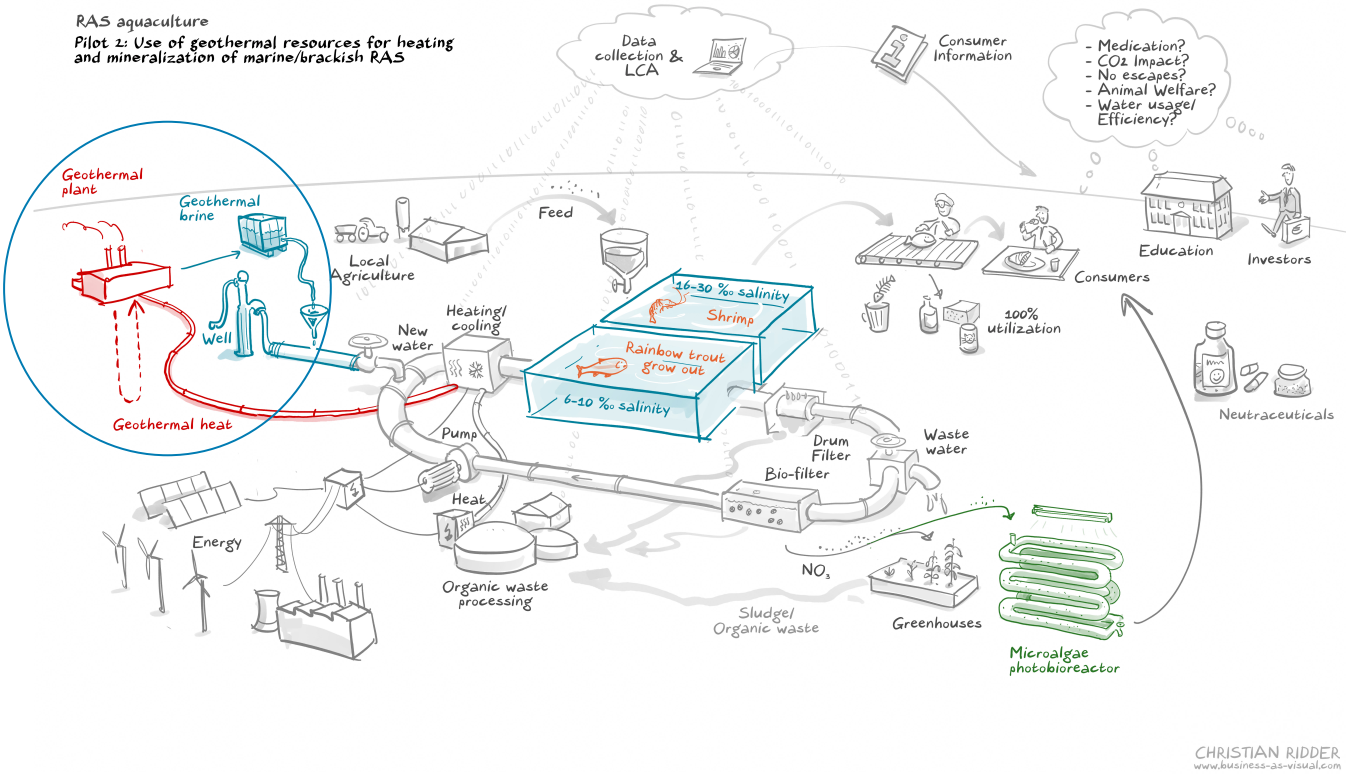

Feasibility Study

Pilot 2 – Geothermal resources and RAS

KLAIPEDA UNIVERSITY

Project co-funded by Interreg Baltic Sea Region

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Context of the report

This feasibility study is a part of Interreg Baltic Sea Region programme project TETRAS – Technology transfEr for Thriving Recirculating Aquaculture Systems in the Baltic Sea Region – activities. Project aims to improve the economic and environmental sustainability of recirculating aquaculture by developing new concepts for more efficient resource utilization.

The **feasibility study** 1.2.2 will analyse the potential **of geothermal resources to be used as a source of heating and mineralization for a large-scale saltwater RAS**. The primary focus in this feasibility study is the resources of Western Lithuania Geothermal Anomaly, with specific case of 110 g L^{-1} mineralization geothermal brine from a 1.1 km deep Klaipeda geothermal powerplant well. This, yet available highly mineralized brine will be practically applied and tested. We will perform series of experiments with warm-water whiteleg shrimp and cold-water rainbow trout in RAS facilities of Klaipeda University to test geothermal brine suitability for artificial marine/brackish water preparation. Performance of standard RAS technology and biological compatibility with cultivated animals will be evaluated: the effect on survival, growth and productivity, the bioconcentration/bioaccumulation patterns of chemical elements found in the geothermal brine. Additionally, Life Cycle Analysis (LCA) will be performed for shrimp cultivation in RAS with geothermal brine-based artificial marine water to assess technology's environmental footprint. And, finally, the desk study will be performed by external experts on the spatial and vertical distribution, characteristics of geothermal resources in Lithuanian territory, its economic potential and technical accessibility to be applied in large-scale RAS. The results of Pilot 2 experiments and desk study will complement the business model for large-scale shrimp RAS farming (D 2.2).

These biological, technical and economic results and business solutions for application of geothermal resources may be of interest to existing RAS companies offering alternative source for mineralization of RAS water, or to other companies, like balneological SPAs, geothermal powerplants etc., showing the diversification possibilities for extracted heat and exploited technical water to be used in industrial symbioses with RAS sector. The results of the feasibility study and Pilot 2 will be transferrable to other Baltic Sea regions even with lower geothermal resources than the analyzed western Lithuania case.

This is the first version of 1.2.2. feasibility study. Finally, all Pilot 2 outcomes will feed into final version of this feasibility study and the synthesis document (D 1.2) which will provide innovative RAS concepts and technologies feasible for Baltic Sea Region.

Executive Summary

This Pilot 2 feasibility study aims to evaluate the technological and economic viability of using geothermal resources from Western Lithuania for mineralization and heating in recirculating aquaculture systems (RAS), focusing on inland saltwater RAS for high-value aquaculture species. The study is part of the Interreg Baltic Sea Region programme project TETRAS and targets both resource sustainability and RAS innovation.

