Understanding environmental risks related to geothermal fluids

An integrated approach from natural and social sciences in three countries

J.A. Steijn

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An integrated approach from natural and social sciences in three countries

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Jeanne Steijn

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Supervisor:	M. Brehme	TU Delft
Thesis committee:	G. de Vries	TU Delft
	D.F. Bruhn	TU Delft, GFZ Potsdam
	S. Regenspurg	GFZ Potsdam
	A. Trisiah	TU Delft

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GFZ
Helmholtz-Zentrum
POTSDAM

TU Delft

Executive summary

The main objective of this thesis is to understand the environmental risks related to geothermal operations. The aim is to provide an integrated approach from both natural and social sciences and to perform this in three different country settings. These countries are Indonesia, Turkey and the Netherlands and they were selected because of their different geothermal system types. The integrated approach in this study results in a research process that requires a broad range of measurement and analysis techniques and a clear understanding of the natural and social disciplines. From the natural sciences approach this report studies the environmental risks through a geochemical characterization of the geothermal fluids, whereas the social sciences approach studies the risk perception on geothermal operations. The outline of the process followed is visualized in Figure 0.1.

From the natural sciences approach, an extensive geochemical data set is used to characterize the geothermal fluids and their environmental risk. This contains approximately 750 sample measurements from three countries that were collected through partners and third parties. The samples are characterized with help of two ternary diagrams (Na-K-Mg and Cl-SO_4-HCO_3), their salinity (in TDS), pH and correlation coefficients between commonly occurring elements in fluids, such as Ca, Si and F. These fluid properties help to define the maturity, origin and characteristics of geothermal fluids at a broad range of locations in each of the three countries. Through this analysis we found a strong relation between the fluid classification and the sample type (well or spring) in Indonesia. Besides, a relative high influence of volcanic activity on the geochemistry was observed. The Turkish and Dutch samples are dominated by their geothermal system types that are respectively carbonatic and clastic sedimentary systems.

The concentrations of nine toxic gases and elements dissolved in the geothermal fluids are analysed and compared to guideline values to determine the relative environmental risks in the three countries. The toxic gases are H_2S, CO_2 and CH_4 and the toxic elements Al, As, Cd, F, Hg and Pb. Their effects on the environment differ but all of them affect the health of humans, flora and fauna when they contaminate groundwater or the atmosphere. From the risk analysis in the three countries it was found that the risk of excessive H_2S pollution is highest in Indonesia, for CO_2 in Turkey and for CH_4 in the Netherlands. The contamination risk with toxic elements differs largely per element but often occurs in specific locations, for example with high volcanic impact.

For the social sciences approach, a survey was distributed to measure how the public perceives the risks of geothermal energy. The population for this survey is people affiliated with the geothermal industry because of their prior knowledge on the subject. They are asked to indicate their (risk) perception through several statements and factors to which they indicate their level of agreement. The result indicates that the perceived risks were generally higher in countries with a higher risk, like Indonesia. However, there were several interesting exceptions to this rule in which the perceived risks were low whereas a relatively high environmental risk was identified, like for potential CH_4 pollution in the Netherlands.

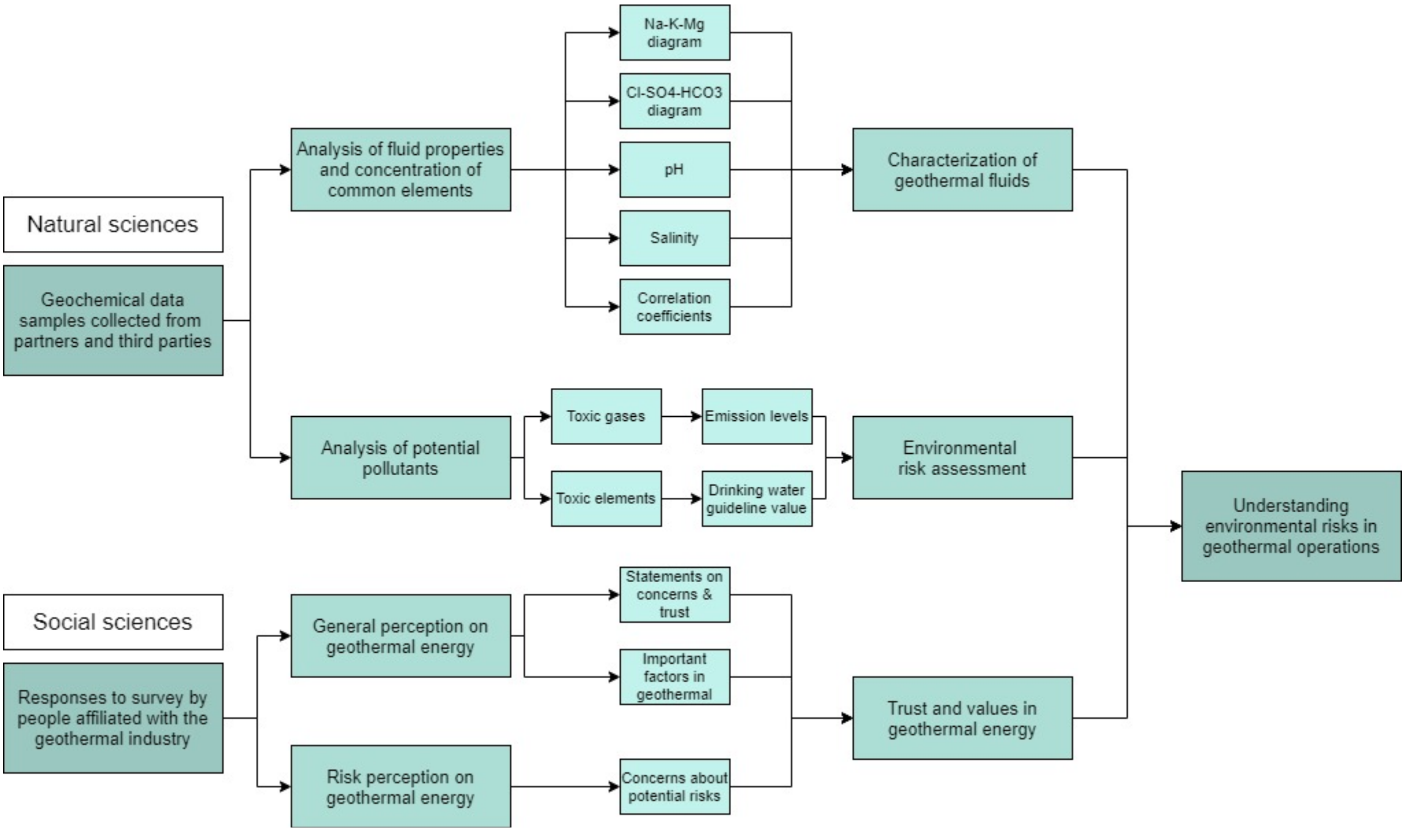

Figure 0.1 Flowchart presenting the outline and process of this interdisciplinary study

Acknowledgements

With this thesis my graduation project and student life at TU Delft are coming to an end. It still feels like such a short time ago that I first moved to Delft to start my first university courses, but I happily look back at the amazing time I had here and all the incredible people I met on the way. I am glad to conclude my time as a TU Delft student with this project, but there are a number of people without whom this would not have been possible and I would like to express my gratitude for their support throughout the realization of my graduation project.

First of all, my main supervisor Maren Brehme was the one who turned my interest for this interdisciplinary research into reality. Your guidance throughout the entire process made my enthusiasm for research grow and it’s been a pleasure working with you and the geo-fluids peer group that you introduced me to. Secondly, I would like to thank Simona Regenspurg for my time at GFZ Potsdam. I learned a lot from your valuable insights and it was inspiring to work within the Reflect project. I want to thank Anita Trisiah and Gerdien de Vries for introducing me to their discipline that was still new to me at the start but made this project unique. It has been a pleasure to work with both of you, especially because of your enthusiasm during our meetings. Finally, I want to thank David Bruhn for taking part in the committee, but especially for introducing me to GFZ Potsdam. We got in touch about a 3-month internship but this turned into this 9-month project and it has been a great experience to me.

Besides my supervisors and the people that I collaborated closely with, there are a number of people without whom this thesis could not have become what it is now. Erdem Dokuz from Niğde University helped out in translating the survey to Turkish and in the collection of local data in Turkey. Irwan Iskandar and his research assistants from Institut Teknologi Bandung provided me with data from Indonesia that waere of major importance to the geochemical analysis. Hester Dijkstra from TNO assisted me in the collection of Dutch fluid data and supported my research with her insights both within the Reflect project and beyond that. Finally, I want to thank everyone who helped me spread the survey, because without the responses I could not have finished my research in this interdisciplinary way.

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Jeanne Steijn
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1. Introduction

The current status of geothermal energy

On January 1st 2020 the people of Jakarta woke up in a drowning city. Heavy overnight rains in the Indonesian capital caused two neighboring rivers, Ciliwung and Cisadane, to overflow and the combination with a high sea level resulted in major flash floods and water levels reaching up to six meters (1) (2). This event killed at least 66 people and 60,000 people were displaced, but this event is not unique to the city. The main part of Jakarta lies below sea level and the combination with the rise in sea level is a major threat to the city's safety.

As we are more frequently confronted with extreme weather conditions and rising water levels, the world is calling for action. Carbon emissions need to be lowered rapidly to prevent global temperatures from rising further in the years ahead. Therefore, today's energy transition requires alternative energy sources that can provide sustainable production (3). One opportunity here is geothermal energy, produced from hot fluids that are extracted from thermal reservoirs in the Earth's subsurface (4). These hot fluids are reinjected to the reservoirs and thereby the natural equilibrium is maintained and the resource can be managed sustainably.

Indonesia hosts the world's largest potential for the development of geothermal power plants, is one of the world's main producers of geothermal energy and one of the studied countries in this work. The country is suffering severely from climate change and is heavily increasing their geothermal capacity. This combination is a clear indication of how restraints as a result of climate change so far can increase a country's motivation for renewable resources. On the contrary, other countries hardly suffer from climate change and have different cultural values, resulting in a less strong motivation for the implementation of sustainable and alternative energy resources. In this research, social and technical aspects of the implementation of geothermal energy in three different countries (Indonesia, Turkey and the Netherlands) will be studied and compared.

Geothermal energy: capturing Earth's heat

Geothermal energy is a renewable, sustainable and popular alternative energy resource and is integrated in long-term energy policies in many countries (4). It is an inexhaustible source that can be used for both thermal and electrical energy supply. Since geothermal energy production is independent of weather conditions, it contributes significantly to the base-load energy demand (4). Further, it is low in carbon emissions, waste, and makes efficient use of land area (5).

Geothermal systems are in operation for a range of applications, from power generation to heating and cooling purposes. What type of application is most suitable depends on the temperature that is produced. Electricity generation from geothermal resources requires high temperature steam (> 100 ºC) to run a generator. Heating from geothermal resources requires less high temperatures (< 100 ºC) and uses the fluid to circulate through pipes where the heat is absorbed (6). The geothermal installations comprise of both the subsurface wells that transport the fluids to the surface and back to the reservoir, and the surface installations that convert and distribute the energy generated in the operation to the grid.

A geothermal reservoir is a natural underground formation that hosts fluids in pore or fracture spaces between the rock grains. The properties of a geothermal reservoir, such as rock type, depth and pore space, depend on the geological formation (7). These conditions rely on the origin of the formation and whether the reservoir is of sedimentary or volcanic type. The temperature of the fluid depends on the distance to the heat source, which can be an igneous intrusion in the Earth's crust or the Earth's interior itself. The thickness of the crust between the surface and interior determines the increase in subsurface temperature over depth, also called the geothermal gradient. In average conditions this gradient is around 30 ºC/km depth, but volcanic activity leads to an increase in the geothermal gradient. There are different methods for classifying geothermal systems, such as sedimentary or volcanic types, or conduction or convection-dominated types. The geothermal fluids that are hosted in the pore spaces are brines that are highly saline as a result of dissolution from the host rock. This high salinity can increase the risk in geothermal operations, for example because of scaling or corrosion in the technical installations (8). Whether the geothermal brines are in liquid or gas phase, depends on the pressure and temperature inside the reservoir.

Development of the geothermal industry

In terms of electricity generation, there are hundreds of projects in place worldwide and there is an installed capacity of over 15.000 MW_e from geothermal power plants (9). Geothermal heating projects can be realized at a much smaller scale, so these hold a large potential for local heating systems. The European installed capacity in 2015 was already 5000 MW_{th} in district heating systems and 20.000 MW_{th} in heat pumps (10).

The first records of the utilization of geothermal heat date back to over 10,000 years ago. A this time, human settlements occurred close to hot springs because these served as a source of heat and cleansing (11). The development of geothermal power generation commenced several millennia later in the Larderello region in Tuscany in Northern Italy (12). The first power plant in Larderello already supplied 250 kW of electrical power in 1913, which increased to 15 MW in 1915 (4). Following Italy, Iceland installed its first large scale heating installations in the 1920s. Ever since, Iceland has continued to increase its geothermal capacity and today it is the number one geothermal energy producer in the world with 53% of its primary energy consumption that is supplied from geothermal resources (4).

The majority of the current geothermal energy production takes place in countries that are located within active tectonic regions, such as Indonesia, New Zealand and Iceland (13). In these locations the potential is relatively high as a result of an increased convection-dominated heat flow that leads to higher subsurface temperatures (6). Conduction-dominated geothermal systems occur in passive tectonic settings and generally have lower subsurface temperatures. Examples of these systems are in the Netherlands and Australia (14). There are numerous locations around the world whose potential is in between these two types of systems, where for example metamorphic core complexes or extensional basins have an increasing effect on the geothermal gradient, like in Turkey and France (14).

Limitations to the future development of the geothermal sector

The potential for the future development of geothermal energy is still mainly undiscovered and there are large uncertainties in the estimation of the worldwide potential. For example, Williams *et al.* (15) assessed the capacity of moderate- and high-temperature geothermal resources and they estimated the capacity of undiscovered geothermal resources in the United States to be 30,033 MW_e, which is over three times the estimated capacity from previously-identified geothermal systems (15). The currently produced capacity in the United States is 3,700 MW_e (13), almost 25% of the total worldwide production. This difference between the identified and estimated capacity proves the scope of the world's undiscovered geothermal potential.

The main limitations to upscaling of the geothermal energy sector are the infrastructure, costs, location constraints and uncertainties in the induced risks (16). Geothermal energy can be produced close to the reservoir location and transportation can be inefficient because of heat loss during transport. Next to the infrastructure, the geothermal installations require high initial investment costs, and only become cost-competitive on the long run. There are few external energy sources required for geothermal installations, so the operational costs are low compared to other renewable resources (17).

A major impact on the acceptance of new energy resources are the environmental risks, which include a broad range of factors like seismicity, pollution, nuisance and waste (18). A previous risk assessment for Turkey has rated most of these factors in geothermal energy production as low risk (5), with the exception of noise levels during installations, the impact on habitat and living life and the potential pollution of water. However, the risk assessment largely depends on a broad range of reservoir and operation-specific properties, such as the structural properties and geochemistry. For example, the risk of seismicity will increase when the rocks are very unstable and faults are reactivated due to changing pressures. The pollution risk in geothermal operations depends largely on the well integrity and the fluid properties, because the fluids carry the potential pollutants. The concentration of pollutants that they carry depends on three factors, namely (1) the host rock-water interactions in the reservoir; (2) the flow rate of fluid discharged by the system and (3) the reservoir temperature (19). If the fluid contains high concentrations of toxic elements or gases and these are released into surrounding subsurface layers, groundwater or the atmosphere, pollution can harm the health of flora, fauna and humans and decrease the sustainability of the geothermal operation. This risk is minimized with the implementation of integer wells and pressurization of the geothermal fluids, on which the operator has a major influence.

The successful implementation of a progressive energy resource largely depends on public acceptance and perception. These are largely affected by external factors such as previous incidents and media frames, but when the public supports the new resource, it can be upscaled rapidly with a thorough risk management plan. This plan requires an accurate risk assessment of the planned project in which the risks are expressed through their probability and impact of an event resulting from them (20). A close risk assessment for geothermal projects consists of data collection and analysis that represents the risk factors. There are two major advantages to integrating this into the risk management plan. Firstly, the data, training and knowledge gained by the persons carrying out the risk assessment allows them to act proactively in a crisis. Secondly, the knowledge gained in the risk assessment process makes the people involved in this process more supportive during the decision-making process (21).

Research objectives

Research opportunities

Since risks are one of the main argument against upscaling of geothermal energy (22), it is important to understand, minimize and monitor these risks. Previous studies have shown that the risk of pollution is a main factor in the acceptance of new energy resources (22), and therefore the goal of this study is to provide an in-depth assessment of both the natural and social aspects of the environmental risks in geothermal operations. More specifically, it focuses on the environmental risks of groundwater contamination and air pollution, which are largely dependent on the geochemistry of the produced fluids and a major threat to the health of humans, flora and fauna.

Environmental risks from toxic gases and elements in geothermal operations have been analyzed in previous research. The majority of these projects focused on a limited number of polluting elements or gases in a specific geothermal field. Such kind of research helps to understand the concentrations of specific pollutants over time or distance. What distinguishes this research from previous studies is that it aims to create an overview of geothermal systems and their potential environmental risks on a larger scale. This overview is created by analyzing around 750 geochemical samples from three countries. This is the first presentation of such an overview and a unique aspect of the study using a vast data set and close assessment of the data. In this way, geothermal systems are characterized and the potential future development in a country-wide setting is assessed by studying potential pollutants. Simplifications are required in this analysis and some samples are studied in detail because they deviate from the common trends in the region or country.

Through the combination of two research domains, natural and social sciences, it is possible to study the environmental risks in terms of the risk scope and the perceived risks. The natural sciences domain can help to optimize the sustainability and to minimize the risks in geothermal operations, and the social sciences domain can improve the understanding of the perception towards geothermal energy. By creating a bridge between these two aspects, future development of the geothermal sector can be accelerated.

Understanding environmental risks from multiple perspectives

To gain an in-depth understanding of environmental risks, the research is approached from two perspectives in three countries. The social perspective is studied through a sample population their general attitude towards geothermal energy and their risk perception on geothermal operations. To make sure the population has prior knowledge on the subject, the population consists of people that are affiliated with the geothermal industry already. This risk perception is compared to the risk assessment that is performed by analyzing the geochemistry of the geothermal fluids.

The study is performed in three countries, which differ in terms of both geological and cultural settings. These are Indonesia, Turkey and the Netherlands. Indonesia has many high enthalpy systems in place, Turkey has medium to high enthalpy systems and the Netherlands has low enthalpy systems (23). The countries also differ in cultural values, which can be quantified with help of cultural dimensions that were for example defined by Geert Hofstede (24). His theory defines a culture in terms of six cultural dimensions, three of which are related to the consumption of renewable energy (25). These are the masculinity, uncertainty avoidance and long term orientation. These respectively represent to what extent a country is driven by competition and success, unknown situations, beliefs and the links that are maintained with the past. Energy consumers in feminine countries are less driven by competition, achievements and success, but more orientated towards quality of life and cooperation (26). This makes them more motivated to switch towards renewable energy resources (24). In Indonesia these three factors are average, whereas in Turkey the uncertainty avoidance index is high and in the Netherlands the masculinity index is low (26).

