid should be carefully monitored over the lifetime of the field, in order to increase the understanding of the processes in play.

3.2 Proposed actions or changes in utilization

3.2.1 Re-casing and/or sealing of wells

Based on the results of the survey of the field, several possible improvements/changes have been considered that could improve the productivity and longevity of the field. The first is the re-casing or sealing of well R-29 which has previously been proposed by Sigurðsson (1995). As was noted in D 6.2 (Tómasdóttir et al., 2022) the well has been largely idle over the lifetime of the field and has shown consistent temperature decline over the years. As can be seen from Figure 9 the temperature in the well has dropped from 90°C to 60 °C at the well bottom, and the temperature decline is the greatest of all the production wells in the field, as shown in Figure 10. Figure 9 also confirms there is significant downflow in the well, from a colder feed zone (~60°C) down to the hotter parts of the reservoir. This flow was quantified within the project using spinner measurements. These measurements confirmed that 14 L/s of water were flowing down the well at the time of measurement in February 2023 (Jónsson, 2023). This amount likely increases with increased production from the field and lower water levels. Sealing R-29 is expected to slow down the rate of cooling in the field. Samples were taken from the downflow at 750 m and 850 m depth and analysed for oxygen. The results showed 0.34-0.5 ppm and 0.18-0.4 ppm O_2, respectively (Clark, 2023). These results are comparable

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with values obtained from regular sampling of combined well water from the field. This indicates that it is unlikely that downflow through R-29 is the sole cause of oxygen in the field in general.

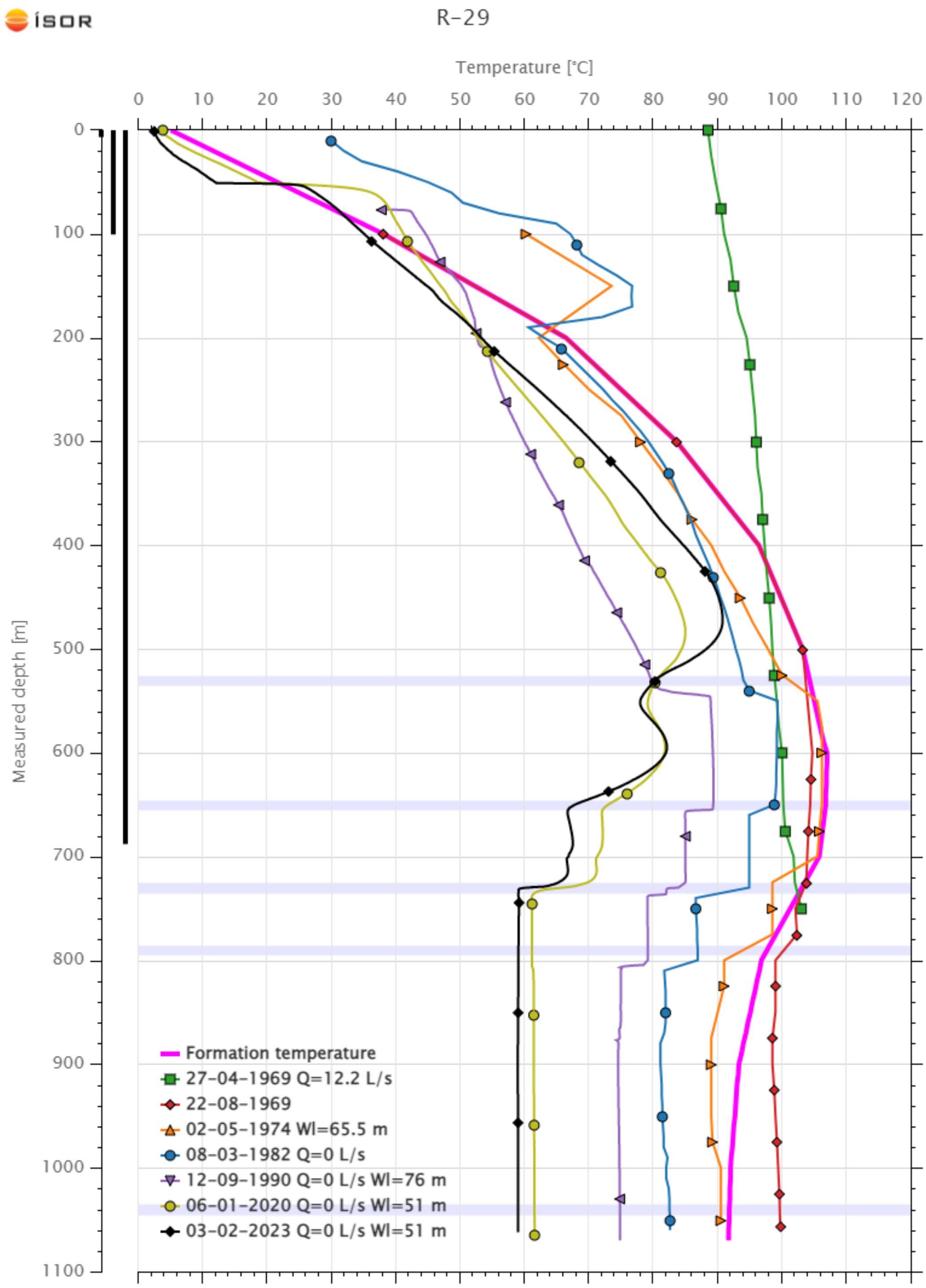

Figure 9. *Downhole temperature logs and estimated formation temperature for well R-29. The estimated feed zones in the wells are shown as blue shadings, and the well casings are indicated as black vertical lines on the left.*

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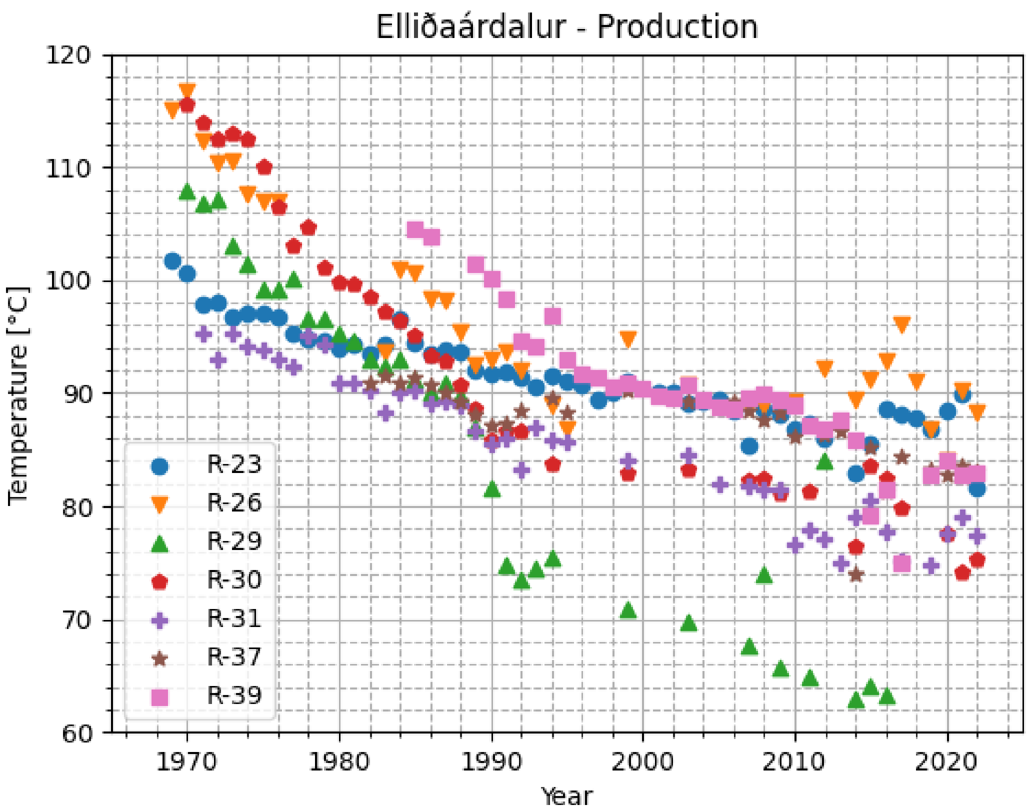

Figure 10. *Average annual production temperature for each production well in the Elliðaárdalur field with time. The substantial cooling in R-29 can clearly be seen.*

Re-casing other wells in the field with shallow casing depths, like R-26, as proposed by Sigurðsson (1995), might also help to slow down the rate of cooling in the field, by reducing the amount of borehole downflow in the field. Conducting a tracer test could aid in better estimating the quantity of cold downflow in these wells as well as the connectivity between the different wells, which could help in estimating the effectiveness of such re-casings.