Through aquaculture experiments, life cycle assessment (LCA), stakeholder interviews, and a geological, technological and economic desk analysis, this study examines the feasibility of using geothermal brine as a replacement for costly natural or synthetic salts in artificial seawater production. Two model species – whiteleg shrimp (*Litopenaeus vannamei*) and rainbow trout (*Oncorhynchus mykiss*) – are cultivated under controlled RAS conditions using 110 g L^{-1} mineralization geothermal brine diluted to salinity levels suitable for full-scale shrimp production and salmonid fish grow-out or purging stages. Whiteleg shrimp showed good growth and survival performance, at the same time no accumulation of unwanted trace elements. Rainbow trout as a model species for salmonid short-term grow-out at RAS in brackish water conditions demonstrated no benefit in growth performance, however higher meat quality was observed. These results indicate promising opportunities for cost reduction and improved sustainability for large-scale production of saltwater species, like whiteleg shrimp, in geothermal brine-based artificial marine water.

Geothermal resources from lower Devonian (up to 80-100 g L^{-1}) and, especially, Cambrian layers with highly mineralised (100-200 g L^{-1}) water, which highly resembles sea water ionic composition could be used as a mean for sustainable artificial marine water production in RAS, particularly within the western Lithuania region.

Western Lithuania hosts numerous active oil exploitation and exploration wells, which present a unique opportunity for repurposing them into geothermal energy and brine production sites with minimal additional cost. These borehole sites generate vast quantities of brine and there are some examples of its extraction, transportation and use by SPA facilities for health procedures. Regional industrial symbiosis with geothermal resource users is the most relevant way for RAS companies to acquire geothermal brine.

One of the essential parameters determining fish growth and health, performance and efficiency of aquaculture systems is water temperature. Keeping fish at optimal rearing temperatures will give a much higher growth rate, which can be increased by 50 to 100%. The cost of reaching and maintaining the optimal water temperature all year round normally requires high demands of energy, therefore, the use of geothermal energy in aquaculture is increasing. The aim of geothermal aquaculture is to heat water to the optimum temperature for species in raceways, ponds and re-circulating aquaculture systems (RAS). (Ragnarsson, 2014; Van Nguyen et al., 2015) Geothermal plant "Geoterma" in Klaipeda (which is using geothermal water from the 1,128m deep Devonian aquifer of 38oC temperature and 110g/l mineralization) together with Klaipeda Science and Technology Park were screening for different possibilities to diversify geothermal utilization. Along SPA and balneology, mineral mining and other options there was warmwater recirculating aquaculture. Based on several feasibility studies, the whiteleg shrimp (Litopenaeus vannamei) was identified as the best candidate to develop warm-water recirculating aquaculture in Klaipeda. These whiteleg shrimp are the Pacific Ocean species, which live and have the highest feed intake rate in water of 28-32oC temperature (Wickins & Lee, 2002). Therefore geothermal water resources of Cambrian-Devonian aquifer perfectly fit to heat water to an optimal 30oC using heat exchanger technology.

Background

The rapid expansion of the aquaculture has brought to light significant environmental challenges associated with traditional farming methods. Sea cage farming of finfish, a prevalent method for species like Atlantic salmon, sea bass, sea bream, involves enclosing fish in net pens submerged in natural water bodies. While efficient in terms of space utilization, this method faces many environmental concerns:

- **Nutrient discharge:** Excess feed and fish waste can lead to localized eutrophication, altering water chemistry and impacting benthic ecosystems [2].
- **Disease transmission:** The high stocking densities in sea cages can facilitate the rapid spread of diseases, which can then potentially transfer to wild fish populations [3].
- **Escapes:** Accidental escapes of farmed fish can lead to genetic interbreeding with wild populations, potentially weakening native gene pools and introducing non-native pathogens [4].
- **Chemical use:** The use of antibiotics and anti-parasitic treatments to manage disease can lead to their accumulation in the marine environment, affecting non-target organisms [5].

Salmon aquaculture has seen substantial growth, now accounting for 70% of global salmon production. This industry has expanded rapidly since the 1980s, with key producing regions including Norway, Chile, Canada, and Scotland. While it provides a significant food source, the industry faces challenges related to sustainability, disease, and environmental impact. Following a period of stagnation, recent research from the seafood industry suggests that the salmon farming industry may increase its production by as much as 27 percent by 2030.

New technologies are being developed to improve sustainability and address environmental concerns, including closed-containment systems and offshore aquaculture systems. The traditional sea-cage farming of Atlantic salmon is increasingly moving on land into RAS facilities.

Similarly, open pond farming, commonly used for shrimp and some finfish, presents its own set of environmental challenges, particularly in coastal regions:

- **Habitat destruction:** The conversion of valuable coastal ecosystems, such as mangrove forests, into aquaculture ponds can lead to significant biodiversity loss and increased vulnerability to coastal erosion [6].
- **Salinization of freshwater resources:** In some areas, the pumping of saline water into inland ponds can lead to the salinization of adjacent agricultural lands and freshwater aquifers [7].
- **Effluent discharge:** Untreated or poorly treated wastewater from ponds can contain high levels of organic matter, nutrients, and chemicals, impacting surrounding aquatic environments [8].

To mitigate the environmental footprint of aquaculture and enhance its sustainability, **Recirculating Aquaculture Systems (RAS)** have gained significant traction. RAS technology represents a paradigm shift from flow-through systems by recirculating and treating the majority of the water within the facility. This closed-loop approach offers numerous environmental and operational advantages, positioning RAS as a cornerstone of future sustainable aquaculture, including the farming of marine species [9]:

- **Reduced water usage:** RAS conserves vast quantities of water by filtering and reusing up to 99% of the system's water, significantly decreasing reliance on external water sources [10].
- **Minimized effluent discharge:** Waste products are concentrated and removed, reducing the release of nutrients and organic matter into natural water bodies. This allows for more effective waste management, including the potential for nutrient recovery [11].
- **Enhanced biosecurity:** The controlled environment of RAS minimizes the risk of disease outbreaks and prevents the escape of farmed organisms, safeguarding wild populations [12].
- **Optimized production:** Precise control over water quality parameters (temperature, oxygen, pH, etc.) allows for optimal growth conditions, leading to faster growth rates and improved feed conversion ratios [13].
- **Location flexibility:** RAS facilities can be established in diverse geographical locations, including inland areas, closer to markets, reducing transportation costs and carbon emissions [14].

While whiteleg shrimp is predominantly farmed in tropical and subtropical regions, its cultivation in Europe is gaining momentum, primarily through advanced indoor systems like RAS or biofloc technology.