Besides the geological and cultural differences, the geothermal sectors in each country are at a different stage, and the geothermal potential is of a different level. Indonesia's geothermal potential is ranked among the highest in the world, and the current future goals are ambitious (27). Turkey has medium geothermal potential and has shown over the past years that its ambitious future growth rates are possible

(28). On the contrary, the Netherlands is a country with a relatively low potential but still there is a number of installations in place already (23).

Approach and Outline

The goal of this interdisciplinary research is to improve the understanding of environmental risks in geothermal systems in different settings, both geologically and culturally. This understanding includes an approach from both natural and social aspects to build a bridge between the actual risks and the perceived risks, which is an essential aspect in upscaling a new energy resource.

The study will compare the data that were gathered from each of the three countries to improve the overall understanding of the environmental risks in different geothermal systems. Therefore, it commences with a chapter that introduces each of the countries in terms of the geothermal system types, utilization and developments. Following this chapter, the natural and social perspectives will be discussed separately in the methods and results chapters.

The geochemistry is analyzed through fluid samples from each country. In general, geochemistry research is performed by sampling the geothermal fluids and measuring the fluid properties and dissolved elements and gases. Numerous samples are taken at a single sample location, but referred to as separate sample points. From those the geothermal fluids are characterized in terms of their origin and equilibrium with the host rock. The interaction of geothermal fluids with surrounding rocks increases the risk of elevated levels of toxic elements. These are aluminum, arsenic, cadmium, fluoride, mercury and lead. Each of the toxic elements have different effects on their environment, and they are considered a major threat for groundwater quality. Arsenic was previously found to be a threat to agricultural soils in the Cerro Prieto geothermal region, in Northwest Mexico (29) and fluoride contamination in groundwater was observed to be a result of geothermal activity in India. This fluoride contamination led to manifestations of fluorosis among the inhabitants of nearby villages (30). The risk of contamination decreases with an improved well integrity, but even inside the wells they can result in implications in the geothermal operation (31).

Even though the contamination risks of toxic gases from geothermal energy generation are much lower than they are in traditional energy sources, the risk of increased pollution should not be underestimated (32). High enthalpy geothermal systems that are used for power generation more frequently contain higher levels of greenhouse gases, but this risk is largely dependent on the chemistry of the extracted geothermal fluids. As geothermal energy production will be upscaled in the future, a larger variety of geothermal fluids will be produced and therefore the risk of high concentrations of toxic gases will increase as well. In this study we will further discuss the main toxic gases that are emitted from geothermal energy production: CO_2, CH_4 and H_2S. CO_2 and CH_4 are the relevant greenhouse gases in geothermal fluids and H_2S is a toxic gas of volcanic origin that has had fatal consequences resulting from geothermal operations in the past (33). The risks of each of the pollutants are compared through plots and correlations with the aim to assess the environmental risks in the three countries in terms of groundwater contamination and air pollution.

A quantitative descriptive analysis was performed on the perception of geothermal energy in the three countries. The data were obtained through a survey, which is a major complement to understanding the population’s values in and perception of geothermal energy in general, and, more specifically, the risk perception in geothermal operations. In the data analysis the survey results are correlated to the demographic information about the population and their general opinion towards geothermal energy. These correlations and the (risk) perception data are compared between the three countries and later integrated with the geochemical analysis within the discussion and conclusion of the report.

Research projects

This work is part of the scientific research projects MiMo and REFLECT. The project MiMo (Misi Monitoring) is a collaborative mission to foster scientific collaboration in the field of geothermal energy between Indonesia and the Netherlands. In this project both social and technical challenges are tackled to increase the growth of geothermal energy development. Project MiMo is funded by the KNAW (Koninklijke Nederlandse Akademie voor Wetenschappen) (34). The REFLECT project aims at redefining geothermal fluid properties at extreme conditions. This project is part of the European Union's Horizon 2020 research program and it covers six major research themes. This thesis is part of the second theme, which aims at creating a geothermal fluid atlas that will be publicly available for both academics and industry (35).

2. Country introduction

This country introduction aims to identify the major differences between the geothermal sectors in Indonesia, Turkey and the Netherlands. Each country is described in terms of geothermal system type, current geothermal energy utilization and the future ambitions for the geothermal sectors. These influence the past and future growth of the local geothermal sectors and thereby affect the risk assessment in each country.

Geothermal system types

When distinguishing between different types of geothermal systems, a possible classification method is by the host rock of the geothermal fluid. These systems can be of sedimentary or volcanic nature. In this section they are distinguished between clastic and carbonatic sedimentary systems, and active and passive volcanic systems. Country examples for each type of system are studied and it is described how the geochemistry is related to the regional geology in terms of tectonic activity and formation type.

Sedimentary systems

Sedimentary systems are formed by the accumulation and deposition of material created by weathering and erosion processes. Clastic sedimentary rocks are composed of grains of pre-existing rock components that have undergone sedimentation and compaction (36). Carbonatic sedimentary rocks are made up of over 50% carbonate minerals, like calcite or dolomite (37). Sedimentary geothermal systems are generally conduction-dominated systems, which means the heat is transferred within the material without movement of fluids or sediments (14). A schematic cross section is sketched in Figure 2.1, with numerous sedimentary deposits such as sandstone and limestone, but also rock salt and its typical deformational effect on its environment.

Examples of clastic sedimentary systems are found in the Netherlands. In most of the Dutch subsurface we find a virtually continuous deposition of predominantly siliciclastic sediments of over 10 km thickness overlying the metamorphic basement (38). The tectonic settings are currently quiet, but extensional rifting in the past led to the formation of horst-graben systems that consist of mainly siliciclastic sediments with alternations of claystone, limestone, evaporites and occasional volcanic deposits (39). The basins and highs that were formed in this time (Appendix 1A) are overlain by deltaic deposits from coastal to deep marine settings. These include an alternation of shales, claystones, sands, salt and some chalks, that are predominantly deposited horizontally. Geothermal production takes place from these deltaic deposits, which contain sandstones that offer good permeability and porosity conditions and makes them suitable for geothermal exploration. The production from deep, mature reservoirs affect the geochemistry of the geothermal fluids, because they are typically fed from the deep geothermal reservoir.

Examples of carbonate sedimentary geothermal systems are found in Turkey. Turkey's geology is divided into three main tectonic units: the Pontides in the North, the Anatolides-Taurides in the middle and East and the Arabian Platform in the Southeast (40) (41) (Appendix 1B). The stratigraphy in Turkey largely differs between the three main tectonic units. The Arabian Platform consists of a crystalline basement that is overlain by a 4 km thick package of a complex mixture of sediments and volcanics (siltstone, shale, sandstone, gabbro, tuff and basalts) (41). The Pontides are characterized by metamorphism. The basement is overlain by an alternation of continental clastic rocks and marine carbonates with sequences of metamorphic and volcanic rocks (41). The Anatolide-Taurides terrane forms the major part of the Turkish subsurface and while the Pontides was largely influenced by metamorphism, the Anatolide-Taurides were

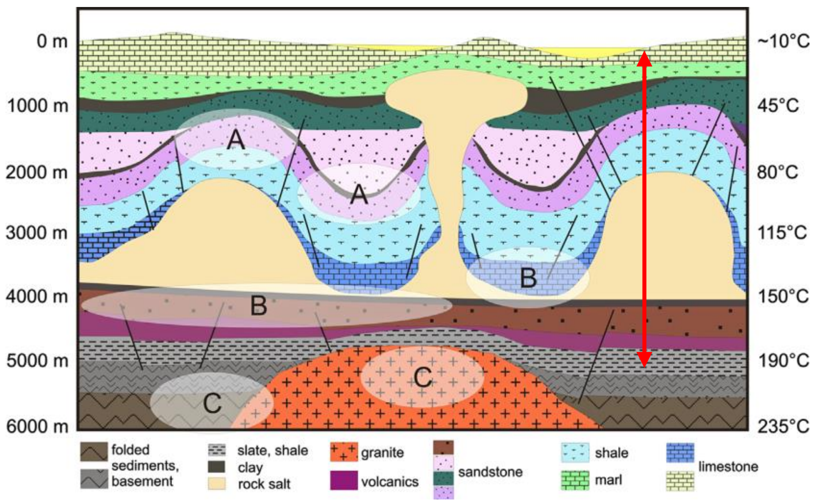


Figure 2.1 Schematic cross section of an intracratonic sedimentary basin and various geothermal play types at different depth and temperature ranges. Temperature is an average assuming a geothermal gradient of 32 C/km. Geothermal fluid temperature depends on the production depth, which can vary largely as indicated by the red arrow. Modified from (163). In this figure are indicated A – Geothermal plays above 3 km depth with temperature suitable for district heating, B – Deep geothermal plays below km depth suitable for heating and electricity, C – Very deep geothermal plays below 4 km depth as potential HDR systems.

an extensive carbonate platform where thick shallow marine carbonates (>1000 meters) were deposited. Most geothermal exploration takes place in the Menderes Massif (Anatolide-Taurides) and in the Sakarya Zone (Pontides), where the geothermal reservoirs mostly consist of clastic-carbonate sediments (41). High levels of carbonates in the reservoir can lead to dissolution of carbonate into the geothermal fluids and this heavily affects the geochemistry.

Volcanic systems

Volcanic systems are characterized by their dynamic interplay between lithosphere and asthenosphere (14). This interplay is generally a result of tectonic activity between plate boundaries. The volcanic systems can be subdivided into active and passive systems, where in the active systems the heat is derived from plate boundaries that are actively moving at present, and passive systems are former active volcanic systems that still have the heat in place. Therefore, passive volcanic systems indirectly heat the geothermal fluids and these are typically conduction-dominated systems. Active volcanic systems are typically convection-dominated systems, which means the heat is transferred directly through the fluid as it moves from the deeper to shallower crust (14). An example of an active volcanic system is sketched in Figure 2.2, which shows how the intrusive heat source from the asthenosphere rises to the lithosphere and there interacts with meteoric water and groundwater. This also results in enhanced temperatures in the geothermal systems that rise up to 300 ºC. The properties in volcanic reservoirs are unique and often infer elements that are hardly found from other sources. An example of an element that is typically found in volcanic settings is hydrogen sulfide, which is the cause of the 'rotten eggs' smell that is common around volcanoes (42).

Active volcanic systems are found in the Indonesian archipelago, which is located on the so-called 'ring of fire', a tectonically active region located along the edge of the Pacific Ocean, stretching from New Zealand to Japan, the USA and Chile (43). The collision of tectonic plates moving in different directions has resulted in a tectonically complex area in which the subduction of tectonic plates (Appendix 1C) has resulted in the formation of 127 active volcanoes throughout the Indonesian archipelago (44). These are mainly located on the volcanically active arcs that stretch throughout the country and host the volcanic reservoirs from which geothermal energy is produced. The Indonesian geothermal reservoirs predominantly consist of andesite alternated with other rock types that depend on the exact locations of the reservoirs (45) (46) (47). For example, in Wayang-Windu (West-Java) a considerable amount of pyroclastics is found (48) whereas in Ulubelu claystone and sandstone are present (49). The production from active volcanic systems largely affects the geochemistry of the geothermal fluids because they are fed directly from the active volcanism through convection.

Examples of passive volcanic systems are found in Turkey. Extensive deformational events in Turkey have led to the formation of the large metamorphic complex called the Western Anatolia region. The metamorphic rocks here are overlain by thick sedimentary deposits in which the heat source is the volcanic rocks that have formed as products of the continental rift zones (41). Crustal thinning has resulted in a large geothermal potential in the region of Western Anatolia, typically found in graben systems such as the Büyük Menderes Graben and the Gediz Graben. Because the fluids are heated indirectly from the passive volcanic systems, their effect on the geochemistry largely depends on the geological features that are present near the reservoir. For example, faults that formed as a result of the extensive deformation can enhance fluid flow to reservoir rocks that are located at shallower depths above the volcanic rocks (14).

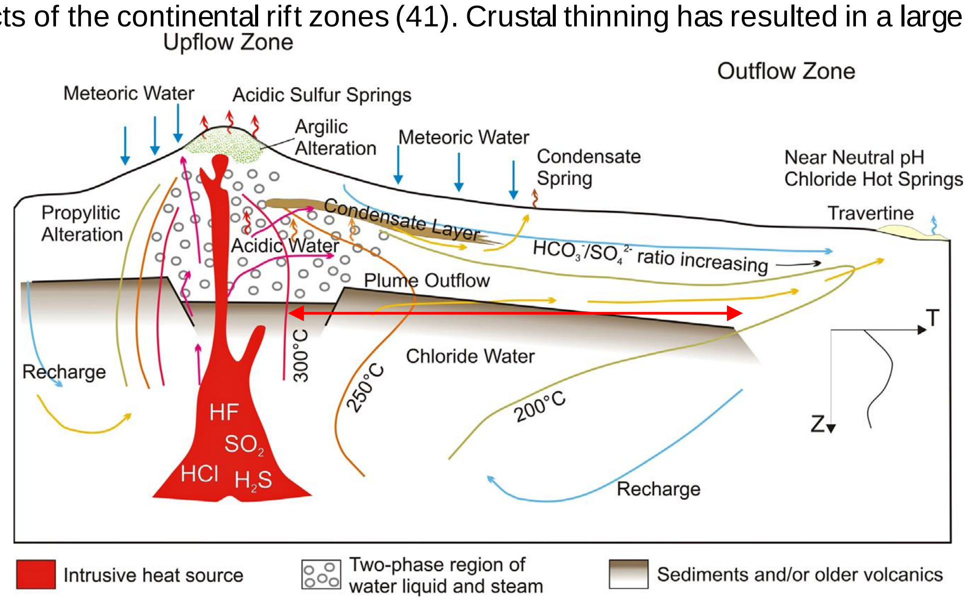


Figure 2.2 Geothermal play type related to an active volcanic field typical for a magmatic arc setting above a subduction zone. Fluids from the intrusive heat source (with elements that are typically present in volcanic systems) rise to the surface and there mix with waters from different sources such as groundwater and meteoric water. This affects the geochemistry and the subsurface temperatures. Temperature of the geothermal fluid depends on the distance from the heat source, as indicated by the red arrow. Modified from (163).

Geothermal energy utilization

To differentiate the geothermal systems further, a classification system is used that was defined by the U.S. Geothermal Energy Association for the United States Department of Energy in 2005 (Appendix 2). This classification system defines seven classes of geothermal systems and is mainly based on temperature. It also includes a broad range of properties like the phase of the fluid (gas, liquid or multiphase) and whether it can be utilized for geothermal heating or electricity generation. For this study the classification is simplified further and referred to as low enthalpy systems (class 1, below 100 ºC), medium enthalpy systems (classes 2 to 4, 100 to 230 ºC) and high enthalpy systems (classes 5 to 7, over 230 ºC). The simplified classification scheme with detailed information is shown in Table 2-1.

Table 2-1: Simplified classification of geothermal systems based on the classification by the U.S. Geothermal Energy Association (50). The classification is based on the reservoir temperature, but also the fluid phase and utilization of the geothermal resource.

Type of system	Reservoir temp. (ºC)	Mobile fluid phase	Resource class	Utilization	Typical well productivity
Low enthalpy	< 100	Liquid	Non-electrical	Heating	Dependent on reservoir flow capacity and static water level
Medium enthalpy	100 – 230	Liquid	Low to moderate temp.	Electricity	2 – 12 MWe
High enthalpy	> 230	Liquid-dominated two-phase	High temperature	Electricity	Up to 50 MWe

This section discusses the geothermal energy utilization in Indonesia, Turkey and The Netherlands in terms of the geothermal potential, current installations and local geothermal community, which includes i.e. geothermal operators, organizations and research institutes. This information helps to identify what geothermal sectors are in place in each country and what the potential is for the development of geothermal energy in the future.

Indonesia

The geothermal resources in Indonesia are mainly a result of the active volcanic systems, where the heat source is the volcanic rock. This has led to a geothermal gradient that differs from 31 to 190 ºC/km on the island of Sumatra (51). The mean temperatures produced from the wells range from 230 to 310 ºC (52), which classifies them as high enthalpy systems. The total geothermal capacity in Indonesia is estimated to be almost 30,000 GW_e, making it one of the highest in the world (43). The current production or geothermal energy is predominantly used for electricity generation through geothermal power plants, because the heating demand in Indonesia is small.

Indonesia currently generates around 2000 MW_e of geothermal power in a total of 15 geothermal power plants (Figure 2.3). This is less than 10% of the total geothermal potential (27). Besides power generation from high-enthalpy geothermal systems, there are some small-scale low-enthalpy heating systems currently in place like coffee bean drying through geothermal heat in Wayang-Windu (West Java) (48). Most of the geothermal installations in place are located in the Sunda-Banda Arc or in the Sulawesi Arc (53) on the islands of Sumatra, Java and Sulawesi. The geothermal power plants produce from volcanic reservoirs that mainly consist of andesite deposits. The average production in the different geothermal power plant locations ranges from 2.5 MW_e to 330 MW_e (52).

The first geothermal installation in Indonesia was started in 1983 and ever since a steady but slow growth of geothermal energy has taken place (Figure 2.4). However, the total estimated potential offers a high potential for the country and its geothermal industry. The Indonesian government has set the goal to become the largest geothermal electricity producer in the world by 2030 (27). By this time, the aim is to produce 10,000 MW_e from geothermal sources. Looking at the current developments in geothermal energy these numbers are still ambitious. To reach 10,000 MW_e, the preliminary goal was to produce 7,200 MW_e by 2025 (23% of total national energy mix), but this goal was already reduced to 4,000 MW_e (27). The ambitions for geothermal energy in Indonesia, Turkey and The Netherlands are visualized in Figure 2.4. This figure shows the past development and future ambitions for geothermal energy in terms of installed capacity.

Indonesia has an active geothermal community. There are official governmental departments in sustainability and geothermal energy specifically, called the Ministry of Energy and Mineral Resources (MEMR) and the Directorate of Geothermal Energy (DGE). The Indonesian Geothermal Association (INAGA) is a governmental partner and has an active role in socializing the benefits of geothermal exploitation. They also aim to minimize the environmental and social issues in the regions. Indonesia has a national database (Geologi Indonesia) for geological data that provides information on sequence stratigraphy, sedimentary basins and geological maps.