3.2.2 Improved production scheme

As previously mentioned, leaving wells idle in the Elliðaárdalur field can allow colder water from aquifer A to reach aquifer B. This can cool down aquifer B, which also means that once production starts again in the previously idle well, the initial produced water is colder and then gradually heats up. An example of this can be seen in Figure 11. Changes in temperature after 2010 follow production changes in the wells for the most part. Prior to 2010 this correlation is harder to see, due to heating in the wells resulting from re-casings performed in the field in the 1990s. Stopping production in wells can also affect the temperature in nearby wells. This is illustrated in Figure 12 which shows the production temperature of R-26 during the winter 2022 – 2023. There is a clear correlation between reduction in production in wells R-30 and R-31 and cooling in well R-26.

Using a more consistent production scheme for the wells, i.e. maintaining similar production from every suitable/producible well in the field, rather than only producing from a subset of wells at any given time and letting the rest idle, could reduce cooling due to well downflow in

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the field. This would, however, require updating the current infrastructure in the field. The analysis conducted in this study, however, does not indicate that the field can sustain an overall increase in production as more production could exacerbate cooling by drawing in colder fluid from the edges of the system.

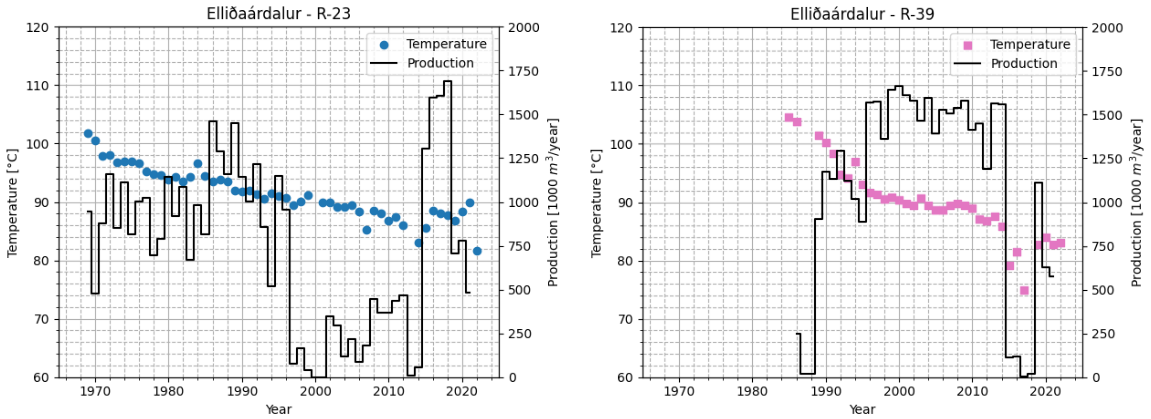

Figure 11. *Average annual production temperature and annual production rate for wells R-23 (left) and R-39 (right).*

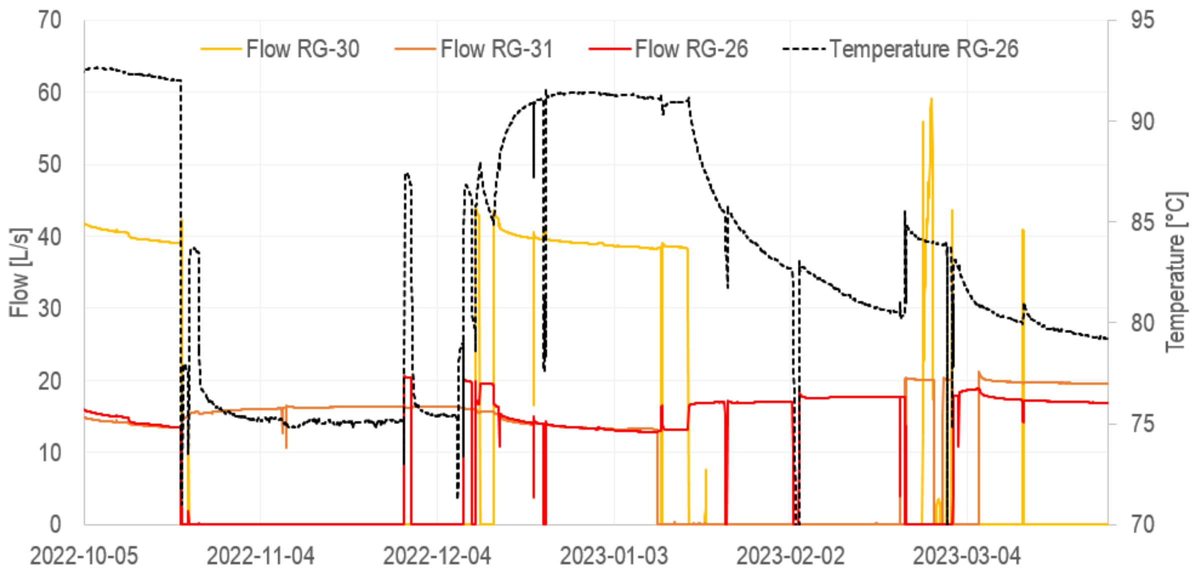

Figure 12. *Changes in production temperature for well R-26 corresponding to changes in flow from wells R-30, R-31 and R-26.*

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3.2.3 The use of chemical additives

As described in detail in deliverable 6.2 (Tómasdóttir et al., 2022) oxygen values in wells in the Elliðaárdalur field have increased substantially throughout the production history. The increase has caused corrosion and scaling of pumps and surface equipment which has required costly measures and repairs. Figure 13 shows pump failures for the active production wells in the Elliðaárdalur field between 2006 and 2023.