A significant challenge for inland marine aquaculture, particularly for species like whiteleg shrimp and land-based salmon RAS that require saline water, is the sustainable and cost-effective sourcing of salts for artificial marine water production. Conventionally, this involves purchasing and dissolving large quantities of commercial salts, which can be expensive and have their own environmental footprint associated with mining and transportation [20].

This highlights a critical need for innovative and sustainable alternatives. Exploring readily available, naturally saline water sources, such as geothermal brines or industrial by-products, could offer a transformative solution. Such approaches could significantly reduce operational costs, minimize the environmental impact associated with salt acquisition, and further enhance the overall sustainability profile of inland marine aquaculture, paving the way for more widespread and economically viable production of high-value seafood closer to consumption centers.

Overview of Alternatives

Considering the strategic goal of Pilot 2 – saltwater RAS technology development and promotion of marine species farming in the BSR, several available alternatives exist for saltwater supply sources.

Alternative 1: Use of natural Baltic Sea water. This is technically feasible only for facilities located on the sea shore, where it would be possible to pump sea water. In Lithuania's case this is not possible or hardly possible, as whole Baltic sea coast (90 km) is dedicated for nature protection (Curonian Spit National park, 50 km), recreation and tourism. The industrial activities in most cases are not allowed or the land is very limited for commercial-agricultural (part of which is aquaculture, according to national regulations) activities and expensive. Only small fraction is dedicated to specific activities like port and oil terminals. On the other hand, there are no precedents yet for the sea water extraction, and legal regulations are very complicated. The low salinity (6 psu) is an issue alone, as it may not fit to most marine high-value species. Based on SWOT analysis, this alternative may cause to many challenges, mostly related with strict environmental regulations (national, regional and European) and Baltic sea water quality itself. These limitations may become even more pressing in the future due to climate change.

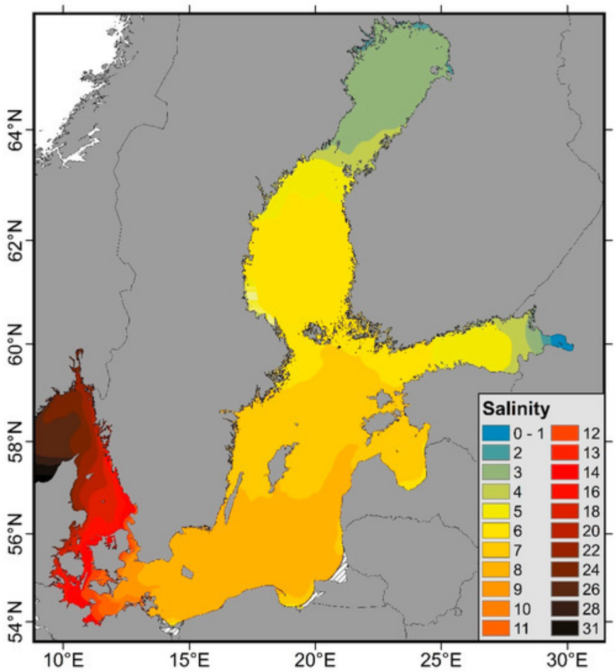

Fig 1: Baltic Sea water salinity distribution by Jaspers et al. (2021). East of the 12°E longitude, the water salinity is too low for high-value species aquaculture.

***Table 2**: SWOT Analysis of Alternative 1: Use of natural Baltic Sea water.*

Strengths	Weaknesses
- Unlimited natural resource of marine water - For the facilities on or near the sea shore it is technologically convenient	- Suitable only for the facilities on or near the sea shore, what specifically for Lithuanian case is hardly possible. Almost all seashore land is used for nature protection and recreation. - Still additional salting of water may be needed as most of Baltic Sea are too brackish (≤6 psu) for saltwater RAS - Environmental pollution issues, permitting and other legal aspects of exploiting Baltic sea water
Opportunities	**Threats**

- Limited resources of freshwater - Saving some costs for mineralization when adding salts to brackish water rather than freshwater	- Increasing environmental regulations put this alternative under high risk in a longer term - Climate change - High pollution of Baltic Sea may impact water quality - Baltic Sea is seen as highly polluted, therefore it may have some negative marketing issues

Alternative 2: Use of sea salt for aquariums. The professional sea salt for coral reef, crustacean or fish aquariums could be either synthetically formulated to best meet specific requirements (like increased Ca and Mg concentrations) or natural, produced by evaporating marine water. Both types, however, have all major, mikro- and trace elements in optimal amounts. This is one of the best options in terms of quality, chemical composition and availability in the market, however constant use even in moderate quantities would cause high costs for water salination. For pilot shrimp RAS in Klaipeda, the salt was in the second-third place of all operational costs. In general, market price of formulated or natural sea salt is at least 2 Eur kg^{-1} or up to 30 Eur for 1 m^3 of 15 g L^{-1} salinity water.

***Table 4**: SWOT Analysis of Alternative 2: Use of sea salt for aquariums.*

Strengths	Weaknesses
- Natural sea salt with optimal composition for marine species, including all necessary elements and with improved some crucial elements concentrations - Many suppliers on the market, easily available product - Established production and supply chains	- High price - Mostly for professional reef aquariums, therefore premium quality may be not necessary for aquaculture - Difficult handling, mostly it is sold in bags or buckets up to 25 kg, and it's not very convenient for large scale operations
Opportunities	**Threats**
- This is convenient alternative for short-term or occasional use	- High share in operational costs

Alternative 3: Use of main cation/anions minerals. This is mixture of salts of major cations and anions: NaCl, $MgCl_2$, $CaCl_2$, KCl, $MgSO_4$. Low Cost Salt Mixture (LCSM) formula was established for whiteleg shrimp cultivation by making artificial sea water (Galkanda-Arachchige et al., 2020). However, this mixture lacks of micro- and trace elements which could be important for cultivated organisms. Also, there could be two supply chains considered: one – cheaper, from countries like Belarus, Russia which are unreliable; and other – from trusted suppliers, but more expensive. The cheapest option to prepare 1 m^3 of artificial marine water of 15 g L^{-1} salinity with LCSM is ~7 Eur.

***Table 5**: SWOT Analysis of Alternative 3: Use of main cation/anions minerals.*

Strengths	Weaknesses

- Established LCSM formula which contains main necessary cations and anions, ensuring osmoregulatory needs for aquatic animals - Cheaper option than natural sea salt	- Still considerable price and third-fourth position in OpEx - Difficult handling of mineral bags and mixing - No micro- and trace elements in the prepared artificial seawater potentially required by species
Opportunities	**Threats**
- This is convenient alternative for short-term or occasional use	- Unstable and unreliable suppliers for cheaper minerals

Alternative 4. Use of geothermal resources. As of existing possibilities to extract warm and highly mineralized brine, which resembles marine water composition in terms of main cations and anions, several geothermal resource application scenarios could be considered.