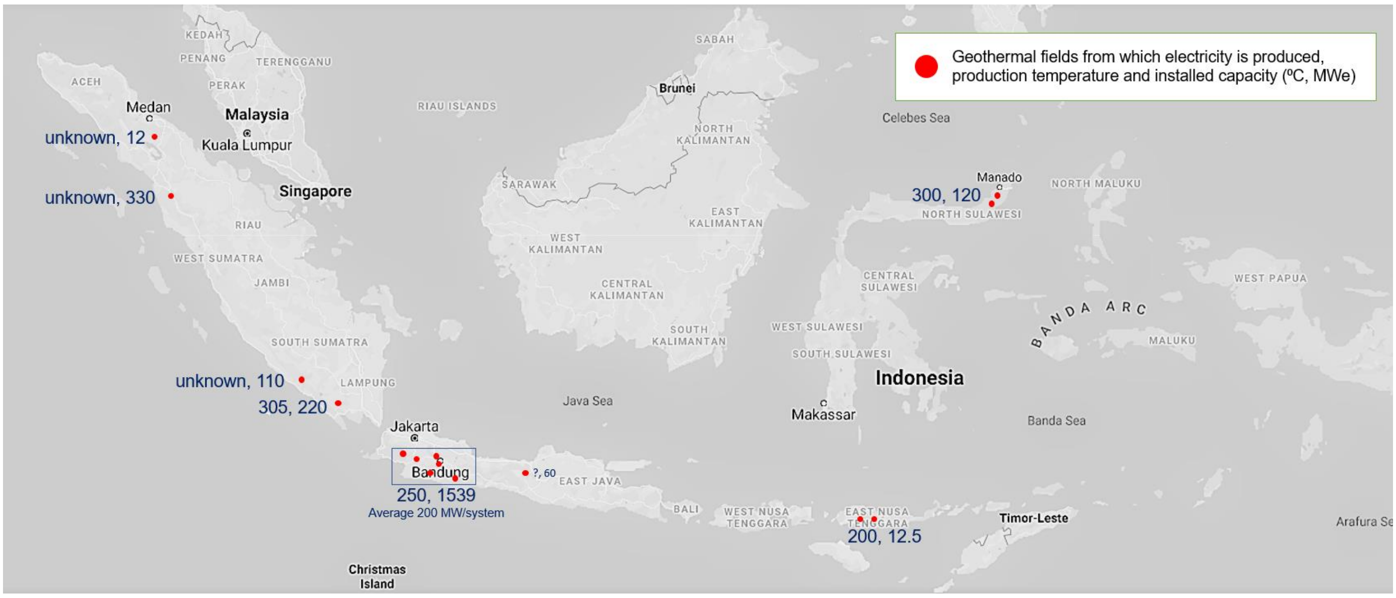


Figure 2.3: Current installations in Indonesia in terms of temperature and installed capacity. The red dots indicate the geothermal fields from which electricity is produced. The blue text indicates the temperature and total capacity that are produced from the field. In these numbers the capacities of all installations in place are added up per geothermal field.

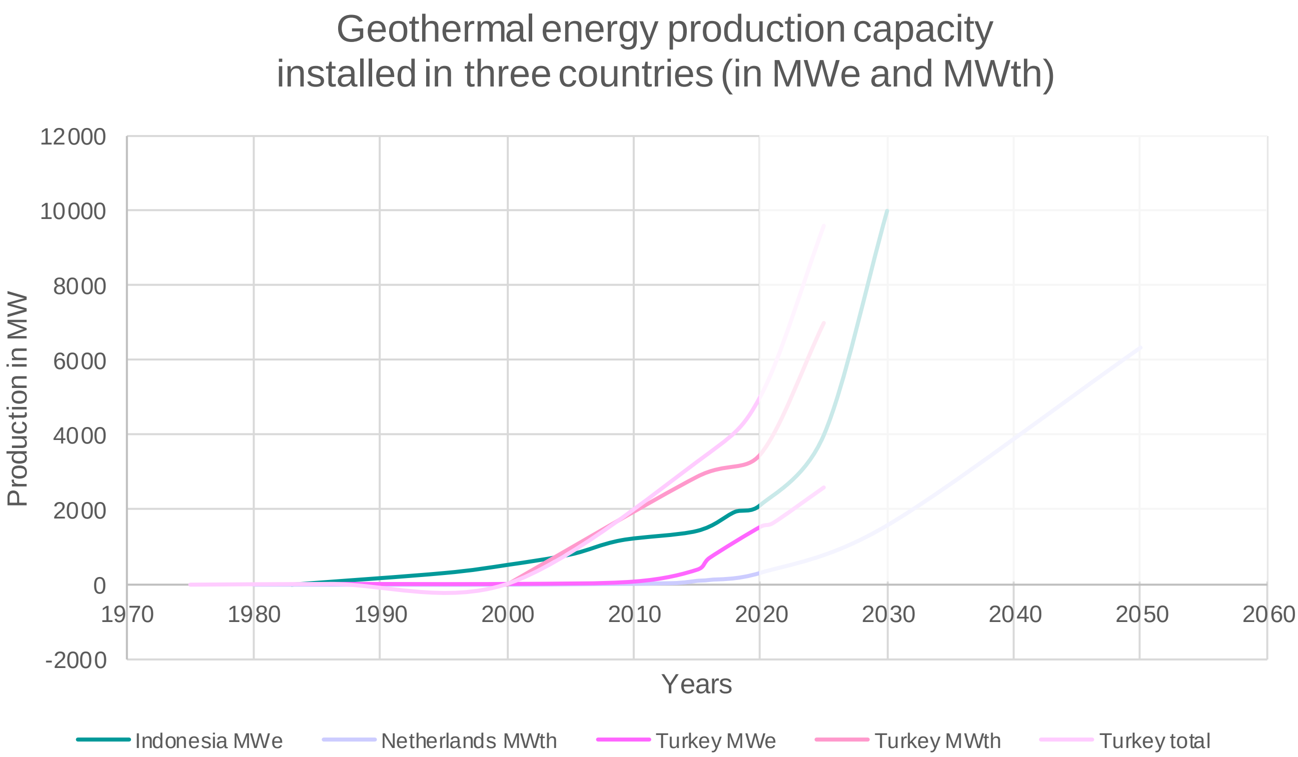


Figure 2.4 Past and future development of geothermal energy in the three countries in terms of installed capacity. The data for Turkey are shown as both electric and thermal capacity because both types of installations are in place here. This is not the case for Indonesia and the Netherlands. The plot is based on the data from Appendix 3. The negative value around the year 1995 in the total Turkish production is a misfit of the connection of the data points.

Turkey

The volcanic rocks found in the Turkish subsurface serve as a heat source and result in a high geothermal gradient in specific regions. The gradient is less than 50 ºC/km in most of the country, but in Western Anatolia (in the Western part of the country) it reaches up to 190 ºC/km (54). The geothermal power plants most commonly produce from systems with temperatures between 140 and 250 ºC. This classifies them as medium to high enthalpy systems. Throughout the rest of the country several district heating systems are in place. These are generally heated with lower temperatures (between 55 and 120 ºC) and do not always run on 100% geothermal energy. The country hosts a high geothermal potential that is estimated at 4,500 MW_e and 60,000 MW_{th} (55).

The current geothermal installations in Turkey are used for a broad range of applications, including balneology, heating and electricity. This section focuses only on heating and electricity generation. Both purposes match the Turkish demand and variety of temperatures that are found in throughout the country. There are currently over 25 geothermal power plants in place and over 10 district heating systems (Figure 2.5). Altogether the current geothermal energy production in Turkey is about 1500 MW_e and 3500 MW_{th}, which are respectively 35% of the MWe and 6% of the MW_{th} potential.

The majority of the geothermal systems that are currently in place are located in the Western Anatolia region and others are spread throughout the country. The high-temperature systems that produce electricity are mostly found in clastic-carbonate formations. The average production from the geothermal wells is about 25 MW per system and in district heating systems it is between 20 MW and 75 MW (56).

The future ambition is to increase production to 2600 MW_e and 7000 MW_{th} by 2025 (28). These numbers require a rapid increase, but the recent growth rates of especially electricity generation has shown that this growth rate is possible in Turkey (Figure 2.4).

Turkey's institutional geothermal community is not as extensive as they are in Indonesia or the Netherlands. A sustainability department belongs to the government (Republic of Turkey Ministry of Energy and Natural Resources) and Turkey has a geothermal association (Türkiye Jeotermal Derneği). Turkey has a national strategy for the total national energy mix describing ambitious plans for the development of geothermal energy.

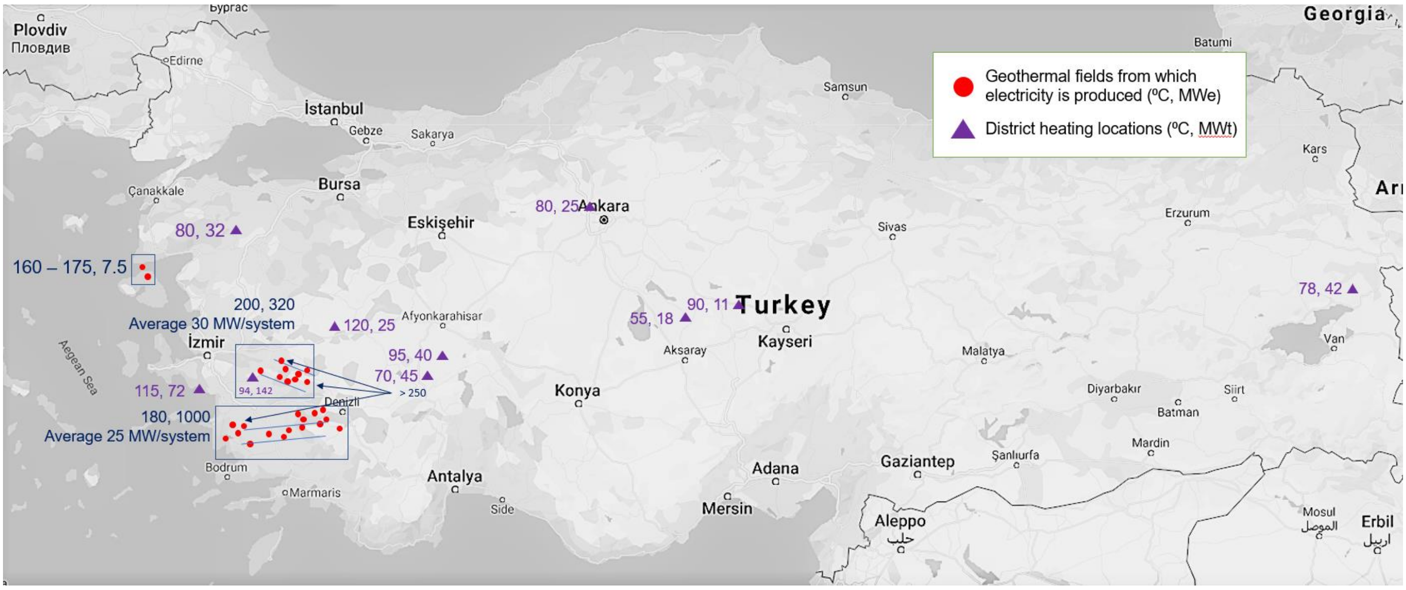


Figure 2.5 Current installations in Turkey in terms of temperature and installed capacity. The installations from which electricity is produced are grouped by locations in the different graben systems. The total installed capacity per region is written in the figure and the average capacities are included for the two grabens that contain a large number of installations.

The Netherlands

The thick sedimentary deposits without tectonic activity have caused the geothermal gradient in the Netherlands to be around 30 ºC/km. Most deep geothermal systems in the Netherlands (typically located between 1500 and 4000 m depth) produce temperatures between 60 and 90 ºC (Figure 2.6). The sedimentary basins in the Netherlands are suitable for geothermal energy production due to their reservoir conditions. Next to these deep systems, there are many Aquifer Thermal Energy Storage (ATES) systems in place in the Netherlands. With over 2,000 ATES systems in place (57), the Netherlands is a leading country in the implementation of ATES systems. These systems will not be considered in this report since they do not produce but store energy.

The total estimated geothermal potential for the Netherlands is 7300 MW_{th} (23). Because temperatures at several kilometers depth still do not exceed 100 ºC, geothermal energy production in the Netherlands is suitable for heating purposes and not for electricity production (23). The current production of geothermal energy takes place in 20 installations throughout the country (Figure 2.6). All installations are deep geothermal wells. These have a total installed capacity of 317 MW_{th}, which is about 5% of the estimated geothermal potential (57).

The majority of the geothermal installations are found in the West-Netherlands Basin (WNB) and a minority in the Central-Netherlands Basin (CNB) and the Texel-Ijsselmeer High (TIH) (Appendix 1A). In the WNB most production takes place from Cretaceous and Jurassic sandstones and a minor part of the production from Triassic and Tertiary sandstones. In the CNB and TIH production takes place from Permian sandstones (58). Two other production locations are found in the Southeast of the country, producing from Carboniferous limestones and clays in the Roer-Valley Graben (59) (60). All systems produce between 5 and 20 MW_{th}, and the most productive area is near the shore of Zuid-Holland, where temperatures between 75 and 95 ºC produce around 15 and 20 MW_{th}.

The Masterplan Aardwarmte NL accurately describes the goals for the development in geothermal energy in the country. This aims to upscale production to about 1500 MW_{th} by 2030 and over 6000 MW_{th} by 2050. In order to achieve this goal, a rapid increase in project development is required (Figure 2.4).

Though the geothermal production capacity in the Netherlands is still low, there is an active but small geothermal community. The Dutch Ministry of Economic Affairs and Climate contributed to the national strategy for geothermal energy that was published in 2018 (Masterplan Aardwarmte NL). The Dutch geothermal sector benefits from the amount of subsurface research that has been done for petroleum exploration previously. The data are stored in extensive national databases about subsurface properties and activities (Dinoloket, NLOG, ThermoGIS), which is unique for countries. The Dutch subsurface knowledge is currently still being updated actively through initiatives like SCAN (Seismische Campagne Aardwarmte Nederland). SCAN was initiated by the Dutch government and attempts to map a large part of the country with the help of seismics. In this way, the Dutch geothermal potential is further discovered (61). The Dutch geothermal community is further supported by geothermal (operator) organizations like GeothermieNL (www.geothermie.nl).

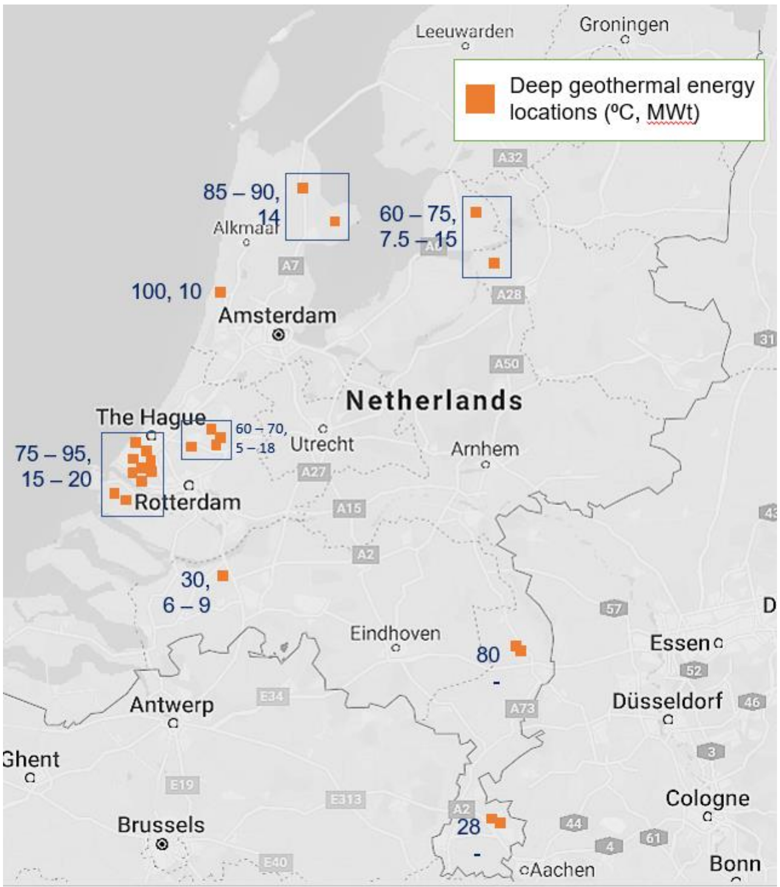


Figure 2.6 Current installations in the Netherlands in terms of temperatures and installed capacity. The installations are grouped by location and the average temperatures and installed capacity per installation is written in the figure.

3. Methods

3.1. Collecting, processing and analyzing geochemistry data

This chapter provides a detailed description of the methods that were used to create a comprehensive synopsis of the geochemistry of geothermal fluids in each country. This is done through the collection of data sets, including sampling temperature, pH, salinity and the dissolved cations, anions, trace elements and gases. The data sets are presented in 2-dimensional figures in which they are sorted by region or the type of system, which can be well or spring samples. These figures make it possible to draw conclusions on differences in geothermal systems in general and the origin and environmental risks of the geothermal fluids specifically.

Data acquisition

The geothermal fluid characterization is based on geochemical data that were obtained through a variety of sources. These include literature, two scientific projects (REFLECT (62) and MiMo (63)), and measurements that are partly published (64) (65) (66) (67) (68). This resulted in a data set from a broad range of locations. The complete table with all data can be found in the online appendices on data.4tu.nl (69). Though the samples are from locations from throughout each country, these are still a selection of samples that are not completely representative of the entire country and its geochemistry.

The Indonesian data set contains a total of 326 sample measurements from 151 locations. It contains a broad range of systems, from manifestations and springs to deep wells, that were sampled on three islands (Sumatra, Java and Sulawesi) at five different production locations. From these samples 95 are from wells and 182 from spring waters. Several of the remaining samples are from yet undescribed geothermal systems. The majority of the samples (225) are measurements taken in the field on Sumatra and Sulawesi and are partly published by Brehme *et al.* (64) (65) (66) (67) (68). Literature sources provided eight measurements from springs in Southern Sumatra (70) and 83 from wells and springs in Western Java (71).

The Turkish data set contains a total of 319 measurements from 291 sample points. From these samples 159 were taken in wells, 76 in springs and 34 in thermal baths. The sample type of the remaining samples were not known. The majority of the samples are from literature (72) (73). 236 samples from Bülbül (73) were taken at 200 locations that are mainly around the Western-Anatolia region. The 80 samples from Özdemir (72) were taken throughout the country. Altogether, the Turkish data set contained information about geothermal fluids throughout the entire country from a variety of systems.

The Dutch data set contains 49 samples from 19 locations. These were all taken in wells and obtained through the Netherlands Organisation for Applied Scientific Research (TNO), a partner in the scientific project REFLECT. The data set included publicly accessible data that were available at the platform DINOloket (Data and Information on the Dutch Subsurface) (60).

The information that was available differed per data set and per data point. Information that was available for most data points are the sampling temperature, pH and major dissolved anions, cations and trace elements. Common dissolved elements that were measured are calcium, magnesium, sodium, potassium and silica. Less common elements to be detected are heavy metals such as lead, nickel and arsenic. A selection of the data points also included information about the conductivity and isotopes present in solution.

Classification of geothermal systems

The data analysis was carried out with the aim to classify each country's geothermal system with help of its geochemistry. We will identify the type of geothermal system, the origin of the geothermal fluids and the potential environmental and health risks. Therefore, this data analysis is split up in two sections: the classification of the geothermal systems and the risk assessment. This chapter will provide an accurate description of the exact research design and methods throughout the different phases of this section. The first phase, classification of geothermal systems, consists of five types of diagrams that each display different properties of the geothermal fluids. Most data sets were provided in different units, so in that case the units were converted to uniform units before plotting them. This was typically mg/L for the element concentrations and salinity. The pH units are uniform. For specific analyses it was necessary to ignore incomplete data sets. For example in ternary diagrams it is essential to only include data points that contain measurements of each of the three elements plotted in the diagram.