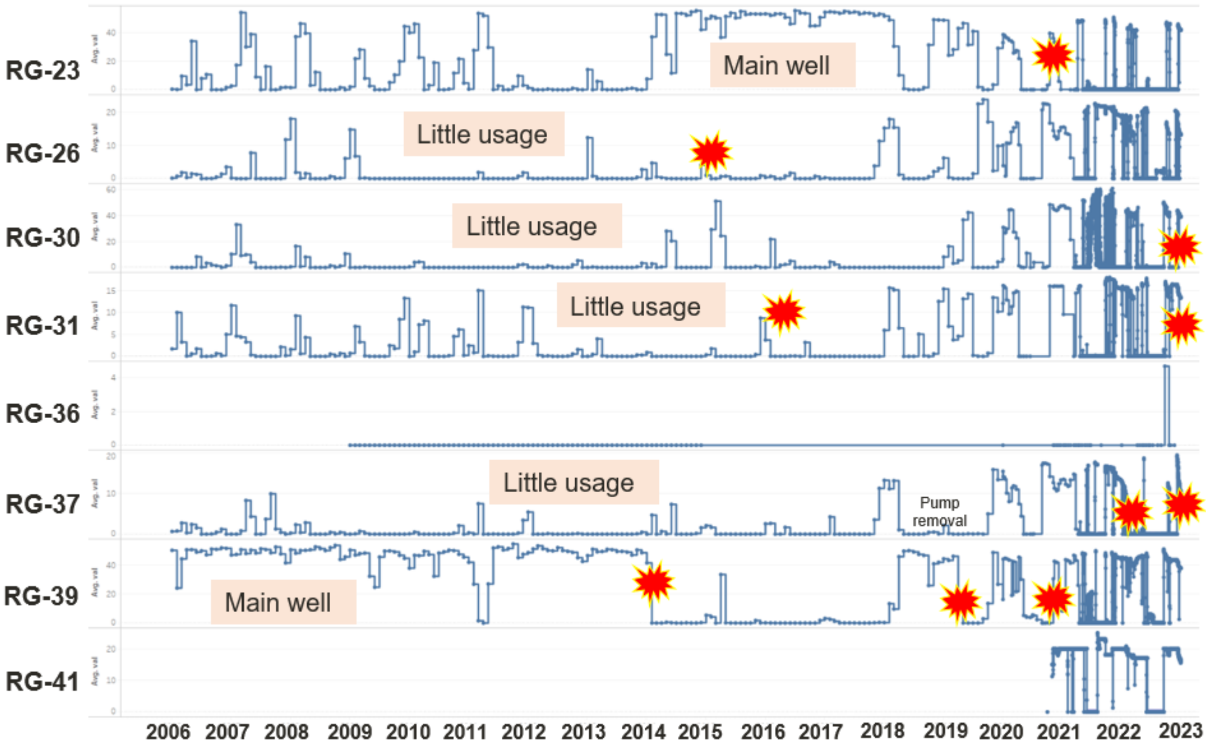

Figure 13. *Pump failures (red symbols) due to corrosion or scaling in the Elliðaárdalur production wells between 2006 and 2023 shown on a production graph (L/s) for each well.*

Elevated O_2 concentrations have not been a challenge in other low-temperature geothermal fields operated by Veitur Utilities, a subsidiary of Reykjavík Energy, as the hot water generally contains enough hydrogen sulfide to remove the oxygen. The increase in oxygen in the Elliðaárdalur field is the result of mixing with colder, oxygen bearing fluids. This can be water that percolates from the surface down into the geothermal system through fractures or other natural pathways, colder water at the edges of the hottest part of the geothermal system or crossflow through idle wells. Crossflow through idle wells can be prevented by sealing wells or by maintaining a more stable production scheme but flow of oxygen bearing fluids through natural pathways cannot be easily hindered. The use of chemical additives to scavenge oxygen is an option. This is, for example, done by the hot water utility in Siglufjörður in North Iceland. In that case sodium sulphate is mixed into the produced fluid on the surface before the water is distributed (Sigurðsson and Kristmannsdóttir, 1996). In the Elliðaárdalur field, which has higher oxygen concentrations, this setup would, however, not suffice as the main problem is downhole corrosion. Oxygen in the distribution system is solved by mixing water from the Elliðaárdalur field with water from the Reykir and Reykjahlíð geothermal fields which contains hydrogen sulfide. Injecting a small amount of concentrated sodium sulfite solution into each well is an alternative way to scavenge oxygen. That way the oxygen is removed as soon as it enters the production system thus preventing corrosion downhole and in wellhead equipment. This is fairly simple to implement because the pumps in the wells in the Elliðaárdalur field are lubricated by reinjecting a portion of the water coming out of the field downhole. Sodium sulfite could be mixed into the lubrication water to make a sodium sulfite solution before it is reinjected. Preliminary calculations of the reactions involved were made in the geochemical software PHREEQC within the RESULT project (Pálsdóttir and Brynjarsson, 2021). Further calculations and system design are now ongoing.

3.2.4 Possible reinjection

Downflow of oxygen bearing water at ~60°C was observed in well R-29 in February 2023. This was demonstrated by spinner logging and downhole sampling. At the time, in late February, the flow down the well was about 14 L/s. The flow rate is most likely sensitive to pressure difference between shallow and deep reservoirs and can be expected to be at a maximum when the when the water level in the production wells is at minimum. This downflow causes cooling in the system and transports oxygen containing water deeper into the system. One idea to stop this downflow of cooler water, that could also scavenge oxygen in the system, is to inject hot and H_2S rich water from the Reykir/Reykjahlíð systems into well R-29. Pipes from Reykir/Reykjahlíð already pass through the Elliðaárdalur field so this change would require only minor changes to the existing infrastructure. Injection of more than 10 L/s over the course of one hour and more than 5 L/s on an annual basis would, however, require permits and extensive seismic monitoring which can be costly as reinjection into a geothermal system within city limits has not been a part of the utilization to date.

The idea of reinjecting spent geothermal fluid (30°C) into the Elliðaárdalur field has also come up in the past. Between 40-120 L/s of such water that comes into the Stekkjabakki distribution station in Elliðaárdalur is currently disposed of into the sewage system as there is no use for the water. Reinjection of water at this temperature is, however, not deemed suitable in Elliðaárdalur as the system is small and flow paths between wells are short, meaning reinjection of cool fluid would only exacerbate the cooling already taking place in the field.

3.2.5 Drilling of new wells

Finally, drilling new wells in the field has also been proposed. The production history has shown that when new wells are drilled, they are initially hotter and contain less oxygen than older production wells. That was for example the case with well R-39 that was drilled in 1980 and connected in 1985. Figure 10 shows that produced fluid from R-39 was hotter than from other production wells until about 1996. Oxygen first started to appear in the well around 2001. Well R-41 was then drilled in 1984. That well was, however, located on the northern side of the river which was inconvenient for the distribution system. For that reason, the well was not connected for the first decades. Due to increased demand it was, however, connected in 2020. To this day the well is still oxygen free and is one of the hottest in the field. As previously mentioned, the production wells in Elliðaárdalur are located at the edge of a thin body of warm water that rises into the area from the north or north-east. Good hydrological connection from the production site towards the northeast is confirmed by water level measurements. Water level measurements in well R-32, which is located about 1.5 km to the NE from the centre of the production zone correlate well with measurements from within the zone and show more than 20 % of the water level fluctuations seen within the zone (Figure 14).

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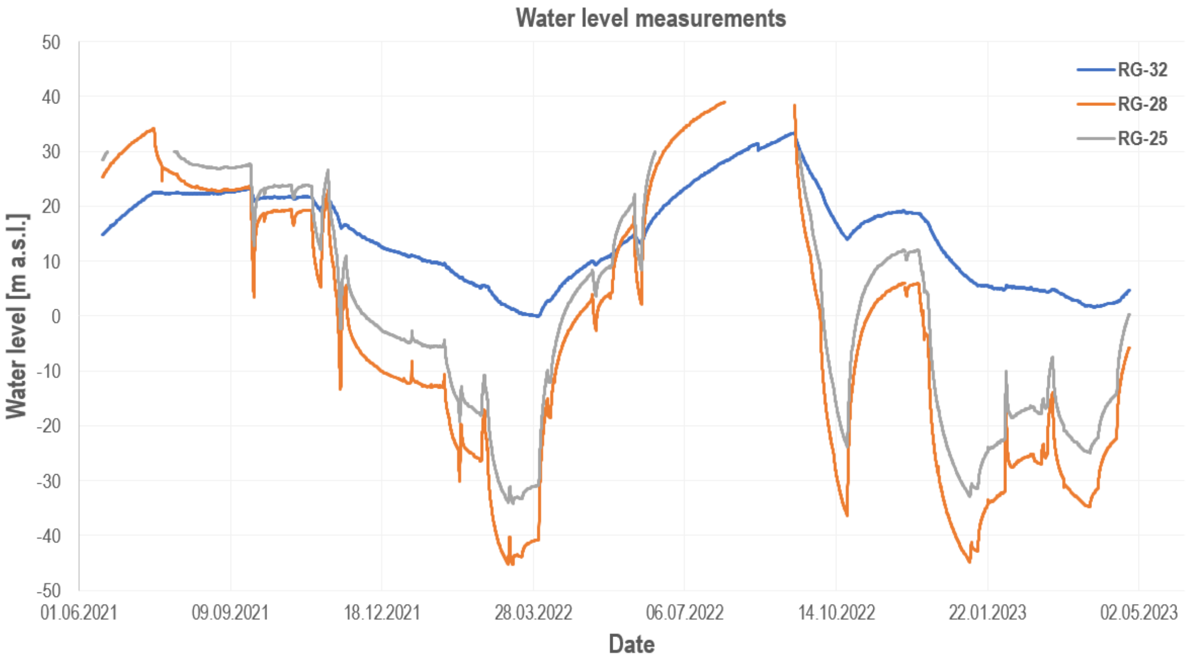