Full-scale geothermal use scenario. Big-scale RAS farms can utilize geothermal heat and mineralization to maintain suitable conditions for full-scale marine cultivation (15-20 psu as for whiteleg shrimp or Atlantic salmon) by using own geothermal resource extraction wells and technology. This is one of alternatives to consider for whiteleg shrimp large-scale business model which will be prepared during this project by PP10. Here, two options are possible: 1) extraction of deep layer (Cambrian or deeper aquifers) geothermal brine with high temperature and high mineralization which would be used for heating (through heat exchanger technology) and artificial marine water preparation by diluting brine to needed mineralization. This option mostly is relevant for heating purposes, therefore closed loop with production and injection wells and heat exchanger technology would be required. At the same time, relatively small amounts of brine would be used as a salt source for process water; 2) use of exact layers and extract specific brine of needed mineralization and temperature (~30 psu and ~30^{o}C) to use it directly (or with pre-treatment) for shrimp cultivation.

This alternative would require big capital investments. However, the desk study performed for Pilot 2 showed, that active oil exploitation and exploration wells in western Lithunaia have the standard design of the past 50 years that can be deployed for converting the boreholes to geothermal exploitation. To heat the water in recirculating aquaculture systems up to 30°C using potentialy available geothermal resources, one should consider factors such as the efficiency of heat transfer, the sustainability of the geothermal resource, and the scalability to different volumes of water. As example, five potential wells of Cambrian geothermal resources in western Lithuania were analyzed for its geothermal energy potential. These sites produce 73-85 ^{o}C temperature and higly saline (140-230 g L^{-1}) brine. Direct use of such hot geothermal water with heat exchangers is the most efficient and reliable for large-scale applications, offering precise temperature control and scalability. However such high mieralization presents substantial challenges. Geothermal heat pumps provide a versatile option for areas with lower geothermal temperatures, with moderate efficiency and lower operational costs. Hybrid Geothermal-Solar Heating Systems offer the highest efficiency in regions with strong solar potential, combining two renewable energy sources for optimal performance. Each of these technologies can maintain the required water temperature of up to 30°C in closed aquaculture systems of 1,000 to 10,000 m³ volume, with 2% water renewal. The choice depends on the specific geothermal resources available, the geographic location, and the project's scale and budget.

Geothermal brine industrial symbiosis. Big-to-medium RAS farms can use only geothermal brine to maintain suitable saltwater conditions for full-scale marine cultivation by using other industries provided brine. Other industrial symbiosis scenario is for RAS farms that are using geothermal brine provided by other industries to raise salinity of water to brackish conditions (3-6 psu) to get better fish growth performance (if proved), for fish treatment, or used only for purging before harvesting. There are some examples of geothermal brine extraction, transportation and use by SPA facilities for health procedures. Regional industrial symbiosis with geothermal resource users is the most relevant way for RAS companies to acquire geothermal brine.

***Table 63**: SWOT Analysis of Alternative 4: Use of geothermal brine – Full-scale geothermal use scenario.*

Strengths	Weaknesses
- Geothermal resources are environmentally sustainable and green source of energy, could be good aspect in marketing - Geothermal brine composition highly resembles marine water chemistry in terms of main cations and anions and many other microelements -	- Substantial capital investments - The hotter geothermal brine, the higher its mineralization, what makes additional challenges for heat extraction technologies - No clear national strategy for geothermal resource use
Opportunities	**Threats**
- Western Lithuania hosts numerous oil wells, which could be repurposed into geothermal energy and brine production sites - These sites can be used for full-scale geothermal application in large-scale RAS farming - Possibility to supply brine to other RAS companies - Scientific groups working in geothermal energetics KTU and LGA - Reduction of effluent discharge by increasing water quality and recirculation rate	- Potential, yet unknown negative impacts on meat quality, bioaccumulation of elements - Unclear environmental and other legal regulations for geothermal brine-based marine water discharge and treatment

***Table 74**: SWOT Analysis of Alternative 4: Use of geothermal brine – Industrial symbiosis scenario.*

Strengths	Weaknesses
- Geothermal resources are environmentally sustainable and green source of energy, could be good aspect in marketing	- At the moment, not enough potential suppliers of geothermal brine - Unclear situation with KGDP - No established supply chains and not enough transportation options

- Geothermal brine composition highly resembles marine water chemistry in terms of main cations and anions and many other microelements - Existing industrial symbiosis examples - Geothermal brine itself is cheap solution - Easy to handle and apply at RAS facility	
Opportunities	**Threats**
- Flexibility in use - Possibility for geothermal resource users to diversify and supply brine to RAS companies	- Potential, yet unknown negative impacts on meat quality, bioaccumulation of elements

Selected solution for Pilot 2

Industrial symbiosis scenario is the most promising solution for RAS salting in regards of potential for only salting of RAS process water with brine from external geothermal producers seems most relevant considering existing situation with two main stakeholders target groups: innovative RAS farms and geothermal resource users. There are several issues which should be analysed in Pilot 2 to assess feasibility of this symbiosis:

- Availability of geothermal brine – existing or future suppliers' possibilities to provide brine for RAS (the production and supply capacity, technical solutions of retrieval of brine from producer, transportation means and distances, legal aspects of selling geothermal brine);
- Technological readiness at RAS farms (suitability of RAS, needs for adjustment of the system, storage and dosing technological solutions);
- Suitability of brine in terms of its chemical composition (assessment of accumulation risks of specific elements, meat quality, are there benefits for animals and technology performance);
- Legal regulation and permitting of geothermal brine use for food production;
- Economic feasibility of that type of industrial symbiosis (prices, market size and readiness, business model).
- Branding, storytelling and marketing possibilities (clean, sustainable, hundreds of millions of years old brine from times when or even before fish was appearing and evolved on Earth, consumer acceptance etc.).

Outline of the Pilot 2

Description of the pilot

Pilot 2 aims to test feasibility of using geothermal heat and highly mineralized brine for saltwater RAS. The geothermal aquaculture is already established technology but mostly applied geothermal heat for pond or RAS water heating or stability. In Pilot 2 this aspect will be analysed only at the theoretical level by external expertise implementing desk study, as at the moment there are no operational hot water well in the area to use it for testing.