Na-K-Mg ternary diagram

The first diagram is a triangular diagram that was first proposed by Giggenbach (74) and plots the relative concentrations of sodium (Na), potassium (K) and magnesium (Mg). This figure is used to find the maturity of the geothermal system and to determine the geothermometer temperature. The level of equilibrium of a fluid describes how active the exchange of chemical elements is between the fluid and its host rock. In deep, stable reservoirs there is little to no exchange. In shallow systems (like springs), that have active exchange of groundwater, the fluids are often immature. An example of the Giggenbach diagram is shown in Figure 3.1.1. The parameters plotted in the corners are Na, 10 · K and 100 · √Mg. The maturity of the system is indicated by the curved lines running from bottom left to bottom right. The lower curve indicates the immaturity boundary and the upper curve indicates the full equilibrium boundary. The geothermometer temperatures are plotted as straight lines that run from minimal to maximal Mg concentration (from left to bottom right). These temperatures are calculated through the geothermometer equations proposed by Giggenbach (74).

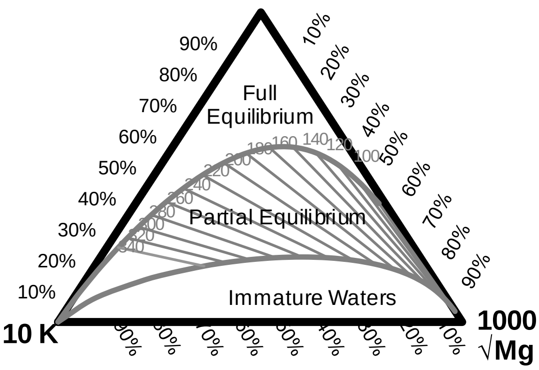


Figure 3.1.1 The triangular diagram as proposed by Giggenbach. Interpretation of the ternary diagram in terms of geothermometer temperature (in grey) and level of equilibrium (in black text) are shown in the diagram *(74)*.

Cl-SO_4-HCO_3 ternary diagram

To study the origin of geothermal waters, a ternary diagram of the relative concentrations of chloride (Cl), bicarbonate (HCO_3) and sulphate (SO_4) is plotted (74). This diagram was also proposed first by Giggenbach (74). The concentrations of these elements in the geothermal fluids reveal information about the origin of the fluids. An example is shown in Figure 3.1.2, where the Cl waters are shown on top, the SO_4 waters on the lower left and the HCO_3 waters on the lower right of the plot. This diagram helps to identify the source of the geothermal waters. The relation between the major anions (Cl, HCO_3 or SO_4) and the source of the geothermal fluid can be seen in Figure 3.1.2. A high Cl concentration is associated with the maturity of the waters, and thereby whether they are fed from the deep geothermal reservoir (19). High SO_4 concentrations are generally associated with magmatic gases and volcanic activity (74). A high concentration of HCO_3 in the geothermal fluid is typically associated with a higher amount of groundwater mixing (19) or with dissolution of CO_2-bearing gases that condensate from the deeper subsurface fluids (19).

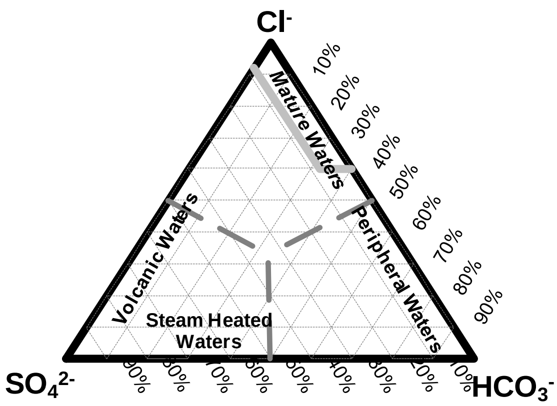


Figure 3.1.2 Plot of relative Cl, SO_4, HCO_3 contents as proposed by Giggenbach. Interpretations of each type of water are written in corners of the ternary diagram (74).

pH

The pH values of the samples in each country are plotted in box-and-whisker diagrams to create a clear overview of the pH ranges. The box-and-whisker diagram is a way to show the range and median values of a data set (75) and therefore it is a useful tool when comparing distributions between different groups or datasets. It plots the minimum, maximum, median and quartiles of the data set. An example of a boxplot is shown in Figure 3.1.3. Based on the probability density function for a normal distribution, it was determined that the outer 0.7% of the data (in green) are considered outliers for a normal distribution (76). The central 50% of the data that are shown in pink are the second and third quartiles.

The pH is influenced by fluid composition, temperature and salinity, but also affects the concentrations of certain elements in geothermal waters. At normal ambient temperatures a pH of 7 is considered the neutral pH, but in high-temperature reservoirs this is at pH 5.5 (19). This is because the equilibrium that determines the pH is a temperature dependent equilibrium.

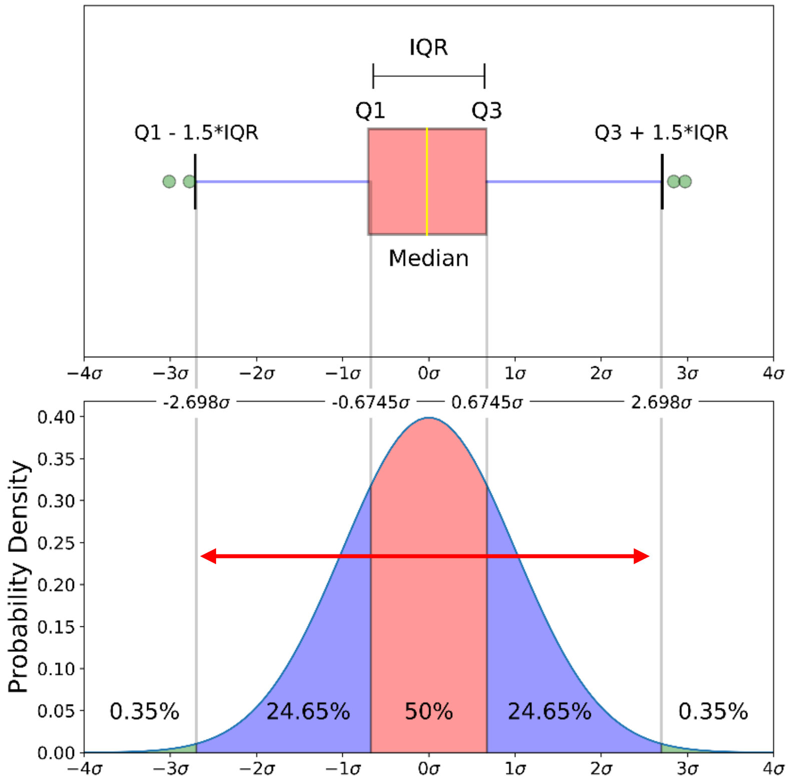


Figure 3.1.3 Example of a box-and-whisker plot in the top figure, with in the bottom figure an explanation of what data are plotted where from the normal distribution. The second and third quartiles are plotted in the pink box, and the outliers in green. In this work the focus will be on the pink and purple areas of the figure, indicated in red. Modified from (76).

Salinity

In order to compare the salinities in each country, the data points are sorted per country and the range of values are plotted in box-and-whisker diagrams (Figure 3.1.3). The salinity is highly dependent on the long-term mineral-fluid interactions that have taken place, and therefore it reveals information about the source and reservoir rock. The salinity affects the chemical reactions in the geothermal fluids, but it can also contribute to mineral scaling and corrosion problems. Because the pH largely depends on the proton consumption in the mineral-fluid reactions, the salinity of the fluid also affects its pH (19).

Correlation coefficients

The correlations between different element concentrations present in the geothermal fluids are calculated because they explain what minerals are commonly dissolved from the host rock. The correlations in the sample solutions are calculated using Microsoft Excel's CORREL function. This function calculated the Pearson Product-Moment correlation coefficient for two sets of values. The Pearson correlation measures the linear correlation between the two concentrations. This is done through a calculation in which the deviation from the mean in one variable is multiplied by the deviation in the other value (77).

The correlation between common elements in geothermal fluids are calculated through this method. The common elements of which the correlations are studied are Al, Ca, K, Mg, Na, Si, F, Cl, HCO_3 and SO_4 and the correlations are calculated by country for well and spring waters separately. After all values are calculated, the correlations are compared between well and spring waters and between each of the three countries. This comparison is done with help of the interpretation of Pearson's correlation coefficients by Dancey & Reidy (78) (Table 3.1-1).

Table 3.1-1 Interpretation of Pearson's correlation coefficients by Dancey & Reidy (78)

Correlation coefficient		Interpretation
+1	-1	Perfect
+0.7 – 0.99	-0.7 – 0.99	Strong
+0.4 – 0.69	-0.4 – 0.69	Moderate
+0.1 – 0.39	-0.1 – 0.39	Weak
+ 0 – 0.09	-0 – 0.09	Zero

Risk analysis

The risk assessment is performed by studying three toxic gases and six toxic elements in geothermal fluids. The gases are H_2S, CO_2 and CH_4 and the elements are aluminum (Al), arsenic (As), cadmium (Cd), fluoride (F), mercury (Hg) and lead (Pb). These gases and elements were selected because of their occurrence in geothermal fluids and the known implications that result from pollution with these gases and elements.

The effects of each of them on their environment differs. Short-term exposure of humans to low concentrations of H_2S causes headaches and nausea, but at high concentrations it can lead to serious damage to the eyes and lungs. This can have fatal results within seconds (79). CO_2 is known as the most common greenhouse gas in the atmosphere and gives rise to global temperatures. CH_4 is a less common greenhouse gas, but has a larger greenhouse effect. Besides the effect of climate change on the environment and human health, both these gases are toxic and have fatal effects depending on the concentration and exposure time. Toxic elements in ground and drinking water can have direct and indirect consequences for humans, flora and fauna. Even though some elements commonly occur in drinking water already (such as As) or are commonly used in human appliances (such as Pb and F), high concentrations or longer exposure times can have fatal effects to their environment. For humans, these can result in cancer (As) (80), kidney diseases (Pb) (81), damage to the nervous system (F) (82), or many other health effects. Flora and fauna can be damaged from toxic elements as they lead to fetal malformations (Cd) (83), acid rains (Al) (84) or fish extinction (Hg) (85). The toxic effects on flora and fauna indirectly also affect human health, as toxic heavy metals can settle in, for example, fish that is consumed by humans again.

To analyze the potential environmental risk for the studied geothermal fluids, the concentrations of potential pollutants are plotted. For the gases, this is done as relative concentration of each gas present in solution. The concentrations are plotted in box-and-whisker diagrams, together with the provisional guideline values for drinking water quality that were set by the WHO (86). These values can be found in Table 3.1-2. Again, a unification of units was done. For the elements all units were converted into mg/L and for the gases they were converted to their relative percentages in the gas solution.

The guideline value is indicated in the box-and-whisker diagrams for each element. Subsequently, it is calculated which percentage of samples exceed the guideline value and by how much. To analyze the risk in each country, the toxic element concentrations in the three countries are compared to each other.

Table 3.1-2 Provisional guideline values (in mg/L) for drinking water as determined by the WHO (86)

Potential pollutant	Provisional guideline value for drinking water (mg/L)
Aluminum (Al)	0.1
Arsenic (As)	0.01
Cadmium (Cd)	0.003
Fluoride (F)	1.5
Mercury (Hg)	0.006
Lead (Pb)	0.01

3.2. Respondents, instruments and procedures in the survey

To increase the understanding of the risk perception on geothermal energy in Indonesia, Turkey and the Netherlands, quantitative research is employed through a survey. The survey is a major complement to investigating how geothermal energy and its potential risks are perceived among people from different geothermal communities. The surveying method was selected because it is an efficient data collection for studying perceptions among large groups of people because it can be easily distributed through online platforms and newsletters (87). The data obtained were analyzed quantitatively and descriptively presented with help of visualized data and correlation coefficients. This section discusses the respondents, instruments and procedures of the survey.

Respondents

The population for this study are people affiliated with the geothermal industry prior to the survey, either through their professional careers or geothermal organizations. The aim is that this population is as diverse as possible, so for example they work in different professions like academics, industry and government. This population was chosen because the goal is to study the perception of people with prior knowledge of or experience in the local geothermal energy sector. The respondents are from the three countries, which are indicated in the survey through their nationality.

Since the survey results should be representative of the entire population, the sample size needs to be determined accurately. When the sample size is too small, the risk is that there are a disproportionate number of outliers. But when the sample size is too large, the risk is that the research becomes too complex and time-consuming (88). Therefore, due to the time limitations, a minimal sample size is preferred (89). Considering the population size, confidence level and margin of error, Cohen *et al.* (88) found that the minimal sample size is 30. The total sample size that was reached is 89 respondents, with 41 responses from the Netherlands, 22 responses from Indonesia and 26 from Turkey.

The survey was distributed to the respondents through various contacts worldwide (Table 3.2-3). They were approached by e-mail with the additional request to distribute the survey among their networks within the geothermal community. For this they used their social media platforms, newsletters and direct mails. This technique is called snowball sampling (90). Therefore, the contacts had a major influence on the selection of respondents. The demographic information that was gathered about the respondents will be discussed later in the results chapter, and it is shown in Table 4.3-1.

Before sharing the survey through the online software, the official privacy procedures of the Human Research Ethics Committee (HREC) (91) from Delft University of Technology were followed. These procedures required a Data Management Plan (DMP) and a survey introduction in which the respondents were informed about the legal issues involved when participating in the survey. The DMP includes information about the storage location of the data, personal data that was asked for and whether the data will be made public. The introduction to the survey provides information to the respondents about the anonymity, goal and length of the survey. Both the DMP and the introduction were approved by the HREC.

Table 3.2-3 Population and contacts for the survey

	Organizations
Worldwide	Geothermal news platform European geological organization
Indonesia	University Personal contacts Research institute Industry partners
Turkey	Operators organization University Personal contacts International research project
Netherlands	Operators organization Geothermal association University Research institute Personal contacts International research project

Instruments

Since the respondents varied in terms of nationality, three different languages were applied in the survey next to English. These are Indonesian, Turkish and Dutch. The translations were performed by direct contacts that are native speakers in these languages. With these translations, the respondents should not be limited by linguistic barriers and impositions and misinterpretation should be avoided in the survey (92). Furthermore, the survey is distributed online in the surveying software Qualtrics (www.qualtrics.com). This software enables both a computer and mobile version for the respondent and easily allows the respondent to change language. Besides being user-friendly, this TU Delft-supported software enables uncomplicated adaptation and sharing of the survey. The survey commonly took the respondents between 2 and 6 minutes to complete and is presented in Appendix 5.

Research design

The survey was set up in four sections with different question styles. The questions were partly based on previous research about the public acceptance of geothermal energy (93) (94), and partly self-formulated. The four sections are (1) Demography, (2) Level of knowledge, (3) Perception on geothermal energy and (4) Risk perception). Figure 3.2.4 presents a detailed overview of the content of each section.

The aim of the first section is to obtain demographic information about the respondent that will be used to sketch a generalized profile of the population and to analyze the relation with the (risk) perception on geothermal energy. This section asks about nationality, location of residence, level of education and professional expertise. The nationality is used to differentiate the responses per country and to link it to the social context of the local population. The country and region of residence are asked to study the influence of specific events and the local geothermal sector on the (risk) perception. Each country was separated into regions derived from NUTS-1 and ISO 3166-2 standards (Appendix 4). Prior knowledge was previously found to be a major influence on the public perception of new energy sources (95), so the respondents are asked to indicate their level of education and professional expertise to study the correlation.

In section 2 the respondents are asked to rate their level of knowledge on three topics, (1) global warming, (2) renewable energy and (3) geothermal energy. These are asked because knowledge is a major influence on perception, as described previously. Only the level of knowledge on geothermal energy is used in the data analysis, because it is expected to have the most straightforward impact on the perception on geothermal. The three topics were selected in a research project through which this survey was shared, so the set-up was copied to equalize both surveys. This research project is performed by A. Trisiah and studies the public perception of local Indonesian residents on geothermal energy by media research and interviews.

To introduce the respondent to the research subject, an explanatory text is provided before they enter the third section of the survey (Appendix 5. Survey). The text offers a brief description of the developments in the geothermal energy sector worldwide and the advantages and disadvantages of this energy resource. The goal of this text is to explain the subject to the respondent in a neutral but encompassing way.

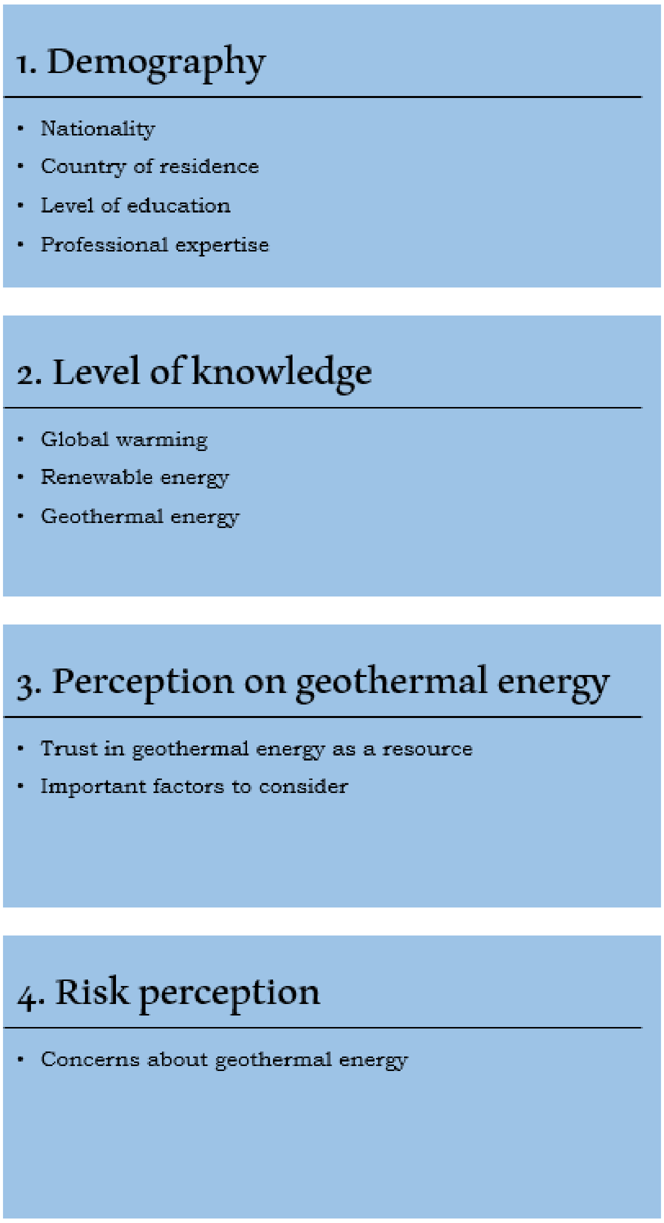


Figure 3.2.4 Survey set up with four sections. The content of the questions that are asked in each question are shortly summarized below the section titles.