Figure 14. *Water level measurements in well R-32 located 1.5 km to the northeast of the production zone and wells R-28 and R-25 located at the southwestern edge of the production zone.*

One possibility could be drilling new wells to the NE of the current production zone to get hotter, oxygen free water, at least for the first years or decades. Moving the production zone to the north of the river to delay cooling was for example suggested by Tómasson and Thorsteinsson (1983). Wells outside of the main production zone have, however, not been as productive as wells within the zone indicating less permeability towards the edges. As an example of this it is worth looking at wells R-32 and R-41, which are north of the river, see Figure 1. R-32 produced 14 L/s of 73°C warm water when tested in 1971 and R-41 currently produces 20 L/s.

3.2.6 Monitoring of the Elliðaárdalur system

Regular chemical monitoring in Elliðaárdalur consists of annual chemical sampling in all production wells and biweekly H_2S and O_2 analysis of combined well flow. Flowrate, temperature and water level in each production well were logged biweekly but from 2021 flowrate and temperature are continuously logged. Water level in monitoring well R-27 is continuously logged. Temperature profiles are taken when pumps are removed from wells and are therefore more sporadic. There were very few such measurements taken between 1995 and 2018 but more have been taken since, in connection with pump failures. In addition to this more measurements have been conducted in connection with specific projects. These include isotope measurements and more frequent chemical sampling. In light of the challenges related to oxygen content it would be useful to have more frequent O_2 measurements in production wells in the future, especially to monitor the changes following the start of chemical additive usage in the area. A tracer test in well R-29 before it is permanently closed or put in production with chemical additives would give useful information on flow paths in the area. If the well will be sealed, a measurement pipe needs to be put in place to allow regular temperature profile measurements to shed light on how much the rock itself has cooled.

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3.3 Alternative drilling paradigms to enhance production from single wells

This chapter presents a discussion on recent advances in geothermal drilling and potential methods that could be considered for future drilling and completion of wells in Elliðaárdalur, along with potential methods that could be used to stimulate wells that have poor connection to feed-zones.

Drilling of production wells in Elliðaárdalur was primarily conducted in the years 1967 – 1969. During drilling of the first wells, prior to production, the system remained over-pressurized, and the wells were artesian. Feed zones were noticed during drilling not as losses but rather as hot inflows into the wells, visible on surface with increased temperature and additional return volume of the drilling fluid. In drilling of later wells the feed zones were noted as losses during drilling. Analysis of past drilling showed that drilling went smoothly for the most part with only minor problems. The reported drilling problems were predominantly hole collapses, difficult hole cleaning leading to slow drilling speed and stuck drill-string, and bad equipment quality of drill string and drill collars. Workovers were aimed at reducing cooling of the system and blocking oxygen from entering the wells by deepening the casings. Seven wells were re-cased to various depths and two wells were lined with a 2" cemented steel tubing to bottom for water level monitoring and temperature profile measurements. Following re-casings, cooling rates diminished in some of the wells, but the overall cooling of the production field continued.

Drilling equipment and methods in shallow low-temperature drilling have for the most part remained the same since the main drilling operations were conducted in the late 1960s in Elliðaárdalur. However, innovative developments have progressed, resulting in better quality equipment, quality control and procedures, to name a few examples. Improvements in geothermal drilling over the past decades go hand in hand with the increased knowledge and experience gained by drilling in various geothermal conditions. Drilling rigs and auxiliary equipment for shallow low-temperature drilling in Iceland are rather simple compared to their larger counterparts that can drill thousands of meters with hundreds of tons hookload capacity. Maximum depth capacity of these smaller rigs is around 2000 m. Recently, a combination of a larger drill rig with "low-temperature" auxiliary equipment has been used with good results. If relevant and economically viable, new technologies from oil and gas have occasionally been used and implemented in geothermal drilling. Drilling in various types of geothermal fields has, with time, resulted in improved practices, e.g. in better well design, targeting and drilling procedures.

Main advances in geothermal drilling in high-temperature areas include:

- well design, e.g., design criteria on casing depth and quality of casing and wellhead material
- targeting and surface footprint with implementation of directional drilling
- use of mud-motor that has increased drilling speed considerably
- increased control with the use of top-drive systems replacing rotary table and kelly drive, permitting torque deliverance to the drill string while moving the drill string, saving drilling time and reducing non-productive time
- increased quality control of drilling equipment, e.g. drill string components and drill bit, that has reduced unnecessary downhole problems by replacing the equipment before it reaches its usable lifetime limit
- increased information on drilling parameters with data acquisition systems

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Although directional drilling has been widely implemented in high-temperature drilling in Iceland, it was only recently used for the first time in Iceland in low-temperature drilling with good outcome, using one of the smaller drilling rigs. Using directional drilling in low-temperature drilling increases the potential of drilling successful wells where surface footprint and location of well pads is constrained. One successfully implemented practice in drilling for hot water in already producing fields is to use so-called underbalanced drilling, where conditions allow. The method where drilling is done with aeriated drilling fluid has improved hole cleaning with less cuttings plugging feed zones, leading to less need for stimulation after drilling. The method is excellent for fracture dominated hard rock formations. However, where unstable formations are expected it needs to be used with caution since the fluid column in the wellbore becomes lighter increasing the risk of well collapse. Additionally, the use of under-balanced drilling has less impact on nearby wells, since the effect of cooling and/or contamination from drilling fluids and cuttings is minimized. Air compressors are used to inject air to lighten the drilling fluid (usually water) within the well to generate pressure balance rather than loosing drilling fluid and cuttings into the formation, minimizing the risk of clogging. This has proved to work well even while production is ongoing in neighbouring wells. However, the method is costly due to use of compressors and is not always applicable due to formation conditions.

Many of the wells in Elliðaárdalur were stimulated after drilling using injection with well packers. These were, for the most part, successful in increasing the injectivity index of the wells. However, where wells are not well connected to the fractured system the use of packers is limited and therefore other actions may be required to increase their potential. Following is a discussion on novel stimulation methods that could potentially be implemented in hard-rock formations to target specific feed-zones of fractured reservoirs. Commonly used stimulation operations include matrix acidizing, air-lifting, cleaning through circulation, hydraulic fracturing with or without inflatable packers or localized between packers, and thermal cycling fracturing. Propellant stimulation using high energy gas flow (HEGF) has also been tried with some positive results, but is most effective for the near wellbore permeability (Sigurdsson, 2015). Matrix acidizing is mainly used to remove near wellbore permeability damage with the objective of restoring the well's inflow performance (Flores et al., 2005). Acidizing has thus less impact further away from the wellbore and is not likely to improve flow capacity within a fractured reservoir. Hydraulic fracturing can be done with wellhead water injection at high pressure, using a packer to pack off and pressurize a zone below the packer or by using two packers to stimulate a section of the well. Hydraulic stimulation has been used less in recent years in low-temperature wells, partly because air-lift aided (underbalanced) drilling has reduced the need for such stimulations (Axelsson et al., 2006).