The primary focus in this feasibility study is the resources of Western Lithuania Geothermal Anomaly, with specific case of 110 g L^{-1} mineralization geothermal brine from a 1.1 km deep Klaipeda geothermal powerplant well. This, yet available highly mineralized brine will be practically applied and tested by series of experiments.

We will perform series of experiments with warm-water whiteleg shrimp and cold-water rainbow trout in RAS facilities of Klaipeda University to test geothermal brine suitability for artificial marine/brackish water preparation. Performance of standard RAS technology and biological compatibility with cultivated animals will be evaluated: the effect on survival, growth and productivity, the bioconcentration/bioaccumulation patterns of chemical elements found in the geothermal brine. Additionally, Life Cycle Analysis (LCA) will be performed for shrimp cultivation in RAS with geothermal brine-based artificial marine water to assess technology's environmental footprint. And, finally, the desk study will be performed by external experts on the spatial and vertical distribution, characteristics of geothermal resources in Lithuanian territory, its economic potential and technical accessibility to be applied in large-scale RAS. The results of Pilot 2 experiments and desk study will complement the business model for large-scale shrimp RAS farming (D 2.2).

Geothermal Resources

The main prerequisite of Pilot 2 is the availability of good geothermal resources. Usually the availability and potential of geothermal resources are measured through the heat energy that geothermal fluids store. In this Pilot we concentrate on the highly mineralized geothermal fluids, which should be called brine. The chemical composition of brine is less assessed, but usualy the hoter and deeper geothermal fluids are, the higher mineralization it have.

Lithuania is located on the East of Baltic sedimentary basin and has a geothermal anomaly situated in the southwestern region of the country. There are two *primary geothermal complexes* within the anomaly, composed of Cambrian and Devonian aquifers. The Cambrian formation is composed of sandstones that have a reservoir temperature reaching up to 96 ◦C (depth > 2000 m). The Devonian aquifer is composed of unconsolidated sands of Parnu–Kemeri and has a reservoir temperature of up to 46 ◦C (depth > 1000 m). Historically, both formations have been investigated for geothermal energy production (Memon et al., 2024).

In the year 2000, the Klaipeda Geothermal Demonstration Plant (KGDP) was constructed, to transfer geothermal energy to the district heating system using heat pump technology. The KGDP plant drew geothermal water from the Lower Devonian strata at a temperature of 40 ◦C (estimated at 42 ◦C) at a vertical depth of 1000 m. With a total thermal capacity of 41 MW (18 MW geothermal and 23MWfrom boilers), the KGDP plant extracted approximately 215,000MWh of heat in 2003.

Initially, only injector 1I was drilled, but it proved insufficient for injecting the desired 700 m^3 h^{-1} of geothermal water. Consequently, a new injector, 4I, was drilled. Presently, the KGDP plant features two production wells (KGDP-2P, KGDP-3P) and two injection wells (KGDP-1I, KGDP-4I), all identical in design and completed at depths of 1128 to 1228 m (Zinevicius et al., 2020).

For Pilot 2 practical testing, several potential sources were identified (Table 2), however the only reliable source is the exploited but stored in reservoir brine of high mineralization from Klaipeda (KGDP) well.