In section 3 the respondents are first asked to indicate to what extent they agree with two statements about geothermal energy. These statements are about their trust in and concerns about the future development of geothermal energy as an alternative energy resource. With this question the aim is to identify the respondents their general opinion on geothermal energy. Secondly, the respondents are asked to indicate how important they consider a range of factors in their opinion on geothermal energy. This question aims to put the risk perception in perspective to the respondents their opinion on geothermal energy. The factors that are proposed in this question are sustainability, pollution, nuisance, energy production per land area, costs and the continuity of energy supply. The choice of these factors was based on a previous study in which these were the main factors contributing to the social opposition against geothermal development projects among a varied group of people in Chile (94).

In the last section the respondents are asked to rate their level of concern about five potential risks in geothermal operations. These potential risks are groundwater contamination, air pollution, nuisance, seismicity and sight pollution. These were chosen because they were previously discussed in a study on risk perception on geothermal energy in France (93).

Question styles

The questions from section 1 are straightforward multiple-choice style questions with the option to insert an "other"-answer (Table 3.1-2). This option was integrated to ensure that the respondent is not limited by pre-defined answers. The numbers 1-4 above the answers are used in the calculation of the correlation coefficient.

Table 3.2-4 Example question from section 1 of the survey: 'Demography – Level of Education'. Ranks that were assigned to the different answers are used for the calculation of the correlation coefficients.

Question	1	2	3	4	-
Level of education	High school	Bachelor	Master	PhD	Other, namely: …

A similar question style is applied in section 2, in which the respondents are asked to indicate how they rate their level of knowledge on three topics (Table 3.2-5). These topics are global warming, renewable energy and geothermal energy.

Table 3.2-5 Example question from section 2 of the survey: 'Level of knowledge'. Ranks that were assigned to the different answers are used for the calculation of the correlation coefficients.

Question	1	2	3
"How would you rate your level of knowledge on the following subjects – geothermal energy?"	Low	Moderate	High

The questions in which the respondents are asked about their perception are Likert-scale style questions of which an example is presented in Table 3.2-6. The Likert-scale is a psychometric response scale in which respondents specify their level of agreement to a statement typically in five points: (1) Strongly disagree; (2) Disagree; (3) Neither agree nor disagree; (4) Agree; (5) Strongly agree (96).

Table 3.2-6 Example question from section 3 and 4 of the survey: 'Perception on geothermal energy' and 'Risk perception'. Ranks that were assigned to the different answers are used for the calculation of the correlation coefficients.

Question	1	2	3	4	5
Statement 1: "Geothermal energy is suitable as an alternative energy source for the future."	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree

Procedures

The responses were collected over a period of five weeks (35 days) between April 12th and May 24th. After this time the data were exported from Qualtrics and processed into SPSS (97). This section will go through the data processing and analysis.

Data processing

To process the survey results correctly into SPSS, some adjustments were made to the data. Incomplete responses were left out and some responses came in from people from countries that were not part of the study population. To be able to calculate correlation coefficients, some of the responses were ranked with numbers. These rankings are also indicated by the numbers above the answers in the example questions in Table 3.2-4 to Table 3.2-6.

Analytic strategies

The data that were obtained through the survey contains a range of descriptive panels about the respondents' perception of geothermal energy. The analysis of these panels results in a range of similarities and differences between the three countries. This kind of analysis technique is also called quantitative descriptive analysis. In this way, the responses between the different countries are compared between the different factors and risks that are questioned in sections 3 and 4.

This analysis is performed with help of the visualization of results in tables and histograms that were created in the research tool SPSS. SPSS also enables the calculation of the correlations. To prevent the limitation by linear or normal relationships (77), the Spearman correlation was selected for this analysis. Calculating the Spearman coefficient in SPSS gives an output of three numbers for every correlation. These are the sample size (N), the significance of correlation (Sig.), and the correlation coefficient. The significance describes whether the correlation is significant at a chosen confidence interval. A smaller value means the correlation is more significant. For this study, the correlation is considered significant if sig. is less than 5% (so less than 0.05 from the calculation). The interpretation of the correlations used in this analysis is based on the method proposed by Dancey & Reidy (78), which is shown in Table 3.2-7.

Table 3.2-7 Interpretation of the Spearman's correlation coefficients by Dancey & Reidy (78)

Correlation coefficient		Interpretation
+1	-1	Perfect
+0.7 – 0.99	-0.7 – 0.99	Strong
+0.4 – 0.69	-0.4 – 0.69	Moderate
+0.1 – 0.39	-0.1 – 0.39	Weak
+ 0 – 0.09	-0 – 0.09	Zero

4. Results

4.1. Analysis of overall geochemistry by country

The results discussed in this section are used to provide a characterization of the geothermal fluids. The chemical properties of the geothermal fluids help to understand their origin and the processes that have influenced the fluid compositions. This is done using two types of ternary diagrams (Na-K-Mg and Cl-SO_4-HCO_3), the pH and salinity ranges and correlation coefficients that show the interdependency between concentrations of different elements. The data used for this analysis and the way they are processed are visible in the digital appendices on data.4tu.nl. A detailed interpretation of the data is found in the discussion.

The files in the digital appendices are spreadsheets that are separated for each of the three countries. These contain the sheets listed in Table 4.1-1. The first sheet, 'Well data', contains information about the sampling locations such as their geographic location in longitude and latitude, elevation and depth. The second sheet contains the information about the fluid samples in terms of their fluid properties, such as temperature, pH and salinity, but also the dissolved elements and gases. This data set was processed for analysis by excluding the values that are below detection limits and converting all information into uniform units (sheet 3). In sheets 4 and 5 the sample data are respectively separated in terms of their fluid type and averaged by their sampling locations. The relative compositions of the gases produced are calculated from the fluid sample data in sheet 6. Sheet 7 analyzes in what samples the guideline values for different elements are exceeded, and the percentage of samples in which this was exceeded is calculated in sheet 8. Following this, the correlation coefficients and graphs are calculated and plotted in sheets 9 and 10. Sheet 11 compares the concentrations of different elements between the three countries and sheets 12 to 14 are used to plot the ternary diagrams that will be discussed later in this chapter. The exact numbering of the spreadsheets differs slightly per country, depending on the data availability and geothermal system types that are present.

Table 4.1-1 Information included in the digital spreadsheets available in the digital appendices on data.4tu.nl

Spreadsheet	Information included
1. Well data	Location of the samples, e.g. latitude, longitude, elevation, depth
2. Fluid sample data (complete)	Composition of the fluid samples, e.g. fluid properties, dissolved elements and gases
3. Fluid sample data (processed)	Fluid sample compositions, edited for processing purposes, e.g. values below detection limit excluded
4. Well and spring data	Fluid sample compositions, sorted by samples from wells and springs
5. Sample averages	Fluid sample compositions in which the measurements were averaged by location
6. Toxic gases	Gas composition present in the geothermal fluids
7. Toxic elements	Samples in which the guideline values for toxic elements were exceeded
8. Guideline values exceeded	Histograms with the number of samples in which the guideline value was exceeded
9. Correlation coefficients	Correlation coefficients between common elements in geothermal fluids
10. Correlation graphs	Correlation graphs between common elements in geothermal fluids
11. Histograms	Comparison the measured values of element concentrations and fluid properties
12. Ternary diagram input	Input file for the ternary diagram plotting for the full data set, spring data and well data
13. Na-K-Mg diagram	Ternary diagram of the Na-K-Mg concentrations for the full data set, spring data and well data
14. Cl-SO4-HCO3 diagram	Ternary diagram of the Cl-SO4-HCO3 concentrations for the full data set, spring data and well data

Na-K-Mg diagram

The Na-K-Mg ternary diagram is used to determine the level of maturity of the geothermal fluids. This chapter will analyze the data from each country using this ternary diagram. The data sets are separated into well and spring data, and through the different locations in each country.

Indonesia

The Na-K-Mg diagrams for the Indonesian well and spring data are shown in Figure 4.1.1 and Figure 4.1.2. All well samples have geothermometer temperatures of over 200 ºC. The majority of the samples are in partial equilibrium, while ~ 30% are immature waters with low Na content. The spring waters are all found at high Mg contents compared to Na and K. Therefore, all samples are found as immature waters, which means that the fluid samples are not in equilibrium with their host rock.

Figure 4.1.3 shows the Na-K-Mg diagram with all Indonesian data sorted by geographical region. The data set contains samples from one production location in Sulawesi, one in Java, two in North-Sumatra and two in South-Sumatra. It is clear from the figure that each region contains samples that are in partial equilibration or immature. From Java only one sample is found in partial equilibrium. The other samples have a relatively high Mg concentration and are therefore immature waters.

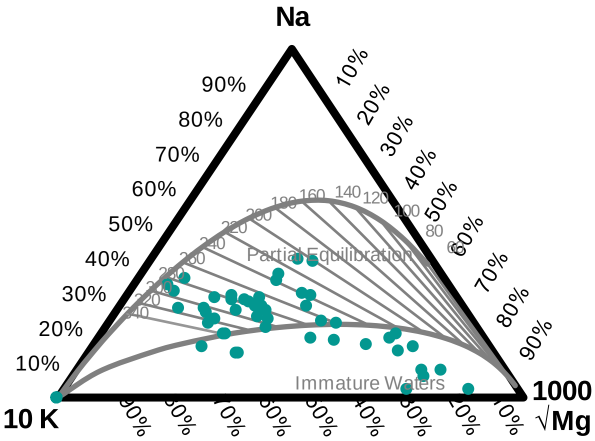


Figure 4.1.1 Indonesian well data samples plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

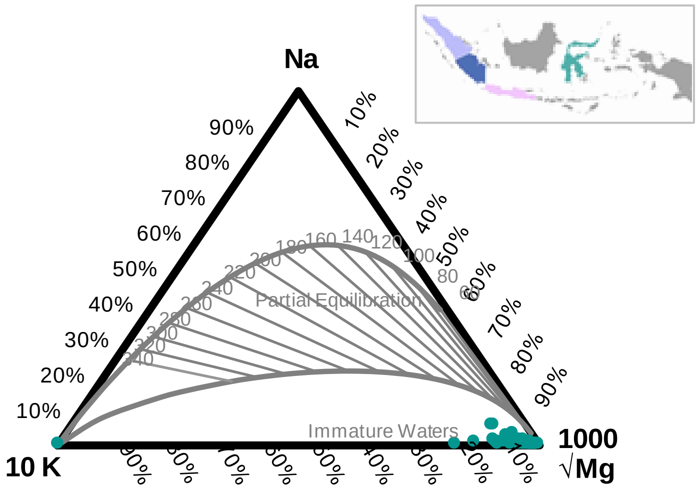


Figure 4.1.2 Indonesian spring data samples plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

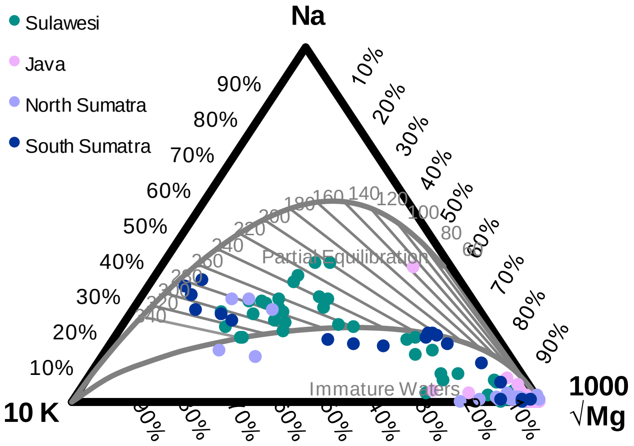


Figure 4.1.3 Indonesian data samples sorted by geographical region and plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

Turkey

The data from wells and springs in Turkey are plotted in Figure 4.1.4 and Figure 4.1.5. The well samples range from immature waters to partial equilibration, with ~ 75% of the samples having high concentrations of Mg. A broad range of geothermometer temperatures is observed in this figure, between 100 and 280 ºC. In Figure 4.1.5 around 90% of the spring samples have high Mg concentrations, and are therefore classified as immature waters. The number of spring samples found in partial equilibration is lower than for well samples.

The Giggenbach diagram for samples in different regions is shown in Figure 4.1.6. The majority of the samples are from the Anatolide-Tauride Block, which is also the major geothermal production region. The remaining samples are from the other five regions. In this figure it is visible that most samples in the Istanbul Zone, Arabian Platform and Kirsehir zone are immature waters. The samples that were found to be in partial equilibrium are all from the Menderes Massif, Sakarya Zone or the Anatolide-Tauride Block. There are two samples from the Kirsehir zone that are classified to be in partial equilibration.

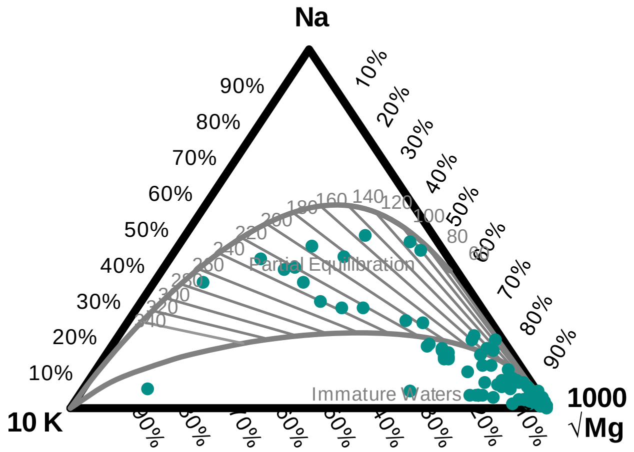
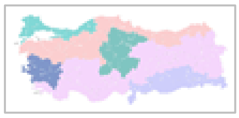


Figure 4.1.4 Turkish well data samples plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)



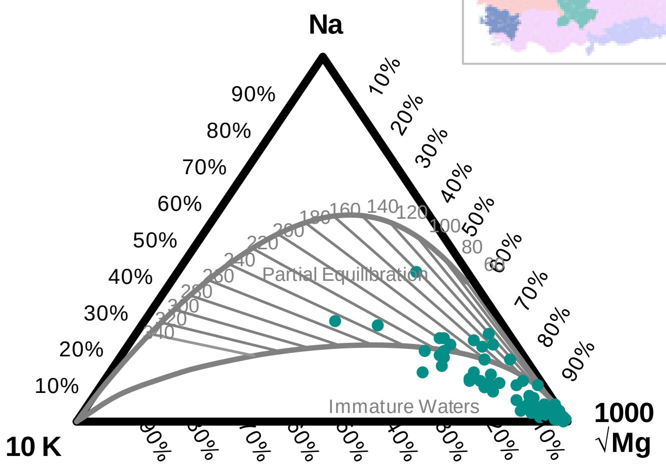


Figure 4.1.5 Turkish spring data samples plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

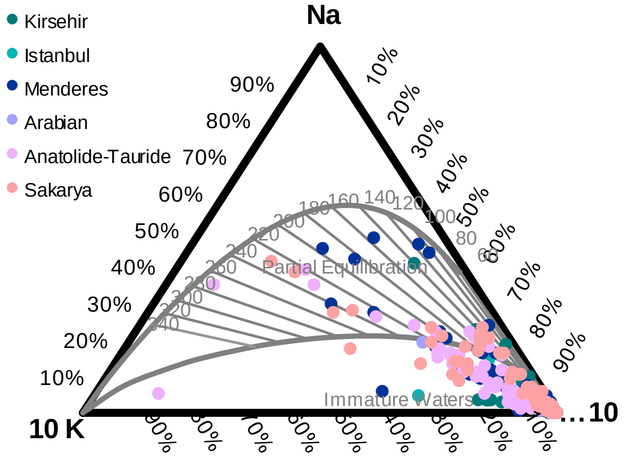


Figure 4.1.6 Turkish data samples sorted by geographical region and plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

Netherlands

All available geothermal fluid samples in the Netherlands are from wells. Therefore, all samples are plotted in one diagram and differentiated per reservoir source (Figure 4.1.7). From the figure it is obvious that the majority of the samples, ~ 90%, are around the full equilibrium line. The five remaining samples are in partial equilibrium with the host rock. The samples are found to be between geothermometer temperatures of 80 to 200 ºC.

The data points in Figure 4.1.7 are shown by geological region. Of the 50 samples, 45 of 50 are from the Central- and West-Netherlands Basins, which are also the main geothermal production locations. From this graph it can be seen that all data points from the Roer Valley Graben are found in partial equilibrium. The samples from the Central Netherlands Basin are located along the full equilibration line. The samples from the West-Netherlands Basin are mainly located along the full equilibration line as well, except for one sample that is in partial equilibration.

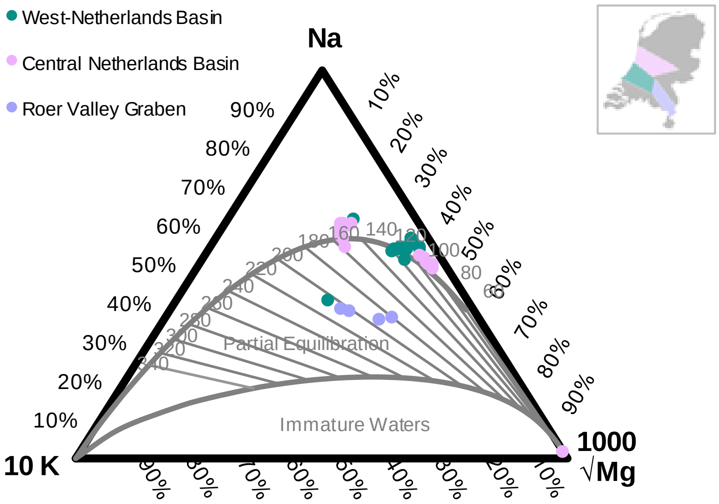


Figure 4.1.7 Dutch data samples sorted by geographical region and plotted in the Na-K-Mg diagram that was proposed by Giggenbach (74)

Cl-SO4-HCO3 diagram

The ternary Cl-SO4-HCO3 diagram is used to understand the type of the geothermal fluids (chloride, sulphate or bicarbonate waters (19)). The type of geothermal fluid can help to understand the origin and geothermal system.

Indonesia

The Cl-SO4-HCO3 diagrams for the Indonesian data set is shown in Figure 4.1.8 and Figure 4.1.9. For the well data it can clearly be seen that ~ 90% of the samples have high Cl concentrations with some exceptions with lower Cl contents. These exceptions are generally found at HCO3 contents of less than 50%. One sample has a very high SO4 concentration, classifying it as a volcanic water.

The data from the Indonesian springs show a less clear picture, but ~ 80% of the samples are found to have a high HCO3 concentration. Around ten samples have lower HCO3 content and high (Cl-)SO4 contents. These fluids have a higher SO4 content and therefore they are more related to volcanic waters.