In hard rock formations, such as basaltic formations commonly found in Iceland, the rock matrix permeability is close to zero and the global permeability of the formation is controlled by fractures that, when intersected, provide feed-zones into the wellbore. When drilling into such fracture dominated systems, as found in Elliðaárdalur, feeding fractures can be bypassed resulting in low productivity of the well. Stimulation by injection is unlikely to open-up new flow paths towards fractures in such wells. Where such feed-zones are not present, the condition may be such that the well path has only slightly missed the fractures and a pathway between the wellbore and the fracture could immensely improve the productivity of the well. The most prominent method may be to side-track out of the well. This requires a cemented whipstock to guide the drill bit out of the wellbore, closing off the section of the well below the side-track, or by using a retrievable whipstock that can be a complex and costly operation.

In these situations, where poor connection is found between the wellbore and the formation's fractured feed zones, novel stimulation approaches by use of mechanical methods may have greater potential than conventional stimulation methods. Methods that could provide extended reach into the formation may include full size side-tracking or the drilling of smaller diameter laterals. New “stimulation” methods of drilling narrow laterals out of the main wellbore have been developed over the past decades. The main ones are radial-jet drilling (RJD) (Figure 15) that cuts a hole into the rock formation with high velocity nozzles, and fishbone drilling (Figure 16) where laterals are drilled mechanically with rotating motors, both requiring specialized equipment and a drill rig on site. These novel methods have been implemented in the oil and gas industry, mainly in sedimentary formations. New methods are being developed to produce laterals effectively, e.g. Fraunhofer’s novel micro drilling turbine (Figure 17) that builds on the same principle as RJD. As for the previously mentioned propellant stimulation method, these methods may require, or benefit from, a conventional follow-up stimulation, as described by Sigurdsson (2015) on propellant stimulation, where cleaning of debris and rock cuttings may nevertheless be needed. For such small diameter laterals, only around 1-2 inches (25-50 mm) to provide enough influx into the well without too much pressure drop, several successful laterals are needed.

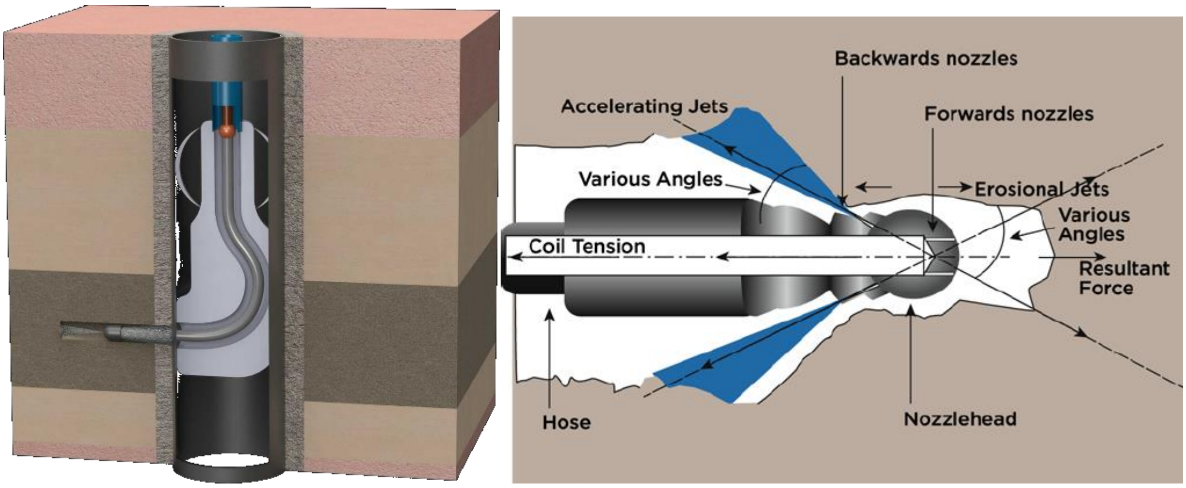

Figure 15. *Left: A deflector shoe is placed in the wellbore and coil tubing with attached nozzle feed led through it and directed towards the wall of the borehole (Reinsch & Blöcher, 2017). Right: setup of a nozzle head used in radial jetting (Peters et al., 2015).*

These methods have predominantly been used in sedimentary basins where matrix permeability is present. However, the methods could well be used to connect to nearby structures of wells in fracture dominated systems that are poorly connected. The potential for such stimulation is large within Iceland. RJD was tested in North-Iceland within the EU supported Horizon 2020 project SURE (Kaldal, et al., 2020), the principle was proved at the surface by jetting holes into blocks of basaltic rocks, but the technique needs further full-scale trials to prove its viability in hard rock formations.

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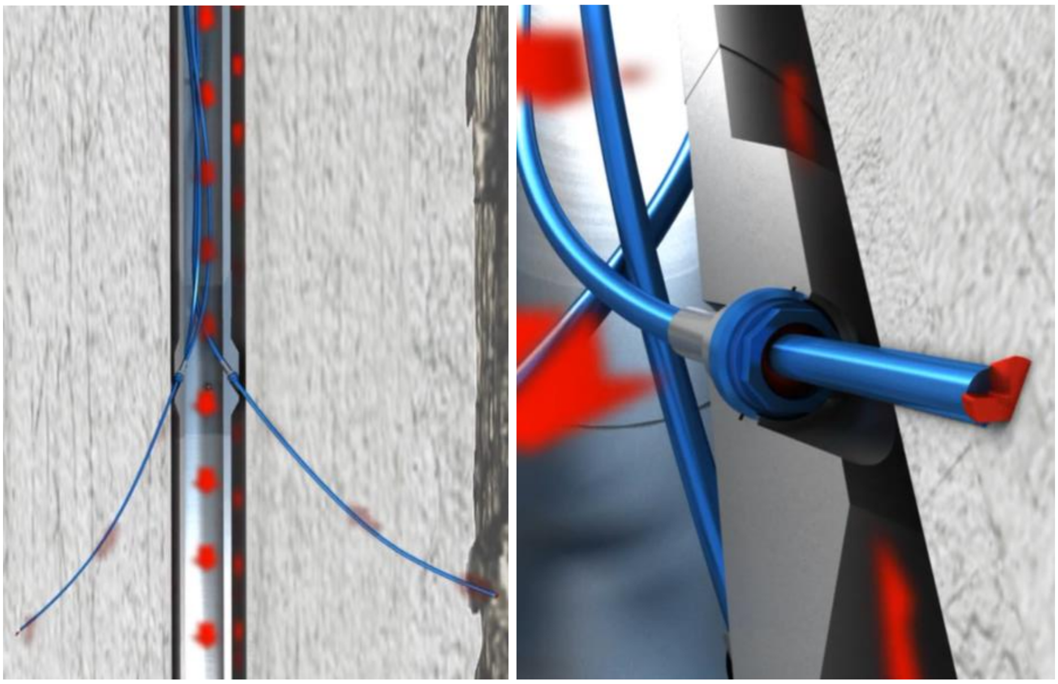

Figure 16. *Fishbone drilling (https://www.fishbones.as/drilling).*

Figure 17. *Micro-turbine tool. Deflection shoe directing the drilling tool outwards at a 45° angle (Fero, 2022).*

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For these novel methods to work, information on the formation is needed. Well logging, i.e. temperature, pressure, caliper and televiewer can greatly improve decision making during and after drilling, as these are used e.g. to locate loss- or feed-zones, determine the cement volume needed, and improve understanding of fractures.