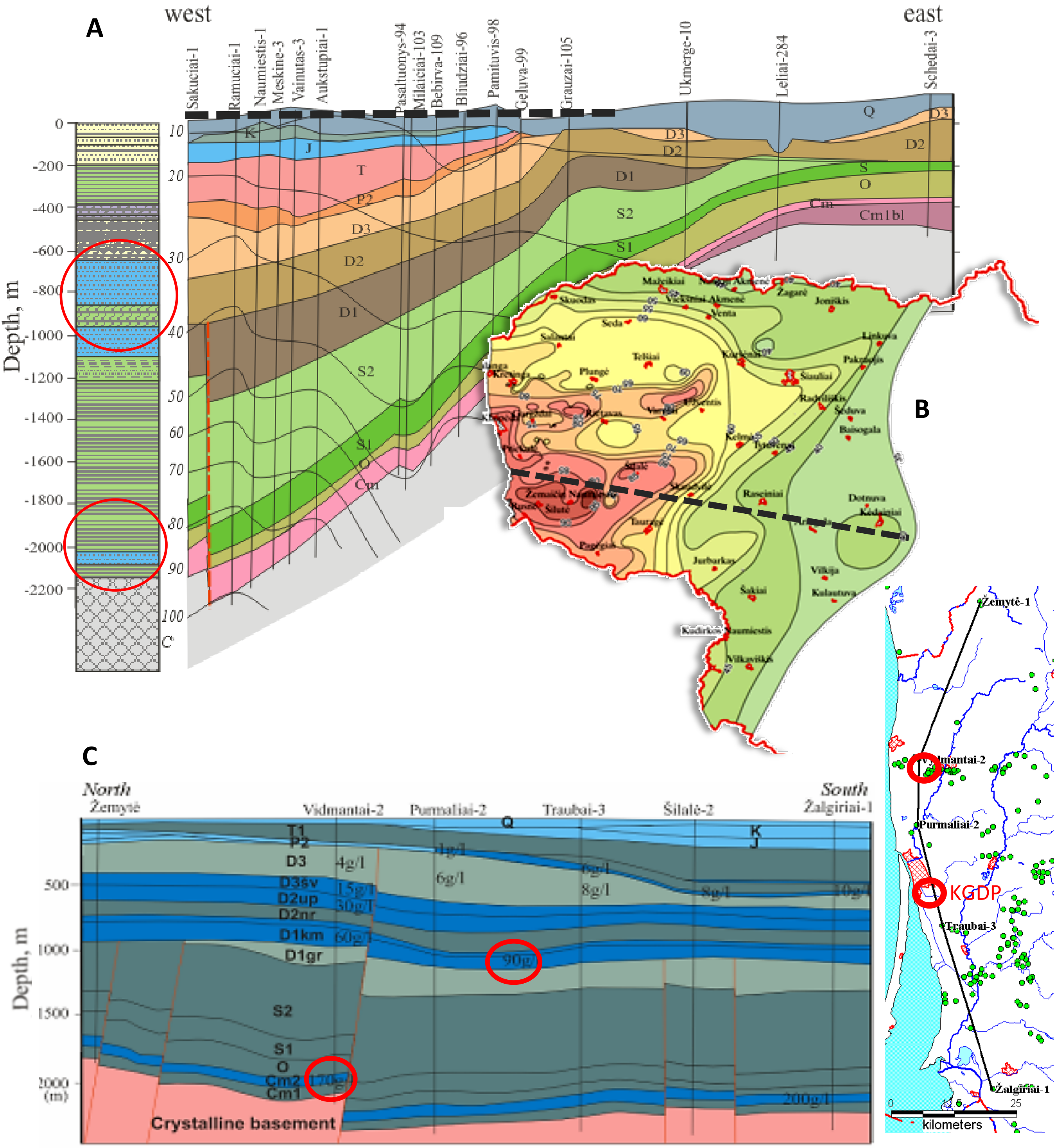

Figure 1. Geothermal resource distribution and characteristics in Lithuania: **A** – West-East cross-section of Lithuanian territory showing thickness and distribution of different geological layers (Q – Quaternary, K – Cretaceous, J – Jurassic, T – Triassic, P – Permian, D – Devonian, S – Silurian, O – Ordovician, Cm – Cambrian, grey – crystalline basement) and distribution of temperature (10-100 °C) shown by black line isotherms. Devonian and Cambrian geothermal aquifers are shown as blue layers (circled in red). **B** – temperatures of the Cambrian geothermal aquifer indicating heat energy potential distribution. Dashed black line shows plan of full geological cross-section shown in A picture. **C** – geological North-South cross-section across western Lithuania. Blue layers indicate geothermal aquifers and its mineralization (g/L). Red circles indicate existing wells.

The chemical composition of brine provided in Table 2, was estimated for freshly extracted brine in 2010. The actual concentrations of chemical elements after roughly 8 years of storage could be changed but still fits and will be used for Pilot 2 case study.

Genčiai (Vydmantai) wells now belong to Vydeko company, but extraction of highly mineralized brine is possible only for research needs in limited quantities.

Table 2. Geothermal wells – potential source and characteristics of geothermal brine for Pilot 2.

Parameter		**Klaipeda well (KGDP)**	**Genčiai/Vydmantai well (Vydeko)**	**Gradiali SPA**
Well depth	m	1100	1800	-
Temperature	°C	38	40	34
Mineralization	g L^{-1}	110	180	16,8
pH		6.07	n.m.	-
Anions	mg L^{-1}			
Cl^-		66930	89664	8650
Br-		<0.2	741	
HCO_3^-		74		119
SO_4^{2-}		1330	15	1862
NH_4^+		<0.05		5.41
NO_2^-		<0.05		<0.05
NO_3^-		<0.5		<0.10
Cations				
Na^+		24700 / 27580	29264	4274
Ca^{2+}		7560 /8990	19347	1267
Mg^{2+}		2330 /2630	3475	417
K^+		632 /690	688	157
Fe		18.8 / 12.14		0.11
Mn		1.00	14.75	
Al		0.019		
Other elements				
Si		7.06	4.8	2.25
B	µg L^{-1}	13000	18700	
Li		4450	7360	
Sr		160000	368300	
Ba		256	102650	
Cr		3.61		
Zn		17.8		
Cu		<1.00		
Ti		1.43		
Au		1.70		
As		<1.00		

Hg		0.081		
Pb		2.26		
Cd		1.45		
Reference		Analysis protocol, 2010 / Gerber et al., 2017	Gerber et al., 2017	Analysis protocol, 2023

Figure 2. The storage reservoir of exploited brine of KGDP at the injection wells in Rimkai, Klaipeda. Now it is the only available source of highly mineralized brine for Pilot 2 experiments.

Chemical element		Fresh tap water 0‰	Baltic Sea water 6‰	Geothermal diluted 6‰	Geothermal brine 110‰
Chloride (Cl)	mg L^{-1}	159	2789	3122	**55192**
Sodium (Na)		261	1814	1678	**25989**
Potassium (K)		28,9	72,5	55	**570**
Calcium (Ca)		24,3	134	350	**7106**
Magnesium (Mg)		16,7	229	153	**2440**
Lithium (Li)		<0,05	0,05	0,2	**3,42**
Iron (Fe)		0,06	0,08	0,03	**<0,01**
Boron (B)		2,11	1,25	2,38	**9,87**
Silicate (SiO_2)		7,4	3,9	8	**4,7**
Aluminium (Al)	µg L^{-1}	<10	260	260	**1100**
Barium (Ba)		10	23	62	**300**
Cadmium (Cd)		<0,3	<0,3	<0,3	**<0,3**
Chrome (Cr)		<1	1,7	<1	**<1**
Manganese (Mn)		<4	9,3	6,3	**530**
Lead (Pb)		<1	<1	<1	**<1**
Zinc (Zn)		<40	<40	<40	**<40**
Stroncium (Sr)		380	1300	8300	**170000**

Stakeholder Identification

Aquaculture farms

The primary target group in terms of main Pilot 2 solution – mineral brine utilization – is RAS farms cultivating salmonids (Atlantic salmon and rainbow trout) and saltwater shrimps, but also percids (tilapia, European perch, pikeperch) and other euryhaline species which may benefit from brackish conditions. Full cycle of Atlantic salmon in RAS avoiding grow-out in open cage systems, whiteleg shrimp RAS established in land with limited or no accessibility to marine water are fully dependent on artificial saltwater. Easily available, cheap and safe source of minerals would be of high interest for big-scale farms, where even low water renewal rate would require high demands for minerals. The other potential solution, which is tested in the Pilot 2, is for traditionally in freshwater RAS cultivated species which was shown benefiting from brackish conditions: better wellness, growth, meat quality []. Existing RAS installations don't need any essential modification of technology to operate with brackish water. Such option – to raise water salinity to 3-6 PSU gaining some benefits will be analysed through direct interviews with relevant RAS farms in Lithuania (at least 3 farms). The Pilot2 experiments will provide results on the effect of geothermal brine-based brackish water for rainbow trout growth, meat quality and technology performance.

The geothermal water producers

The companies which operate wells of deep geothermal layers with highly mineralized water. As the primary potential geothermal brine suppliers, we consider: balneological SPAs and geothermal power plants. Other geothermal heat and brine producers extracting considerable amount of brine could also diversify their business supplying the brine. In Lithuanian case by now there are several deep geothermal mineral water users.