Figure 4.1.10 plots the data per geographical region. It is seen that the data from Sulawesi have mostly high Cl contents and are therefore classified as mature to peripheral waters. The data from Java are predominantly found with elevated HCO3 concentrations, but some samples have minimal HCO3 concentrations and are found to be (Cl-)SO4 waters. The samples from North Sumatra are mostly found on the bottom right part of the diagram, with HCO3 levels over 50%. There are three exceptions to this that are Cl fluids and one SO4 fluid. The data from South Sumatra are predominantly SO4 waters, or moderate Cl waters.

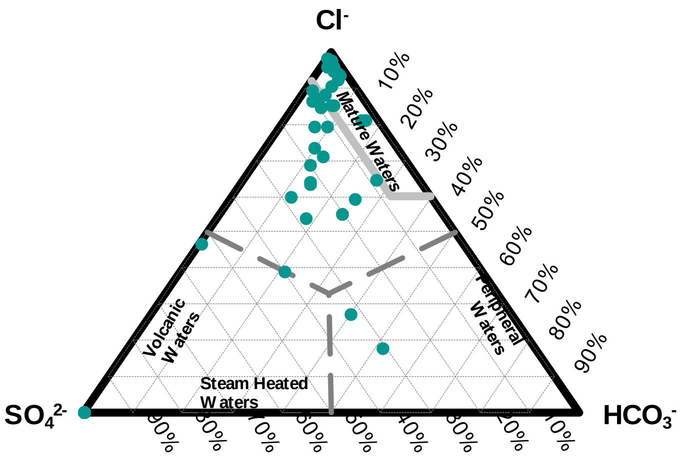


Figure 4.1.9 Indonesian well data samples plotted in the Cl-SO4-HCO3 diagram that was proposed by Giggenbach (74)

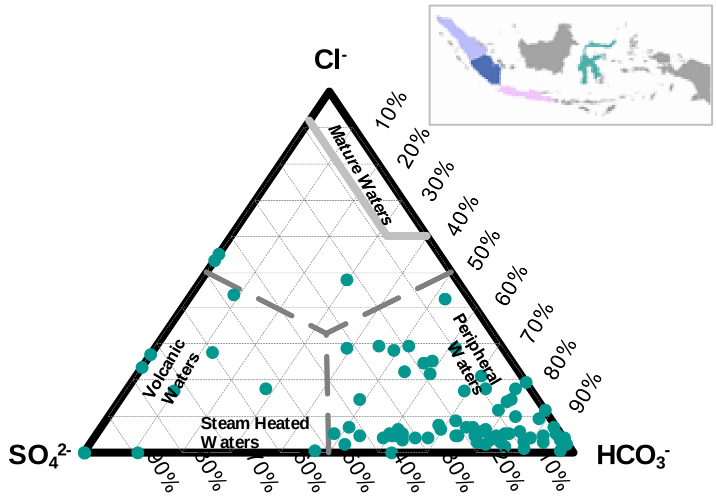


Figure 4.1.8 Indonesian spring samples plotted in the Cl-SO4-HCO3 diagram that was proposed by Giggenbach (74)

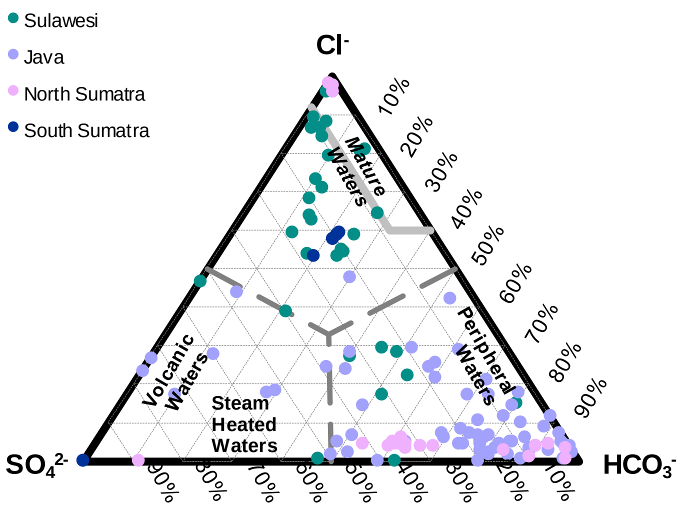


Figure 4.1.10 Indonesian data samples sorted by geographical region and plotted in the Cl-SO4-HCO3 diagram that was proposed by Giggenbach (74)

Turkey

The Cl-SO_4-HCO_3 diagrams for the Turkish well and spring samples are shown in Figure 4.1.12 and Figure 4.1.11. In both the well and spring data the majority (~ 80%) of the samples are HCO_3 fluids. In the well and spring data are <5 samples that have a high Cl content and low SO_4 and HCO_3 contents, so they are mature waters. In both data sets there are also samples with high SO_4 contents and low Cl and HCO_3 contents, which classifies them as volcanic waters.

Figure 4.1.13 shows the data by geographical region. All regions contain samples with high HCO_3 concentrations. The samples from the Arabian Platform and Istanbul region do not contain Cl concentrations of over 30%. The samples from the Menderes Massif, Sakarya Zone and Anatolide-Tauride Block are found throughout the diagram, but the majority of the samples are high in HCO_3 concentration. The samples from the Kirsehir Massif contain less than 50% SO_4 concentration, and often have moderate levels of Cl and HCO_3.

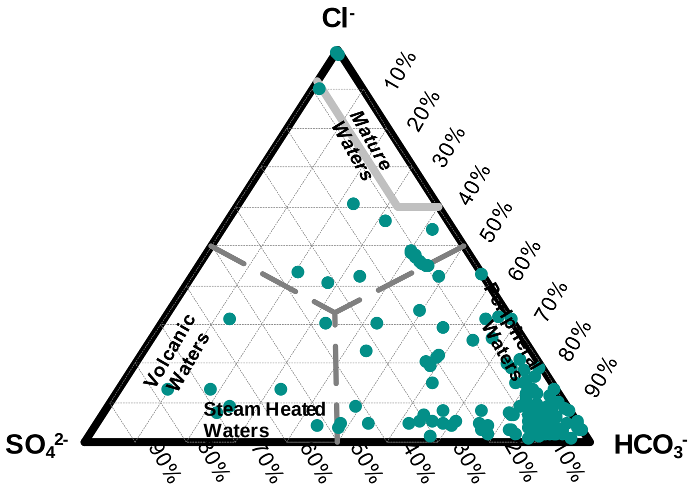


Figure 4.1.12 Turkish well data samples plotted in the Cl-SO_4-HCO_3 diagram that was proposed by Giggenbach (74)

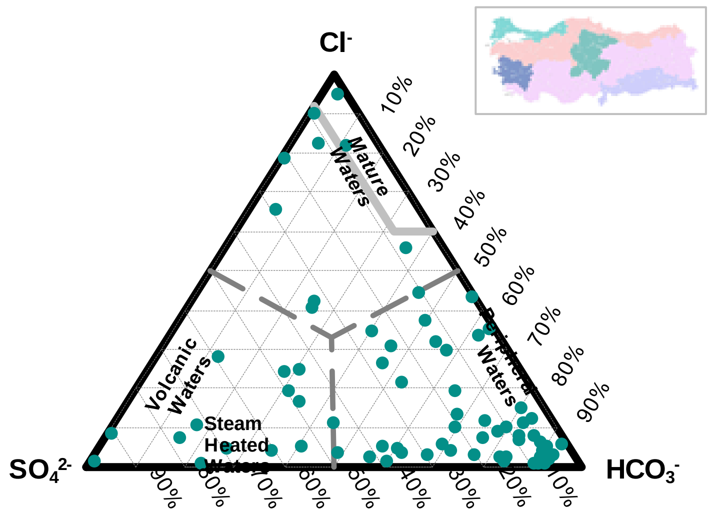


Figure 4.1.11 Turkish spring data samples plotted in the Cl-SO_4-HCO_3 diagram that was proposed by Giggenbach (74)

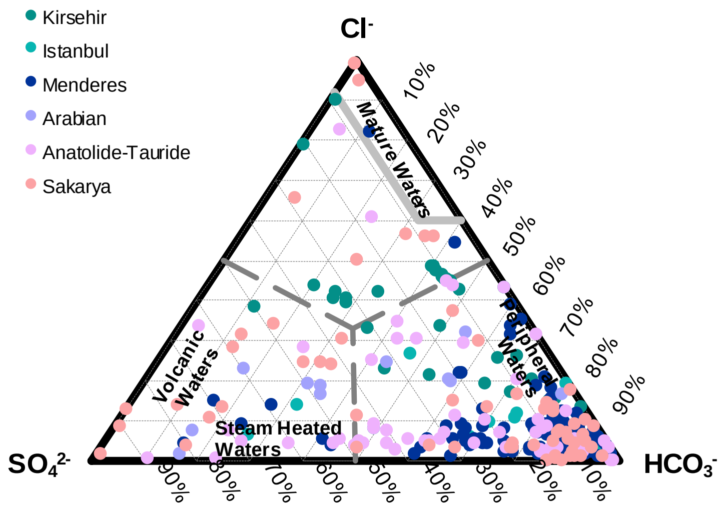


Figure 4.1.13 Turkish data samples sorted by geographical region and plotted in the Cl-SO_4-HCO_3 diagram that was proposed by Giggenbach (74)

Netherlands

The Cl-SO4-HCO3 diagram for the data from the Netherlands is shown in Figure 4.1.14. All samples are concentrated at the maximum relative Cl content, so they are mature waters. There are no exceptions found to this high Cl content, all relative concentrations are > 99% Cl.

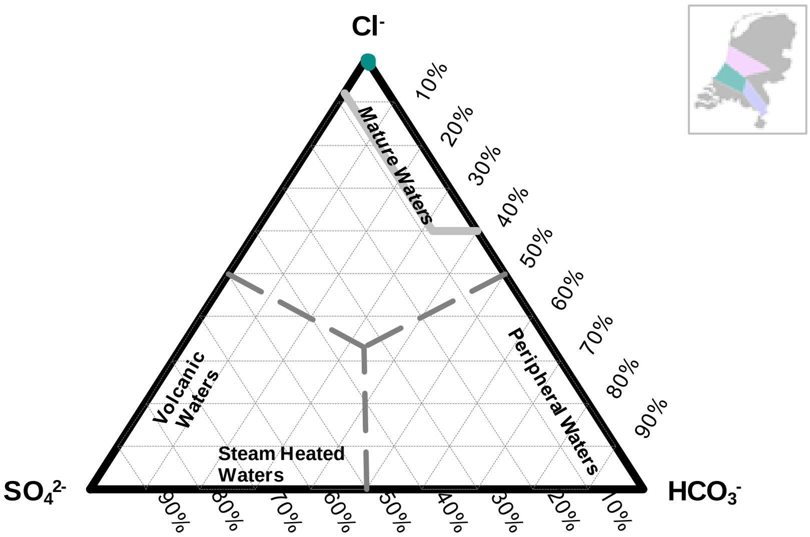


Figure 4.1.14 Dutch data samples sorted by geographical region and plotted in the Cl-SO_4-HCO_3 diagram that was proposed by Giggenbach (74)

pH

The pH range for all samples in each country is plotted in Figure 4.1.15. Here, it can be seen that the pH range is smallest in the Netherlands and largest in Indonesia. The pH ranges in Indonesia between 1.5 and 8.5; in Turkey between 2.8 and 9.7 and in the Netherlands it ranges between 5 and 6.8. The colored rectangles indicate the range in which 50% of the pH values plot. In total pH of the Turkish samples are highest.

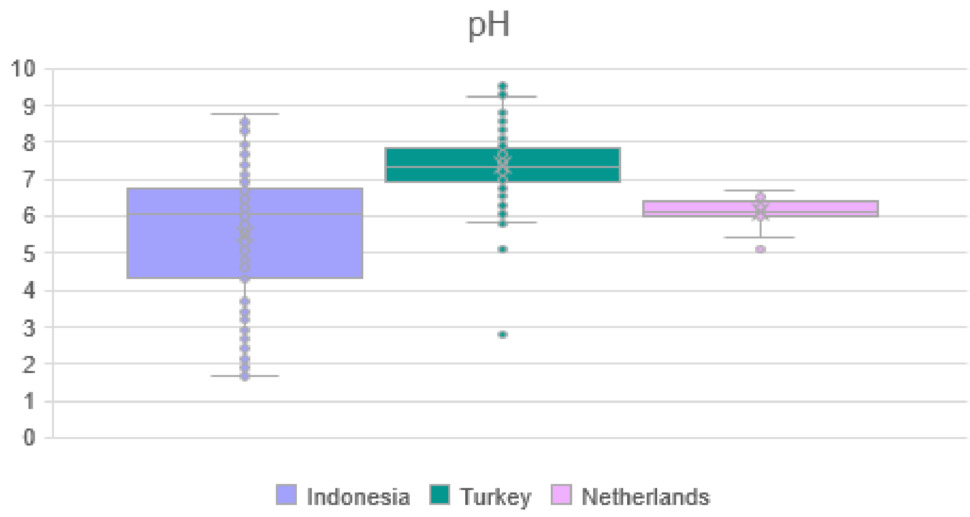


Figure 4.1.15 pH measurements of data samples sorted by country

The pH of the wells and springs in Turkey and Indonesia are also plotted separately in Figure 4.1.16 and Figure 4.1.17. The lowest pH values are found in the Indonesian spring samples, which are as low as 1.5. In Turkey the pH range is slightly smaller and higher in the well waters than it is in the spring waters. The pH ranges between 6 to 9.3 in well waters and 5.2 and 9.3 in spring waters.

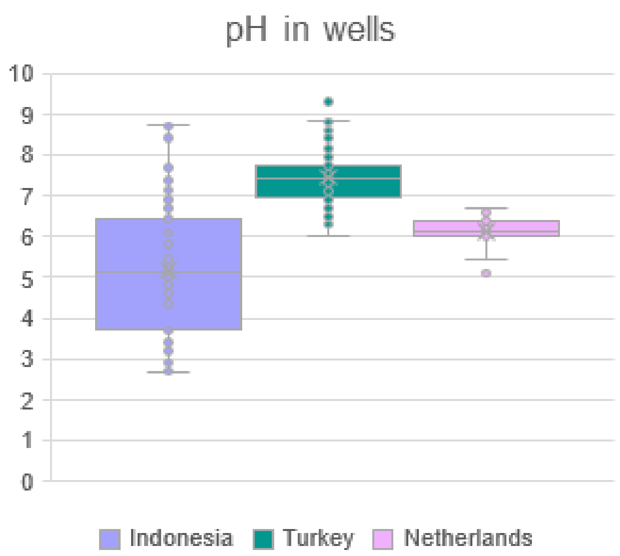


Figure 4.1.16 pH in well data samples sorted by country

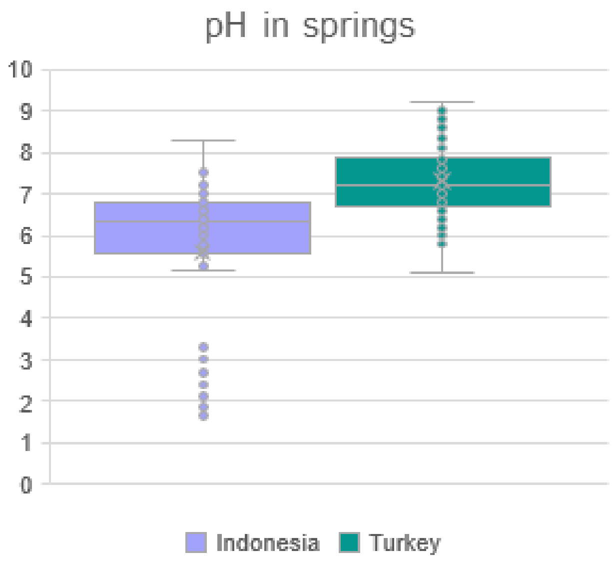


Figure 4.1.17 pH in spring data samples sorted by country

Salinity

The salinity for all samples by country is plotted in Figure 4.1.18 as the concentration of total dissolved solids (TDS) in mg/L. Here it is clearly visible that the TDS is lowest in the Netherlands, where it only ranges between 0 and 250 mg/L. The total ranges of the samples in both Turkey and Indonesia are similar, between 0 and 3500 mg/L, but the average TDS and range of the values inside the rectangles are different. In Indonesia, 50% of the samples are found between 50 and 950 mg/L. In Turkey 50% are between 450 and 1200 mg/L, which is considerably higher.

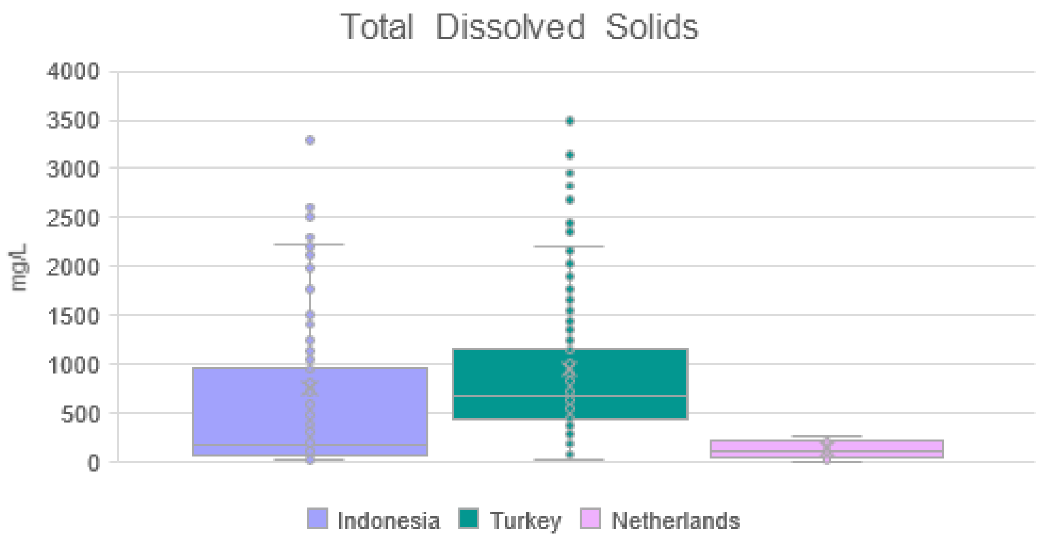


Figure 4.1.18 Salinity plotted as Total Dissolved Solids (TDS) in mg/L sorted by country

The well and spring data for Indonesia and Turkey are plotted separately in Figure 4.1.19 and Figure 4.1.20. In the Indonesian data is a clear difference between wells (0 to 3500 mg/L) and springs (0 to 1100 mg/L). Also the average salinity is therefore very different (600 mg/L in wells and 50 mg/L in springs). In the Turkish data the total range is around 200 to 3500 mg/L. However, the rectangle that indicates 50% of the Turkish data are smaller in the well data (500 to 1100 mg/L) than it is in the spring data (600 to 1700 mg/L). The average TDS in both Turkish data sets is similar at around 700 mg/L.