Directional drilling could be an option for increased reach below now populated residential areas. When drilling in the Elliðaárdalur area started in the late 1960s it was on the outskirts of Reykjavík. The situation now is quite different as residential areas have progressed on both sides of the Elliðaárdalur valley. Directional drilling technology was not available in 1967 – 1969. Since the 1980s the method has been increasingly used in drilling of high-temperature wells where a single drilling platform can support several wells, both increasing reach and reducing impact on the surface with several wells drilled from the same platform. Directional drilling could potentially be used for drilling new wells in Elliðaárdalur, for example to the north below a residential area (Ártúnsholt), where models, and temperature logs, indicate slightly increased temperature than in the current production field. Drilling vertical wells is likely not possible within the residential areas due to footprint of the drilling rig and public acceptance. The possibility of using directional drilling in Elliðaárdalur will depend on drill rig capacity and limitations of maximum torque and drag along with accessibility, and limitations in accessibility and drilling pad size, Potential speculative scenarios of directional drilling are shown in Figures 18 and 19. Note that these suggestions are only speculative scenarios that would need to undergo a special study in order to become a reality, taking into considerations drilling targets, techniques and possibly permits, to name a few.

Additionally, mud-motors that are needed for directional drilling have generally not been used for low-temperature drilling. They could potentially be used for drilling deeper sections and increase drilling speed substantially, leaving more time for well testing and stimulation if needed.

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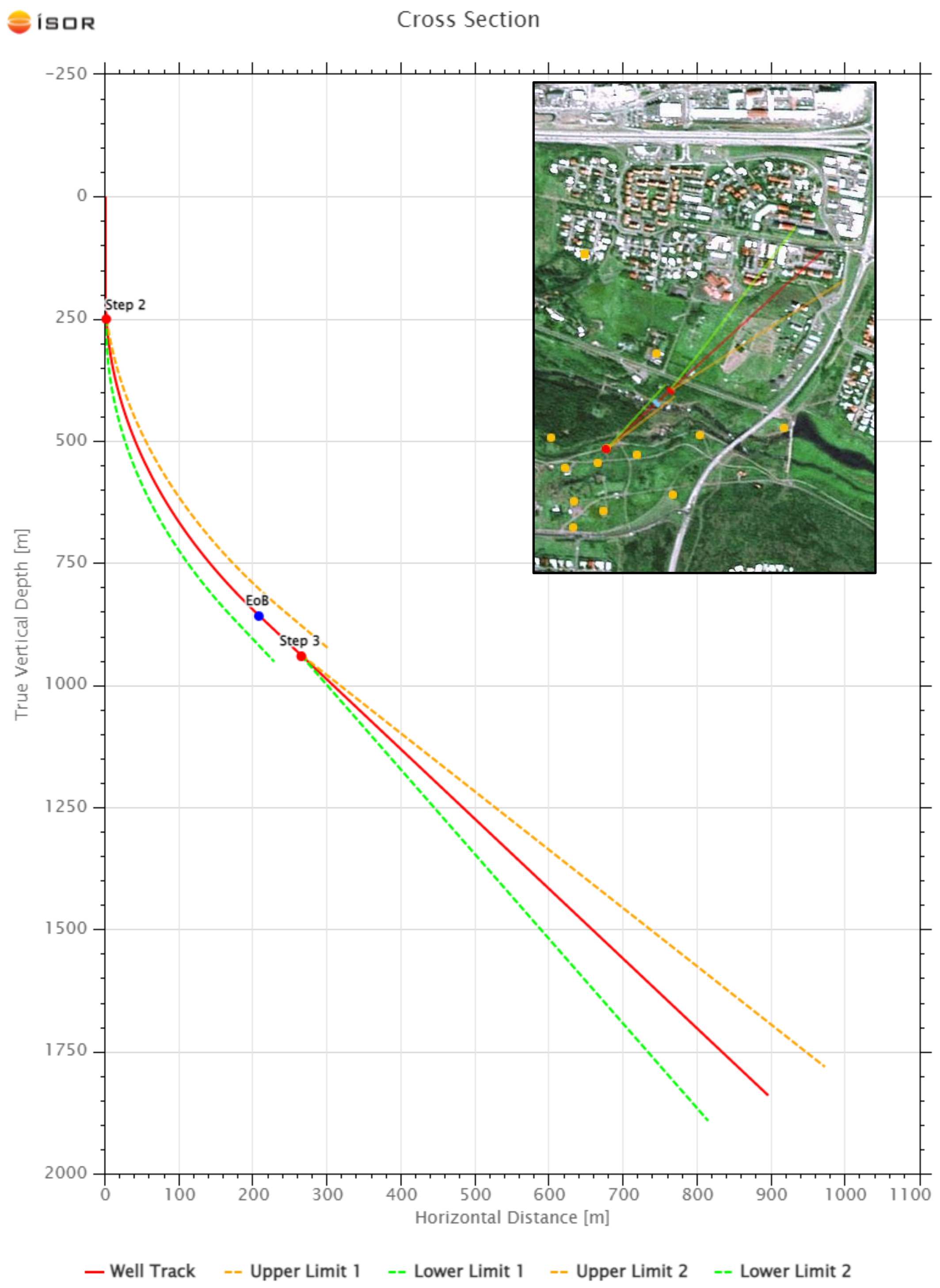

Figure 18. *Speculations on directional drilling that could provide extended reach below Elliðaár river and residential area (Ártúnsholt) to the northeast where temperature model shows increased temperature.*

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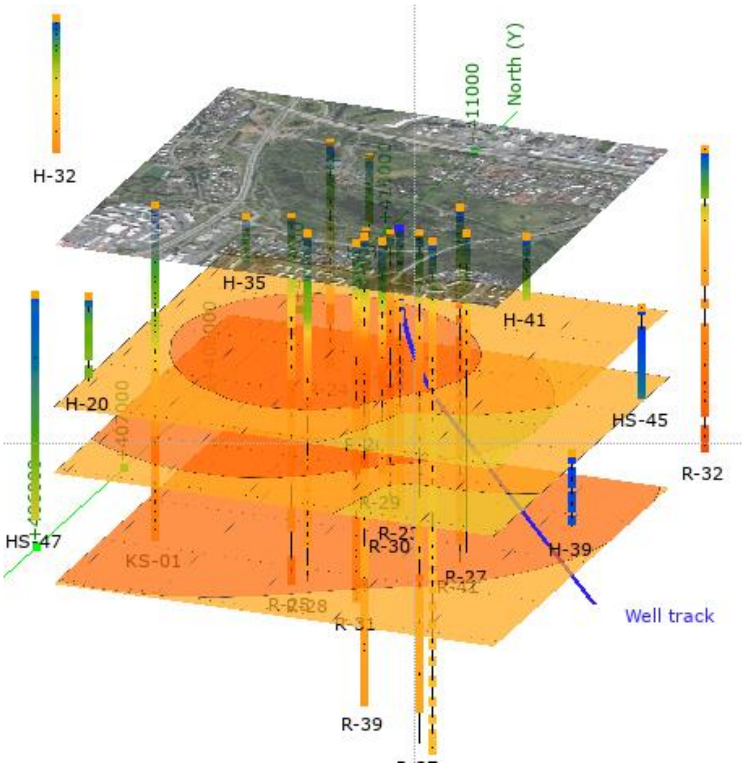

Figure 19. *Speculations on potential well track to the northeast using directional drilling.*

DTH air hammers are used to drill the uppermost sections of the wells until the water table is reached, which is where the drilling method is changed to rotary drilling with generally slower ROP with weight-on-bit (WOB) and rotation of the tricone drillbit as the main rock destruction mechanism. Water hammers have been developed where the DTH air hammer technology is extended to be used in water with air lifting support with promising ROP of over 10 m/hour (Wittig, 2022). Improved DTH fluid hammer is in development in the EU Horizon 2020 supported project GEO-DRILL, using non-mechanical hydraulic DTH percussion system (Fraunhofer IEG) able to drill in mud and water at higher temperature e.g. >250°C (Wittig, 2022).