Klaipeda Demonstration Geothermal Plant (KDGP) operated by JSC Geoterma, with 1100 m deep production well and injection well. The facility was installed in 1997 to use the heat of Devonian geothermal aquifer and shut down by the previous owner Ministry of Energy in 2017. The facility have two production wells and two injection wells which were producing 800 m^3/hr per well (expected 600 m^3/hr) of 110 g L-1 mineralization 38 ^oC temperature brine. Due to low injectivity of injection wells there was always problematic to inject brine back to deep layers, therefore other potential utilization possibilities of extracted brine have been sought all the time. Specifically, the effect of KDGP extracted brine are tested in Pilot 2 experiments.

Now, the management of the plant's infrastructure have been transferred to a municipal company *JSC Klaipedos energija*. For Pilot 2 this company together with *Klaipeda municipality* are one of key stakeholders responsible for the search for KDGP facility revitalization opportunities.

Private Limited Company VYDEKO in 2022 acquired the deepest (1.8 km) but at the moment preserved Genčiai well to Cambrian aquifer with ~180 g L-1 mineralization and ~70 ^oC temperature geothermal resources. The company seeks to invest into the utilization of these geothermal resources considering and analyzing all possible solutions, including aquaculture.

Private Limited Company "Atostogų parkas" (Holiday Park). This is Welness, SPA and Beauty complex established close to Palanga resort. In their Termo SPA warm mineralized geothermal water from ~2 km deep (40 million years) layers is used for balneological SPA and medical procedures. The public information is scarce and a bit contradictory, but during the project we will reach this stakeholder directly.

Private Limited Company "Sveikatos uostas". Company's hotel Gradiali Wellness and SPA in Palanga offers balneological procedures with geothermal mineral water of moderate salinity from their own well.

Investment project "Žuvėdros kopa" is planning to establish geothermal water-based SPA complex in Giruliai, close to Klaipeda. The investment of 40 mln. Eur is planned into the biggest in the Baltic states balneological SPA with warm (~50 ^{o}C) highly mineralized water resources used.

Other relevant stakeholders

The working group on the revitalisation of the KDGP was established by Klaipeda Municipality and Klaipedos energija in 2022. This group of experts seeks for finding possible concepts and alternatives for the use of geothermal water resources in Klaipėda, but the main focus is on KDGP revitalisation.

Lithuanian Geothermal Association brings together private and legal persons interested in geothermal resource utilization issues. LGA supports any initiatives of geothermal use, considering that Lithuania, especially western part of the country, have good resources for that.

Fisheries Department of *Ministry of Agriculture* is the national fisheries and aquaculture policy maker, which promotes aquaculture development, supports this through coordination of European MFA Fund investments. In the new National Aquaculture Sector Development Plan 2021-2030 more attention is given to innovative aquaculture, saltwater RAS, industrial symbioses.

Lithuanian Sea Museum is the most popular museum in Lithuania with more than half million visitors each year. The popularity is based on the life shows of dolphins, fresh to tropical fish aquariums and other maritime expositions. To keep marine animals, museum takes Baltic Sea water (~6.5 psu) and raise salinity to 22 psu for Black Sea dolphins or up to 40 psu for coral reef aquariums. Museum uses big quantities of NaCl premium salt for huge dolphinarium basins and professional sea salt for reef aquariums. LSM would consider other cheaper but safe and approved sources of minerals for their daily operations and was considering geothermal brine in the past.

Methodology

Pilot 2 is based on several activities:

1) Experiments of using geothermal brine for salting RAS water;
2) LCA for shrimp RAS with geothermal brine-based saltwater;
3) Desk study on geological, technical and economic aspects of geothermal resources and its aquaculture application potential;
4) Reaching and interviewing key stakeholders to understand perception and readiness for saltwater RAS and geothermal resource applications.

Experiments will be implemented in the facilities of Klaipeda University Fisheries and Aquaculture Laboratory and facility of Klaipeda Science and Technology Park. Two aquaculture species will be cultivated in diluted geothermal brine of KGDP well (110 g L^{-1} mineralization):

- whiteleg shrimp (*Litopenaeus vannamei*) at 16 g L^{-1} salinity as the main study object for large scale farming business case;
- rainbow trout (*Oncorhynchus mykiss*) at 6 g L^{-1} salinity as the model species of salmonids to test grow-out in RAS tanks with saltwater.

Whiteleg shrimp experiments. Experimental system resembles commercial technology with all main water treatment steps (mechanical drum filter, moving bed biofilter, protein skimmer with ozone, UV lamp, heater, oxygen cone, main parameters monitoring and automatic control system), but on a smaller scale. System is of ~40 m^3 circulating water volume, with 7 cultivation tanks, each 2.8 m^3.

Each experimental cycle takes 3-4 months from PL15 post-larvae stage to average 25 g weight individuals. Post-larvae are purchased externally (White Panther, Austria). Cultivation will be done at ~29 °C, >80 % of oxygen saturation, pH 7.5-8.0, under 24 h light, constant feeding using belt feeders.

The salinity for whiteleg shrimp experimental trials will be kept at 16-20 g L^{-1}. The species is euryhaline, easily bearing salinity as low as 5 g L^{-1}, while optimal salinity of species natural distribution range in Pacific Ocean is 30-35 g L^{-1}. Experimental salinity of 16 g L^{-1} is set as standard of our shrimp RAS technology and mainly is related to maximum efficiency of protein skimmer.

Four separate cultivation cycles in pilot shrimp RAS are foreseen in TETRAS:

- Pre-experimental cycle as a control using LCSM formula for 16 g L^{-1} salinity water preparation by dissolving NaCl, $MgCl_2$, $CaCl_2$, KCl and $MgSO_4$ minerals in tap water;
- 1st and 2nd experimental cycles using geothermal brine diluted with tap water to 16 g L^{-1}, data for LCA collection;
- 3rd experimental cycle using geothermal brine diluted with tap water to 16 g L^{-1}, with denitrification filter included for nitrate removal, better water quality and reuse rate.

The parameters which will be monitored and analysed for each experimental cycle:

- general system performance, especially work of biofilter and protein skimmer,
- water quality,
- shrimp physiological and production parameters,
- meat and shell quality and composition,
- bioaccumulation of specific elements.

Rainbow trout experiments. Fish will be cultivated in 3 systems x3 (2.5 m^3) tanks. Each experimental unit have separate basic filtration system (backwash mechanical filter, moving bed biological filter, protein skimmer, UV lamp, pumps, basic parameters monitoring system). Cultivation will be done under 24 h light, constant feeding using automatic feeders.