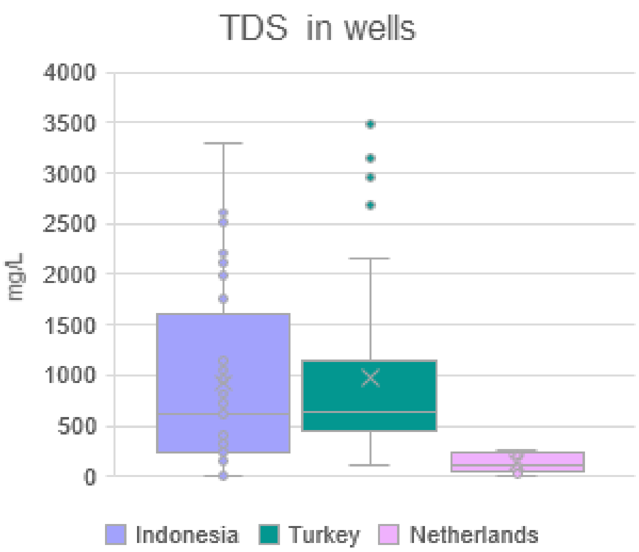


Figure 4.1.19 Salinity plotted as TDS (mg/L) in well data samples and sorted by country

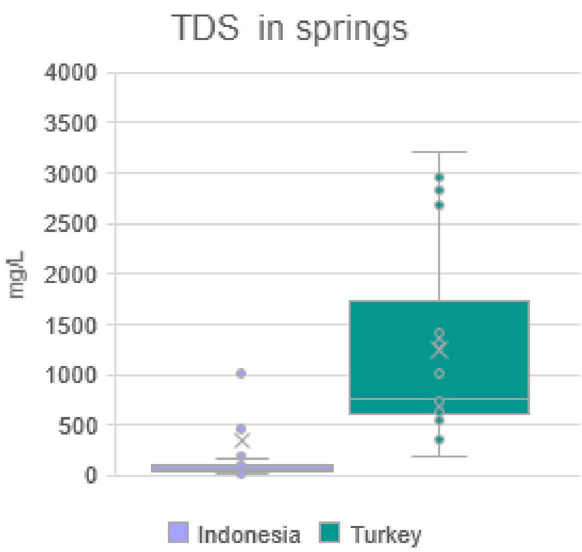


Figure 4.1.20 Salinity plotted as TDS (mg/L) in spring data samples and sorted by country

Correlation plots

In order to study the geochemical water properties in each country in more detail, the correlation between concentrations of common elements is studied using correlation plots. Elements used for these correlations are Al, Ca, K, Mg, Na, Si, F, Cl, HCO_3 and SO_4. The correlations are quantified by calculating the correlation coefficient. The calculated correlation coefficients for Indonesia, Turkey and the Netherlands are respectively shown in Table 4.1-2, Table 4.1-3 and Table 4.1-4. Moderate and strong correlations are indicated in respectively dark and light green. The correlation coefficients are calculated for Indonesian and Turkish wells and springs separately in Table 4.1-5 to Table 4.1-8

In Table 4.1-2 it can be seen that the strongest correlations in Indonesia are found in mixtures with the element pairs Al-F/SO_4, Ca-Mg/HCO_3, Mg-Ca/K/HCO_3 and Na-K/Cl. From the separate tables with well and spring data samples, it can be read that the Cl correlations are higher in the well data and the HCO_3 correlations are higher in spring data. F correlations are higher in well data than they are in spring data. SO_4 correlations are higher in well data than they are in spring data, but also differ largely between different element combinations.

In Table 4.1-3 it can be seen that most of the strong correlations in Turkey are in mixtures with the element pairs Al-Ca/Cl/HCO_3, Ca-K/Na/F/Cl, K-Na/F/Cl, F-Ca/K/Mg/Na/Si/Cl/HCO_3/SO_4 and Cl-Al/Ca/K/Na/F. From the separate well and spring tables, it is clear that the F correlations are all from well samples, and these correlations are very high (>0.9). The Na correlations are stronger in well samples than they are in spring samples. The correlations in HCO_3 are zero in well data, and low in spring data. Some of the Al correlations are moderate, but the element combinations in which is applicable differs between the well and spring samples.

In Table 4.1-4 it can be seen that the strongest correlations in the Netherlands are found in mixtures with the element pairs Na-Ca/K/Mg/Cl/HCO_3/SO_4, Cl-Ca/K/Mg/Na/HCO_3/SO_4, HCO_3-Ca/K/Na/Cl and SO_4-Ca/K/Mg/Na/Cl.

Table 4.1-2 Pearson correlation coefficients calculated from Indonesian samples between commonly occurring elements in geothermal fluids. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.049	-0.047	0.018	-0.087	0.250	0.797	0.146	-0.130	0.728
Ca		1.000	0.348	0.777	0.196	-0.099	-0.002	0.016	0.702	0.146
K			1.000	0.509	0.800	0.382	-0.002	0.657	0.065	0.146
Mg				1.000	0.573	-0.156	0.002	-0.064	0.487	0.176
Na					1.000	0.144	0.234	0.939	0.137	0.001
Si						1.000	0.173	0.389	-0.170	0.089
F							1.000	0.209	-0.144	0.190
Cl								1.000	0.309	-0.122
HCO_3									1.000	0.151
SO_4										1.000

Table 4.1-3 Pearson correlation coefficients calculated from Turkish samples between commonly occurring elements in geothermal fluids.. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.888	0.198	-0.226	0.511	No data	No data	0.484	0.407	0.130
Ca		1.000	0.407	0.223	0.892	-0.039	0.991	0.922	-0.085	0.110
K			1.000	0.181	0.931	0.065	-0.945	0.939	0.070	0.130
Mg				1.000	0.238	-0.033	-0.995	0.104	0.123	0.349
Na					1.000	0.081	-0.989	0.938	0.096	0.186
Si						1.000	-0.995	0.079	0.082	0.061
F							1.000	-0.994	0.984	-0.964
Cl								1.000	-0.059	0.025
HCO_3									1.000	0.002
SO_4										1.000

Table 4.1-4 Pearson correlation coefficients calculated from Dutch samples between commonly occurring elements in geothermal fluids. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	No data	No data	No data	No data	No data	No data	No data	No data	No data
Ca		1.000	0.560	0.396	0.830	0.358	No data	0.883	0.554	0.677
K			1.000	0.246	0.721	-0.144	No data	0.750	0.763	0.527
Mg				1.000	0.668	-0.133	No data	0.648	0.127	0.400
Na					1.000	-0.234	No data	0.750	0.764	0.527
Si						1.000	No data	-0.003	-0.108	0.145
F							1.000	No data	No data	No data
Cl								1.000	0.699	0.845
HCO_3									1.000	-0.300
SO_4										1.000

Table 4.1-5 Pearson correlation coefficients calculated from Indonesian well samples between commonly occurring elements in geothermal fluids. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.489	-0.587	-0.067	-0.736	-0.572	-0.702	-0.655	-0.272	-0.162
Ca		1.000	0.669	0.200	0.215	0.095	0.432	0.592	-0.156	-0.146
K			1.000	0.496	0.733	0.373	0.293	0.897	-0.041	0.281
Mg				1.000	0.686	0.190	-0.004	0.505	-0.161	0.829
Na					1.000	0.470	0.285	0.817	-0.028	0.750
Si						1.000	0.484	0.249	-0.139	0.399
F							1.000	0.336	0.100	0.050
Cl								1.000	-0.110	0.350
HCO_3									1.000	-0.150
SO_4										1.000

Table 4.1-6 Pearson correlation coefficients calculated from Indonesian spring samples between commonly occurring elements in geothermal fluids. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.057	0.024	-0.005	-0.006	0.769	0.834	0.524	-0.141	0.729
Ca		1.000	0.666	0.951	0.645	0.073	-0.038	0.189	0.918	0.146
K			1.000	0.678	0.655	0.187	0.081	0.355	0.630	0.122
Mg				1.000	0.721	0.209	-0.050	0.231	0.906	0.210
Na					1.000	0.253	-0.053	0.394	0.701	0.080
Si						1.000	0.088	0.156	0.203	0.687
F							1.000	0.640	-0.129	0.236
Cl								1.000	0.105	0.002
HCO_3									1.000	0.144
SO_4										1.000

Table 4.1-7 Pearson correlation coefficients calculated from Turkish well samples between commonly occurring elements in geothermal fluids.. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.176	0.304	-0.167	0.549	No data	No data	0.454	0.477	0.189
Ca		1.000	0.905	0.234	0.943	0.083	0.991	0.389	-0.115	0.041
K			1.000	0.131	0.962	0.283	-0.945	0.342	0.030	0.135
Mg				1.000	0.133	-0.042	0.995	0.126	0.039	0.059
Na					1.000	0.281	-0.989	0.570	0.061	0.073
Si						1.000	-0.995	0.333	0.294	0.446
F							1.000	-0.994	0.984	-0.964
Cl								1.000	0.115	0.174
HCO_3									1.000	0.031
SO_4										1.000

Table 4.1-8 Pearson correlation coefficients calculated from Turkish spring samples between commonly occurring elements in geothermal fluids. Strong correlations (>0.7) are indicated in light green and moderate correlations (>0.4) in dark green.

	Al	Ca	K	Mg	Na	Si	F	Cl	HCO_3	SO_4
Al	1.000	-0.115	-0.220	-0.600	-0.279	No data	No data	-0.238	-0.593	-0.490
Ca		1.000	0.450	0.153	0.515	-0.151	No data	0.459	-0.038	0.043
K			1.000	0.143	0.863	0.385	No data	0.664	0.291	0.098
Mg				1.000	0.091	-0.503	No data	0.084	0.314	-0.017
Na					1.000	0.236	No data	0.778	0.357	0.251
Si						1.000	No data	0.050	0.275	0.371
F							1.000	No data	No data	No data
Cl								1.000	0.110	0.134
HCO_3									1.000	0.110
SO_4										1.000

4. Results

4.2. Environmental risk analysis of geothermal waters

This chapter provides an analysis of the environmental risks related to the geochemistry of fluids in the three countries. The risks are associated with toxic gases and chemical elements in geothermal fluids. These can impose environmental and health risks. Therefore, their presence in geothermal fluids increases the potential environmental risks in a geothermal operation in general.

Gases

The emission of certain gases from geothermal systems can result in an enhanced greenhouse effect in the atmosphere or to the release of toxic gases that can impose health threats to humans, flora and fauna. In this subchapter, the relative emissions of CH_4, CO_2 and H_2S from geothermal systems in each country are discussed.

Indonesia

From Indonesia a total of 72 gas sample compositions were measured and the relative percentages are plotted in the box-and-whisker plot in Figure 4.2.1. The gas predominantly consists of CO_2 with minor H_2S concentrations. The Indonesian samples are from the sites Ulubelu (South Sumatra) and Lahendong (Sulawesi). Samples from both locations have CO_2 concentrations of up to 99%, whereas the samples with H_2S concentrations of over 10% were only found in Lahendong. Out of the total 72 samples 14 (19%) have a H_2S concentration of over 10%. The highest H_2S concentration measured was almost 90%.

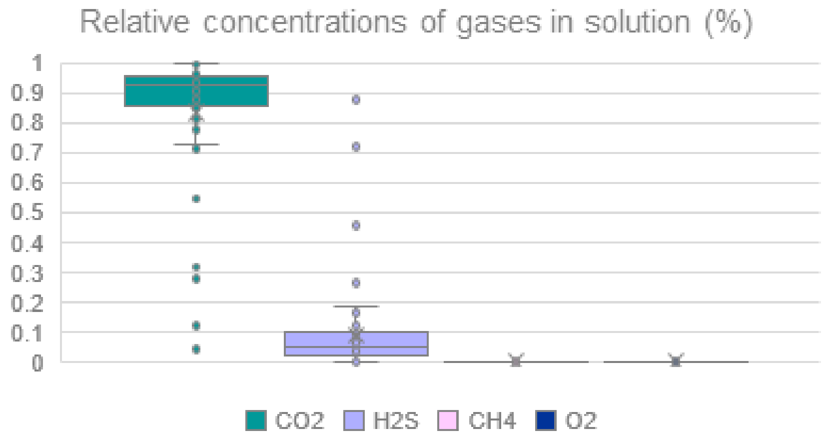


Figure 4.2.1 Relative concentrations (in %) of dominant gases that are present in solution in the Indonesian geothermal fluids samples.

Turkey

The Turkish data set contains 9 gas samples. The relative percentages of these gases in solution are plotted in the box-and-whisker plot in Figure 4.2.2. From this graph it is clear that the geothermal gases in Turkey predominantly consist of CO_2 (>95%), and only minor concentrations of H_2S, CH_4 and N_2. The Turkish samples were taken in the regions Western, Central and Eastern Anatolia and the relative concentrations of all samples are very similar in all regions.

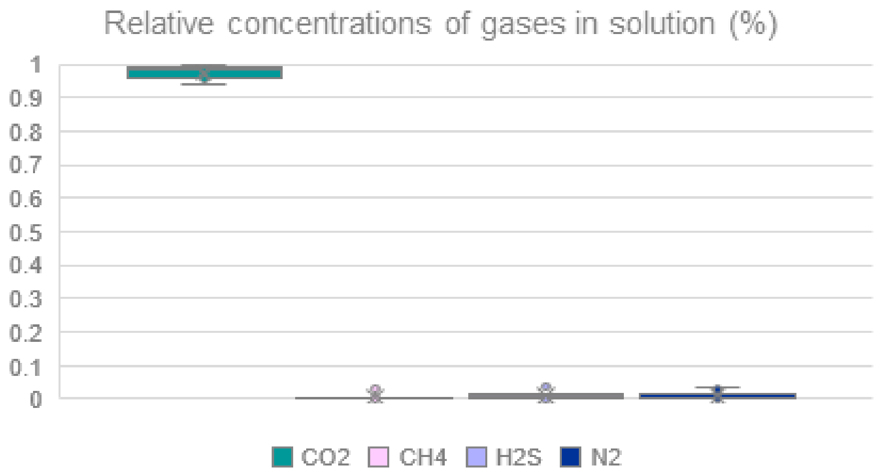


Figure 4.2.2 Relative concentrations (in %) of dominant gases that are present in solution in the Turkish geothermal fluids samples.

Netherlands

The Dutch data on the gas compositions from geothermal wells contain 9 measurements. The relative percentages in Figure 4.2.3 show that the gas consists predominantly of methane (CH_4), and contains variable concentrations of CO_2 and N_2 (<60%) and very minor amounts of other hydrocarbons, C_nH_m (<5%).

The Dutch samples are from locations that produce from the Texel-IJsselmeer High (TIH) and West-Netherlands Basin (WNB) from a variety of depths. The samples produced from the TIH produced higher concentrations of N_2, between 18 and 30%. Their concentrations of CH_4 were 31, 63 and 72%, and the concentrations of CO_2 7.2, 9.5 and 23%. In the samples from the WNB the level of CH_4 was over 75% in 5 of the 6 samples. In these samples the N_2 concentration was always below 5% and the CO_2 concentration below 20%. One WNB sample consisted of 40% N_2, 57% CO_2 and 0.5% N_2.

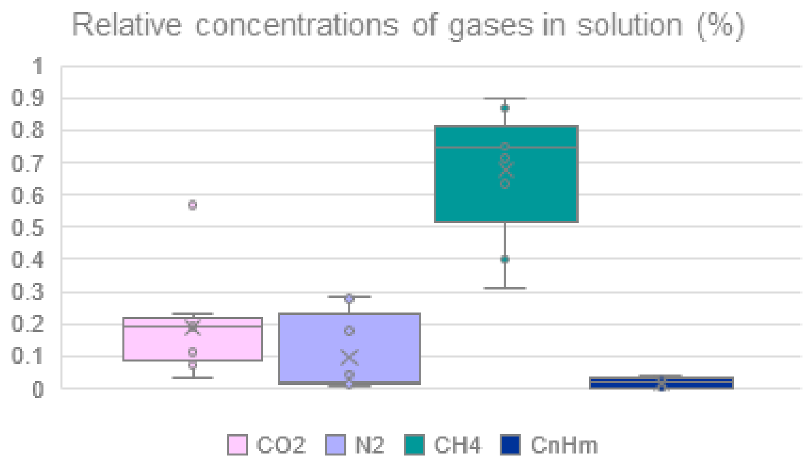


Figure 4.2.3 Relative concentrations (in %) of dominant gases that are present in solution in the Dutch geothermal fluids samples.

Elements

Some elements dissolved in geothermal fluids are toxic and therefore impose health and environmental risks. Therefore, it is important to study how their concentrations in geothermal fluids relate to the guideline values for drinking water. This subchapter will present the relative concentrations of aluminum (Al), arsenic (As), cadmium (Cd), fluoride (F), mercury (Hg) and lead (Pb) in all countries. The guideline values that are used in this report are the drinking water guideline values set by the World Health Organization (86) as worldwide criteria to prevent human health threats.

Aluminum

The concentrations of Al that were measured in each country are plotted in the box-and-whisker diagram in Figure 4.2.4. In this figure, the number of samples plotted in Indonesia, Turkey and the Netherlands is respectively 112, 125 and 2. Since the Indonesian data contain concentrations of up to 340 mg/L, a zoomed plot is used to study the concentrations around the guideline value of 0.2 mg/L (86) (Figure 4.2.5).

The drinking water guideline value by WHO is indicated by the blue line in Figure 4.2.5. The number of samples exceeding the guideline value is 28% for Indonesia, 5.6% for Turkey and 50% for the Netherlands. However, the limited number of samples in the Netherlands disturbs a proper comparison. 16 of the 27 Indonesian samples in which the guideline value was exceeded are located in Lahendong (Sulawesi). The other samples are from Ulubelu (North Sumatra) and Java. From the Turkish samples 6 of the 8 are from Western Anatolia. The two remaining samples are from Central Anatolia and the Black Sea region. The Dutch sample is from the West-Netherlands Basin.

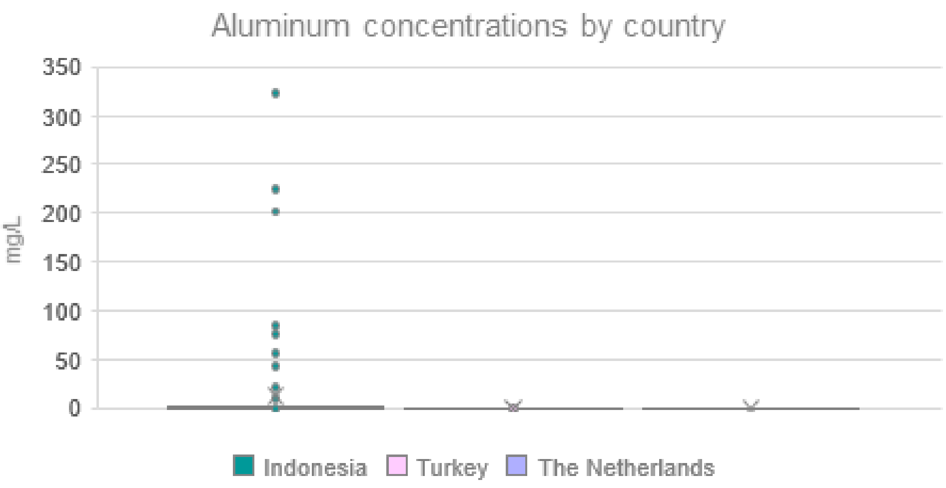


Figure 4.2.4 Aluminum concentrations (in mg/L) sorted by country and plotted on the total range between 0 and 350 mg/L.