The main challenges with the utilization of the Elliðaárdalur geothermal field have been cooling of the system and oxygen contamination of the produced fluid that contributes to corrosion problems in the surface and downhole piping system. Both problems have been somewhat mitigated by deepening of casings in some of the wells as discussed previously in this report and in earlier reports. However, some wells may still need to be deepened or abandoned to avoid cross flow. If new wells will be drilled in the area, replacing older ones, one could consider the following:

- Set casing depth deep enough to seal off cold feed-zones (>600 m) taking main feed-zones of current wells into consideration
- Use proven drilling methods to improve productivity, i.e. underbalanced drilling
- Directional drilling for extended reach
- Side-tracking out of current unproductive wells
- Testing novel “stimulation approaches” as discussed in this section

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4 Geothermal utilization in urban areas

OR organized an online workshop on the 21st March 2023 where all partners in the RESULT project were invited. The aim was to discuss challenges and opportunities with utilization of geothermal reservoirs in general and to get a view of the different challenges the participating countries have met with geothermal exploration and utilization. The Mentimeter (Mentimeter, 2023) software was used for an interactive session focusing on the following questions:

1. What do you imagine to be the biggest challenges with long term utilization of geothermal reservoirs?
2. What challenges come with utilizing such systems within urban areas?
3. What are the most important parameters to monitor?
4. How can we make monitoring and system understanding more cost effective?

The following subsections summarize the workshop answers to the questions and introduce case studies from other participating countries.

4.1 Challenges with utilization

The response from workshop participants to the first question can be seen in Figure 20. Summarizing, the main challenges identified are, in no particular order:

- Reservoir cooling and maintaining production temperatures
- Maintaining pressure
- Accurate monitoring and understanding of the reservoir
- Chemical changes, and resulting damage to infrastructure
- Equipment maintenance and reliability
- Good management
- Costs

Many of the factors mentioned have been discussed in other reports in the RESULT project (Helgadóttir et al., 2021; Jónsson et al., 2021; Jónsson, 2023; Tómasdóttir et al., 2022) as well as in this report. Other factors, like reservoir modelling, well maintenance, pump reliability, management cost and environmental factors have not been investigated as a part of this project.

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Figure 20. *Results from participants to the first workshop question.*

The next question focused on the challenges with utilizing geothermal systems in urban areas in particular. The answers can be summarized as:

- Obtaining the necessary permits
- Lack of space for drilling and for maintenance challenging in urban areas. Companies need to compete for surface area with other infrastructure. There can be a lack of understanding of the importance of considering the geothermal infrastructure in further urban planning and the space needed for its maintenance
- Possible seismicity during drilling and utilization
- Public acceptance or perception of geothermal projects within urban areas
- Exploration challenges within urban areas, noise can affect data quality
- Limited resource available
- The risk of subsidence/rising due to utilization and limited offset data
- High costs and complexity
- Thermal or chemical pollution to groundwater

Participants from the Netherlands and Ireland gave examples of challenges faced in their geothermal utilization or exploration. In the Netherlands this involved corrosion and scaling processes during utilization due to saline brines while in Ireland the challenges stemmed from conducting subsurface exploration of a new system in an urban enviroment. The next two chapters present lessons and results from these two countries.

4.1.1 Corrosion and scaling processes in the Netherlands

There is substantial information available on the risk of corrosion in geothermal assets and case studies in the Netherlands. So far, there has not been much corrosion due to oxygen ingress and H_2S reported but galvanic and CO_2 induced corrosion are two common types of corrosion observed in the Dutch systems. In some of the plants, due to the higher risk of calcite precipitation in the upper section of the production well and surface facilities at higher temperatures and lower pressures, one of the mitigation measures was to increase the surface pressure in order to keep the CO_2 dissolved in the brine. Even though this approach will minimize the calcite precipitation risk it can increase the risk of corrosion induced by CO_2. The main mitigation measure in the Netherlands is the use of chemical inhibitor injection. The common practice in the well design in the past was to mainly use carbon steel or low alloy steel and producing the fluid in the casing without any production tubing or liner. High costs of inhibitor injection (due to high production volumes) and challenges for continuous well integrity monitoring (due to unavailability of the annulus to monitor pressure) led to the new standard for geothermal well design which was proposed in the Netherlands. This standard provides a design process to ensure safe geothermal wells and includes a risk analysis, minimum requirements for design and a set of measures taken during the entire life cycle of the well to prevent leakage of formation fluids to the subsurface. The standard also requires a double barrier in the upper section of the well to physically separate corrosive formation brine from the outer casing and continuous monitoring of the annular space. The standard is mandatory for all members of Geothermie Nederland, and new well designs must be submitted to SodM (State Supervision of Mines) for review to ensure compliance with Dutch laws and regulations (Mathiesen et al., 2021).

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4.1.2 Geophysical surveys in urban environments – the Geo-Urban project in Ireland

The Geo-Urban project explored different methods for geophysical exploration of geothermal resources within urban environments, using passive data collection techniques. Such techniques are cost-effective, non-invasive and limit the disruption caused by geophysical exploration in dense urban areas. Two different passive techniques were tested in Dublin City as part of the project, passive seismic survey and a resistivity survey. The passive seismic survey collected ambient seismic noise from natural and anthropogenic sources, rather than active artificial seismic sources. While the technique provided high quality data in a region where a more traditional seismic survey would be difficult to undertake, the passive survey had two main drawbacks. The first of these was that the quality of the data gathered was deemed insufficient to assist in detailed designs of wells, and the second was that the duration of the survey was significantly longer than for a more traditional active seismic survey. Nevertheless this technique has proven valuable for early-stage exploration. The second technique used was a magnetotelluric electromagnetic method (MT), which is used to determine the distribution of electrical resistivity in the subsurface. This method is commonly used in geothermal exploration to estimate the extent and temperature of geothermal systems. As a part of the project an MT survey was conducted in a public park in the city, over a single night. The hope was that this would limit the anthropogenic noise in the measurements. However, a nearby artificial source rendered the data unusable (J. McAteer, Personal communications, 2023).

4.2 System monitoring

The second part of the workshop dealt with parameters that should be monitored during the running of geothermal facilities. The participants' answers to the question *What are the most important parameters to monitor?* can be seen in Figure 21. They can be summarized as:

- Temperature
- Pressure or water level, both in the reservoir (monitoring well) and in production wells
- Chemical composition of produced water
- Well production
- Flow paths within the reservoir, for example by tracer testing
- Seismicity, both natural and from utilization
- Possible pollution stemming from utilization
- Public consumption and acceptance

Wells should be logged for temperature and pressure regularly or when pumps are taken up for maintenance or other reasons. Spinner tests should also be part of the monitoring. It is recommended to monitor all parameters digitally if possible. All models, simple and detailed should be revised based on new data.

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Figure 21. *Results from participants to the third workshop question.*

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The last question of the workshop was *How can we make monitoring more cost effective?* A part of the participants' answers can be seen in Figure 22. They can be summarized as:

- Good management and good management systems
- Sharing of data and experiences among stakeholders
- Raising public awareness and including the public in responsible management of the resource
- Simple, cost-effective models at all stages of utilization
- Adaptive monitoring of the resource and its usage, e.g. seismic, pressure, temperature, and weather influences. Introduce new technology as it becomes available.