Two experimental cycles will be implemented during TETRAS:

- 1st experiment will start with ~100 g rainbow trout that was kept in freshwater transferring 40-50 fish tank^{-1} with fresh water (0 psu), brackish Baltic Sea water (6 psu) and diluted to 6 psu salinity geothermal water.
- 2nd experiment design will be adjusted accordingly to the first experiment results, but initial plan is to perform grow-out from 100 g to 1000 g fish in freshwater conditions, diluted geothermal water to 6 psu salinity and diluted geothermal water to 10-12 psu salinity.

The parameters which will be monitored and analysed:

- different water mineralization effect on general RAS performance and water quality,
- trout growth, welfare and production parameters,
- meat quality and composition,
- bioaccumulation of specific elements.

Life Cycle Analysis (LCA) will be performed for whiteleg shrimp RAS. Data for LCA will be collected during experimental cycles No. 1-2 and No. 3, if necessary. As shrimp pilot RAS has all main water treatment stages and processes, it resembles commercial technology, just is of smaller scale, the LCA is quite representative for shrimp cultivation.

Rainbow trout RAS was rejected as used experimental systems don't fully resemble commercial technology, the density of fish tank^{-1} and feeding rate is lower than standard commercial salmonid RAS. In our case, the main interest is response of fish to geothermal brine-based brackish water.

Data set for shrimp RAS will include detailed information on: input (post-larvae, consumables, energy consumption, feed use and composition etc.), output production (mortality, growth, production, biomass harvested, water and sludge discharged, nutrient emissions etc.), infrastructure and equipment.

The environmental footprint like CO_2, N, P emissions by whiteleg shrimp RAS cultivation will be assessed per kg of production to be possible to compare with other means of shrimp cultivation or different cultured species.

Desk study on "*Analysis of geological, technical and economic aspects of geothermal resources and its aquaculture application potential in Baltic Sea Region: Lithuanian case*" will be performed by external experts working in geothermal resource field. The aim of this study is to assess the geothermal resources and its technological and economic accessibility for aquaculture uses.

Study will cover such topics and questions:

- *Analysis of geothermal resources in Lithuania* providing available information on the distribution of geological strata, their depths and thicknesses, and the geothermal resources they contain; quantities of geothermal water and thermal energy; chemical properties, if available. This should answer the question for potential investors and regional stakeholders on most promising areas to develop saltwater RAS.
- *Overview of the use of geothermal resources*, providing summary of current geothermal exploitation and future trends in Lithuania and worldwide; overview of geothermal resource

extraction technologies (drilling methods, pumps, heat exchangers, etc); overview of users of deep (>300 m) geothermal resources in Lithuania and in neighbouring (at least three) countries, characteristics of the resources and technology they use. This should identify potential existing and future actors and mechanisms for industrial symbioses.

- *Assessment of the potential for exploitation of geothermal resources for aquaculture*, analysing economic and technical aspects of exploitation of resources focusing on Western Lithuania Geothermal Anomaly; legal framework for resource extraction and use; evaluation of potential/suitable technologies for geothermal (shallow or deep layers) heating of water in RAS up to 30^{o}C maintaining temperature of 1000-10000 m^{3} volume RAS with up to 2 % water renewal rate; evaluation of the economic and technical aspects of the extraction of 30 ppt, 100 ppt and 200 ppt salinities (investment in wells and pumping equipment, technology efficiency and operating costs, waste water treatment). Also, evaluation of technical possibilities and costs to transport geothermal brine to distant RAS facilities.

Conclusion

The feasibility study of Pilot 2 aims to evaluate the technological and economic potential of geothermal resources for heating and mineralization of marine/brackish RAS and support business model for large-scale aquaculture production based on geothermal application and sustainable water use.

The feasibility study focusses on the resources of Western Lithuanian Geothermal Anomaly but results will be transferrable wider to Baltic Sea Region and may be of interest to geothermal brine producers, like balneological SPAs, geothermal powerplants etc., showing the possibilities in industrial symbioses with RAS sector.

The *industrial symbiosis alternative* to provide geothermal brine to RAS users seems most promising solution for different application (full cycle or short-term, high or low salination of process water) and scale of RAS. Generally, the retrieval from producer, transportation, storage and dosage technologies for highly mineralized geothermal brine don't require high investments, the approach seems simple and operational. However, the suitability of Devonian-Cambrian brine still needs to be tested during Pilot 2 experiments and its safety and efficiency proved or solutions to mitigate potential risks provided. This will be done by series of experiments with whiteleg shrimp and rainbow trout through analyses of growth and other physiological response of animals, chemical element bioaccumulation in the meat and its organoleptic properties.

Desk study on resource availability, technical and economic aspects of its use in RAS should help to answer still open questions on economic and technical feasibility of all four Pilot 2 alternative solutions.

We consider symbiosis of geothermal and RAS industries as a logic and straightforward approach, where geothermal producer adds side-stream sales along their main use of brine. It seems that for geothermal brine suppliers it would be not too difficult to adjust to the (small?) market size and fluctuating brine demands. Opposite, Alternative 1 solutions for investment into geothermal brine and heat extraction tech is feasible only in big and stable market for aquacultured production.

Recommendations

- Despite that we aim to develop cheap water salting solutions, the need of saving and sustainable use of water is still very important feature of geothermal resource-based large-scale production business. So, in parallel the work on reducing usage of artificial saltwater by increasing its regeneration through improved/optimised denitrification technique and usage of microalgae PBR. These results should feed into final Pilot 2 report, LCA analysis and considered in large-scale shrimp RAS business plan.
- Additional efforts, not planned in the project application, should be made to assess existing market size and perception for proposed industrial symbiosis by interviewing stakeholders of RAS and geothermal sectors (and potential investors, if some). Relevant stakeholders – Fisheries Department of Ministry of Agriculture and Lithuanian Geothermal Association – will be involved into reaching target audience as wide as possible.
- Beside laboratory analysis of organoleptic properties of trout and shrimp meat, fish processing companies could be relevant stakeholders in Pilot 2 FS by evaluating experimental production. PP4 have several such partners and will try to organize evaluation of geothermal brine-based production from the proffesional perspective.
- Beside focus (monitoring) on the water quality in relation to harmful substances and chemical elements of concern, the benefits of branding (dino-shrimp, Devonian shrimp) and storyteling about the cleanest possible water used in shrimp cultivation (water stored deep underground without any contact with recent world from before dinosaur era) should be used for marketing.
- The focus is on geothermal technology that can be replicated in other areas and support the development of consultancy.