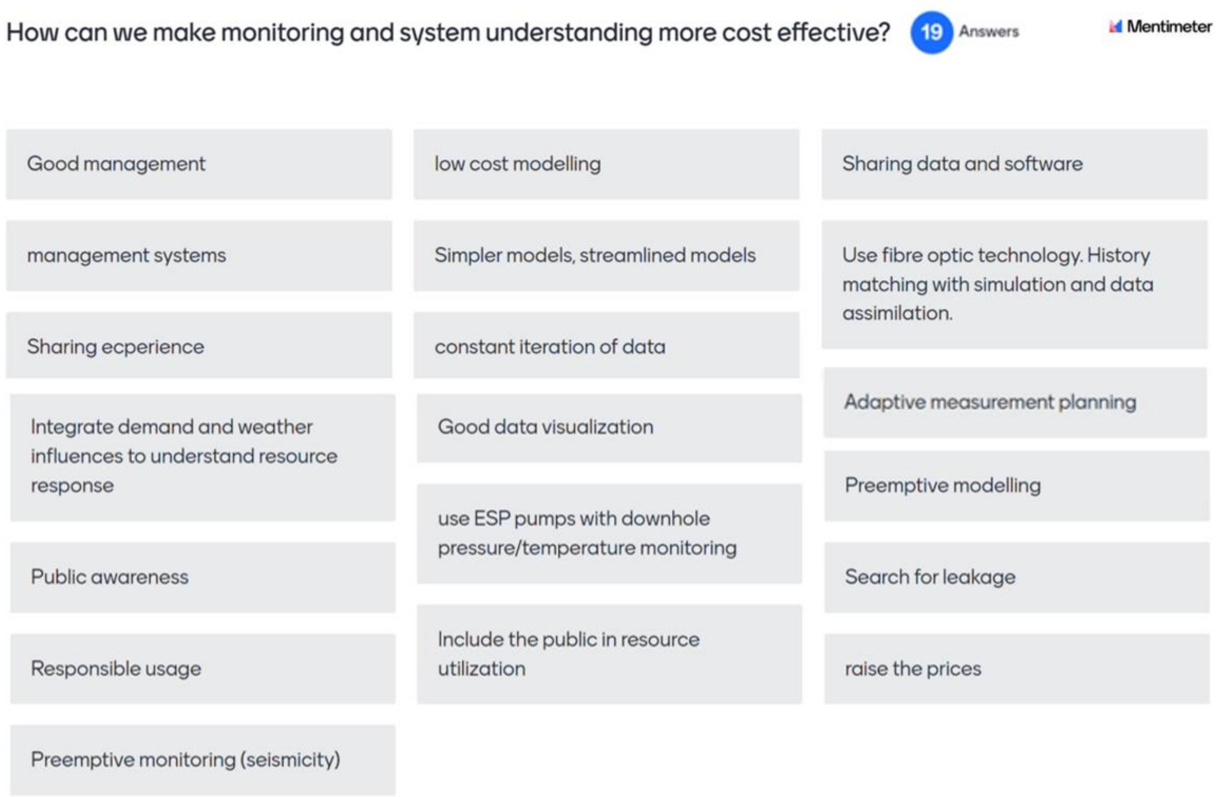

Figure 22. *Results from participants to the fourth workshop question.*

5 Conclusion - Roadmap for responsible production from wells in urban areas

The key result of the workshop discussed in the previous chapter is that the challenges of geothermal utilization in urban areas are versatile. The public perception is a big challenge, since fields in urban areas will, by definition, be more visible to people in day-to-day activities. This closeness to often densely populated areas means that exploration, maintenance, and expansion of urban fields is more challenging than in other, more rural, fields. This also means that the effects of pressure changes and chemical changes can be more noticeable to the public, for example in the form of increased seismicity and possible groundwater pollution.

The previous chapters in this report discussed challenges faced over long-term utilization of the Elliðaárdalur geothermal field in Iceland, such as system cooling, chemical changes and crossflow through idle wells. Possible actions and changes in utilization were suggested. The work and discussions presented here can hopefully highlight potential challenges in operating geothermal fields in other countries, give examples of necessary monitoring and spark ideas to combat said challenges.

Figure 23 shows a roadmap of the process from geothermal exploration, to drilling and testing, onto initial utilization and from there onto the long-term utilization phase. Updates and revisions of conceptual models and production schemes based on data gathered are important. The discussion in the workshop shed light on the fact that not only are the conventional monitoring of pressure, temperature, and chemical composition important in urban fields, but also monitoring of public awareness of the utilization. Any management of such urban geothermal reservoirs means not only managing the resource and its general usage, but also includes engaging the public in helping with treating the resource responsibly.

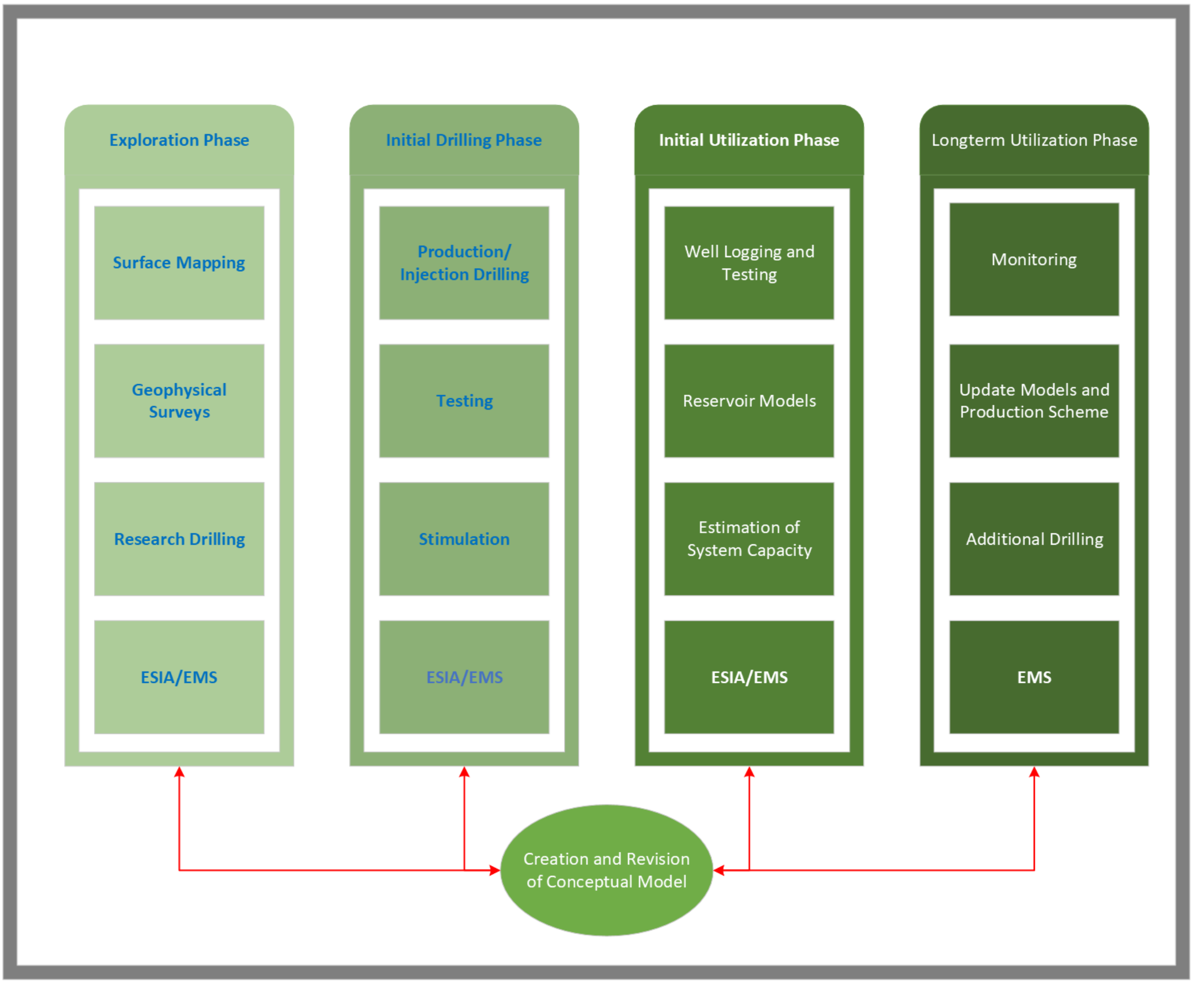

Figure 23. *A roadmap of the process from geothermal exploration, to drilling and testing, onto initial utilization and from there onto the long-term utilization phase. ESIA stands for Environmental and Social Impact Assessment and EMS for Environmental Management System, both are part of public awareness monitoring and public awareness campaigns.*

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