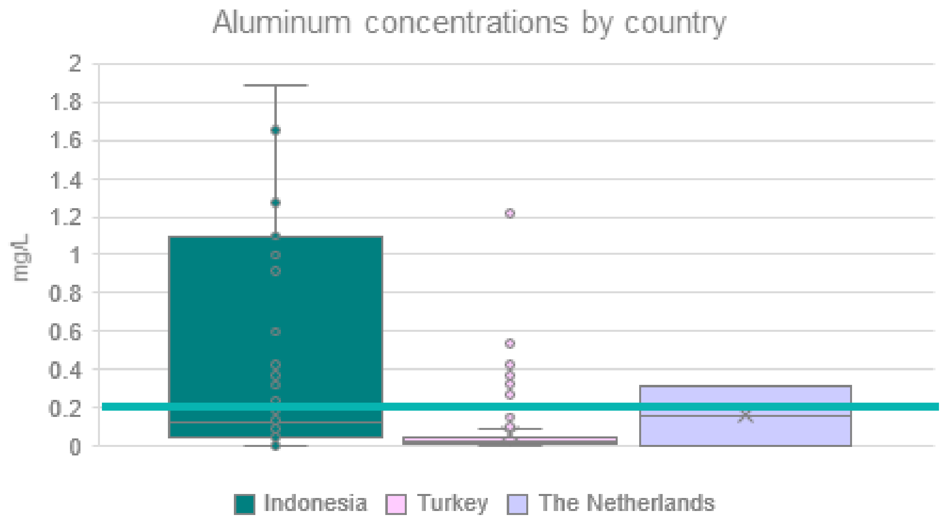


Figure 4.2.5 Aluminum concentrations between 0 and 2 mg/L. Vertical axis is plotted on a limited range to provide a detailed overview of the concentrations measured around the drinking water guideline value of 0.2 mg/L (indicated by the blue line).

Arsenic

The measured As concentrations are plotted by country in Figure 4.2.6. The number of measurements in Indonesia, Turkey and the Netherlands are respectively 103, 125 and 2. A zoomed section of the figure is included because of one Indonesian data point exceeding 200 mg/L (Figure 4.2.7).

The drinking water guideline value set by the WHO for As is 0.01 mg/L (86), indicated by the blue line in Figure 4.2.7. The number of samples in which the guideline value was exceeded is 17% for Indonesia, 13% for Turkey and 50% for the Netherlands. However, the limited number of samples in the Netherlands disturbs a proper comparison. 11 of the 21 Indonesian samples in which the guideline value was exceeded are from Lahendong (Sulawesi), 3 from Sibayak (North Sumatra) and 8 from Java. From the Turkish samples, 19 from Western Anatolia, 1 from Central Anatolia, 2 from Black Sea region. The Dutch sample in which the As guideline value is exceeded is from the West Netherlands Basin.

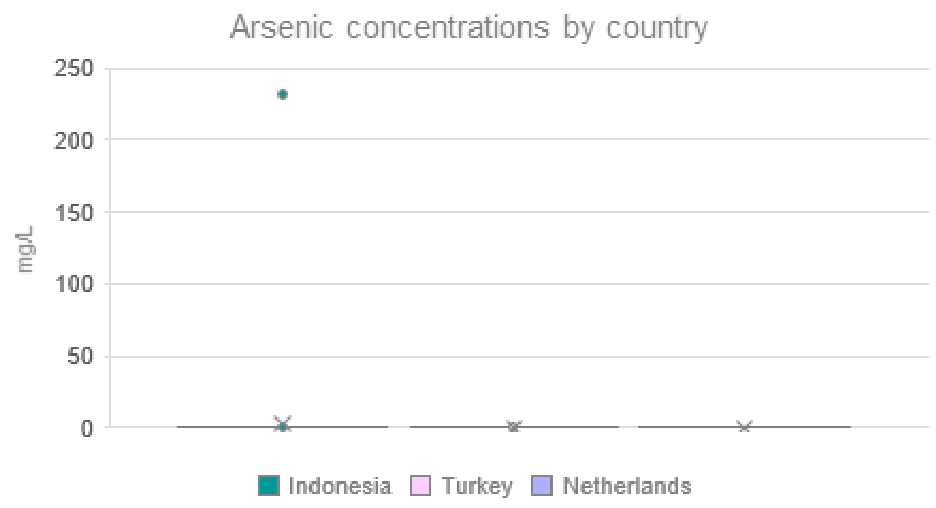


Figure 4.2.6 Arsenic concentrations (in mg/L) sorted by country and plotted on the total range between 0 and 250 mg/L.

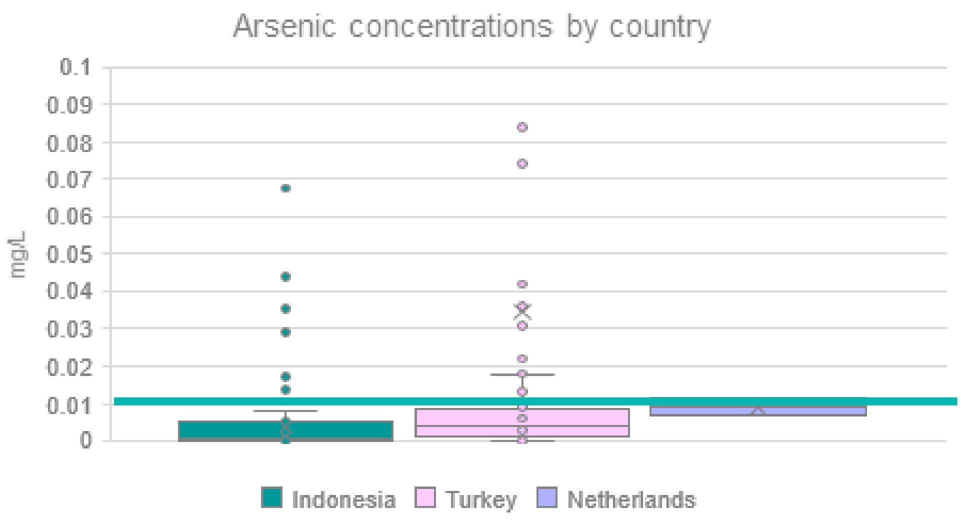


Figure 4.2.7 Arsenic concentrations between 0 and 0.1 mg/L. Vertical axis is plotted on a limited range to provide a detailed overview of the concentrations measured around the drinking water guideline value of 0.01 mg/L (indicated by the blue line).

Cadmium

The measured Cd concentrations are plotted for each country in Figure 4.2.8. The number of measurements in Indonesia, Turkey and the Netherlands is respectively 60, 2 and 1. The Cd concentrations in Indonesia are of lower order than they are in Turkey and the Netherlands, therefore a zoomed section was included (Figure 4.2.9).

The drinking water guideline value set by WHO for Cd is 0.003 mg/L (86), indicated by the blue line in Figure 4.2.9. The number of samples exceeding the guideline value is 3.3% for Indonesia, 100% for Turkey and 100% for the Netherlands. However, the limited number of samples in Turkey and the Netherlands disturb a proper comparison. The Indonesian samples in which the Cd guideline value is exceeded are from Java, the Turkish from Western Anatolia and the Dutch from the Texel-Ijsselmeer High.

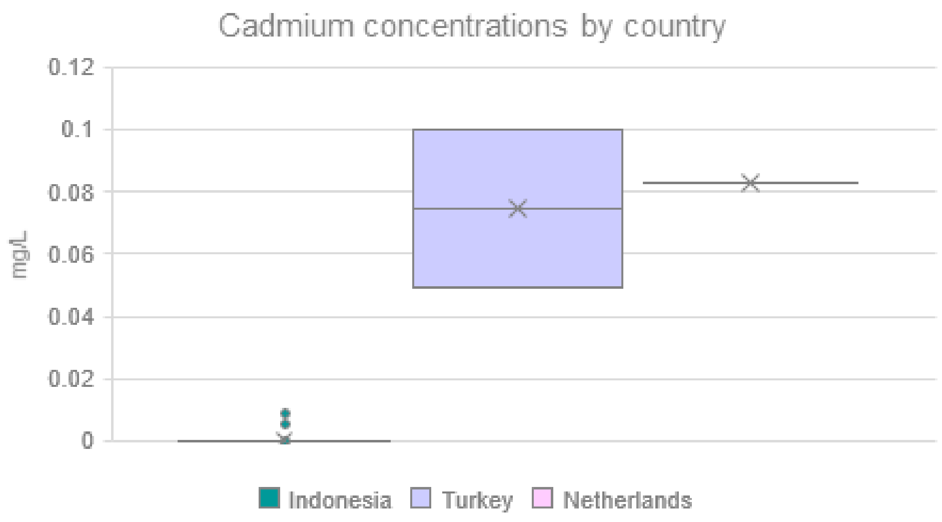


Figure 4.2.8 Cadmium concentrations (in mg/L) sorted by country and plotted on the total range between 0 and 0.12 mg/L.

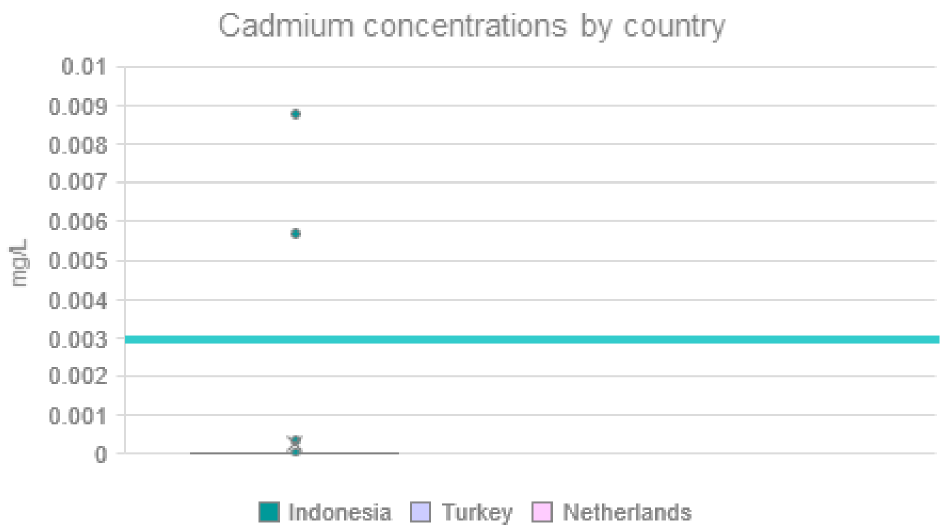


Figure 4.2.9 Cadmium concentrations between 0 and 0.01 mg/L. Vertical axis is plotted on a limited range to provide a detailed overview of the concentrations measured around the drinking water guideline value of 0.003 mg/L (indicated by the blue line).

Fluoride

F concentrations were measured in 180 Indonesian samples, but not in the Turkish or Dutch samples. The drinking water guideline value set by the WHO is 1.5 mg/L (86), which was exceeded in 43% of the Indonesian samples. These samples are from various locations throughout the country, namely one from Ulubelu and one from Sibayak (North Sumatra), 11 from Lahendong (Sulawesi), one from South Sumatra and 17 from Java.

Mercury

Mercury concentrations were only measured in three of the Dutch samples. No data were available from Turkey and Indonesia. The drinking water guideline value set by WHO for Hg is 0.006 mg/L (86), which was not exceeded in any of the samples.

Lead

The measured Pb concentrations are plotted in Figure 4.2.10. This figure contains 65 points from Indonesia, 10 from Turkey and 3 from the Netherlands. The drinking water guideline value set by WHO for Pb is 0.01 mg/L (86), indicated by the blue line in Figure 4.2.11. The percentage of data points that exceeds the drinking water guideline value for Indonesia is 7.7%, 83% for Turkey and 33% for the Netherlands. Of the Indonesian samples in which the guideline was exceeded, three are from Lahendong (Sulawesi) and two are from Java. One of the Turkish samples is from Central Anatolia and four from Western Anatolia. The Dutch sample from the West Netherlands Basin.

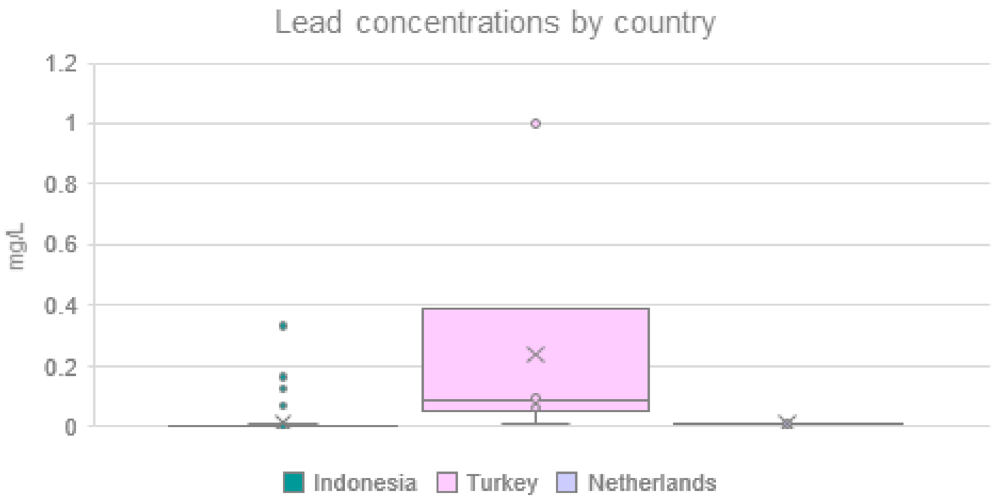


Figure 4.2.10 Lead concentrations (in mg/L) sorted by country and plotted on the total range between 0 and 1.2 mg/L.

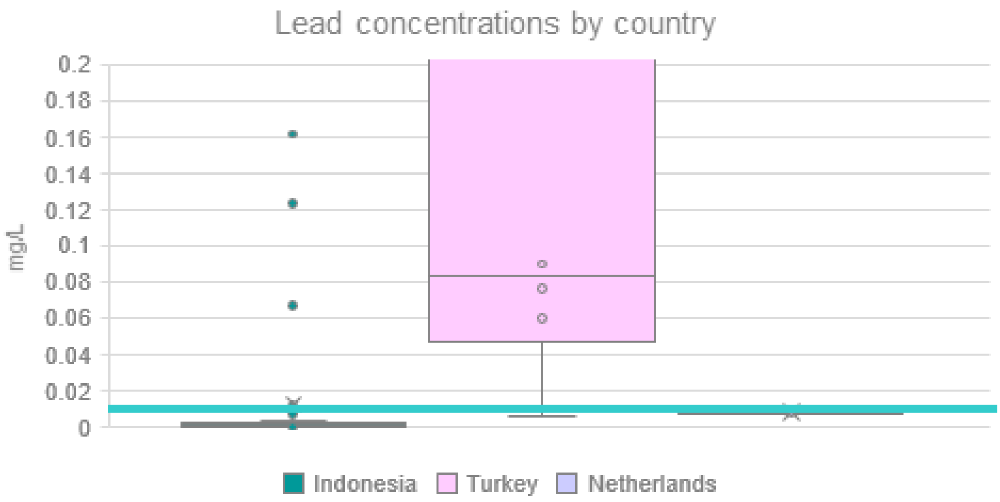


Figure 4.2.11 Lead concentrations between 0 and 0.2 mg/L. Vertical axis is plotted on a limited range to provide a detailed overview of the concentrations measured around the drinking water guideline value of 0.01 mg/L (indicated by the blue line).

4. Results

4.3. Survey data and analysis

This section presents the results from the survey on risk perception in geothermal energy generation. These results can also be found in detail in Appendix 6. Survey results. The survey aims to study the respondents general perception and risk perception on geothermal energy. In each of the following subsections, the results are discussed as a whole and separately by country.

Demography and knowledge about geothermal energy

The total number of responses to the survey is 145. Incomplete responses and responses from outside the study area are left out, which makes the number of responses used in this study 89. The responses gathered from the questions in sections 1 and 2 of the survey are shown in Table 4.3-1. Some of the percentages may not add up to 100 exactly because they are averaged.

Table 4.3-1 Table with answers to demographic and knowledge questions in the survey. The value of n is the number of times the answer was selected, which is calculated into a percentage (%) of all possible answers to that question.

	All countries		Indonesia		Turkey		The Netherlands	
	n	%	n	%	n	%	n	%
Country of residence	89	100	22	25	26	29	41	46
Region of residence	80	100	14	17	25	31	41	51
Java (IN)	-	-	10	71	-	-	-	-
Sumatra (IN)	-	-	4	29	-	-	-	-
Aegean (TR)	-	-	-	-	16	64	-	-
Central-Anatolia (TR)	-	-	-	-	4	16	-	-
Marmara (TR)	-	-	-	-	3	12	-	-
Mediterranean (TR)	-	-	-	-	2	8	-	-
West (NL)	-	-	-	-	-	-	31	76
North (NL)	-	-	-	-	-	-	2	5
South (NL)	-	-	-	-	-	-	5	12
East (NL)	-	-	-	-	-	-	3	7
Level of education	89	100	22	100	26	100	41	100
High school	1	1	0	0	0	0	1	2
Bachelor	13	15	2	9	5	19	7	17
Master	53	60	17	77	10	38	27	66
PhD	22	25	3	14	11	42	6	16
Professional expertise	88	100	22	100	25	100	41	100
Technology	70	80	18	82	17	68	35	85
Science	12	14	4	18	6	24	2	5
Policy	3	3	0	0	0	0	3	7
Social	2	2	0	0	2	8	0	0
Business	1	1	0	0	0	0	1	2

The total number of responses from Indonesia is 22, Turkey 26 and the Netherlands 41. To cope with these different numbers of responses the data are analyzed as percentages. For example, the number of respondents working in technology is calculated as a percentage of the total number of responses on that question from each country. These percentages are compared to each other.

The respondents regions of residence are divided throughout the countries, but often concentrated around one location. This is Java in Indonesia, the Aegean region in Turkey and the West of the Netherlands. These locations are also primary production locations of geothermal energy. In the overall group of respondents 60% hold a master degree. This is similar to the Indonesian and Dutch respondents, of whom respectively 74% and 66% hold a master degree. The Turkish respondents mostly have a master (38%) or PhD (42%) degree.

The majority of the respondents (80%) have technology as their professional expertise. This is the case for 83% of the Indonesian, 70% of the Turkish and 85% of the Dutch respondents. The remaining responses that came in were from respondents with their professional expertise in science, policy or business.

The respondents indicated their level of knowledge on three topics, but the first two were asked to prevent bias among the responses so only the third topic (geothermal energy) will be discussed. These results are presented in Appendix 6. Survey results and visualized in Figure 4.3.1. Here it is clear that the respondents consider their level of knowledge high. This trend is strongest among the Turkish respondents and less strong among the Indonesian.

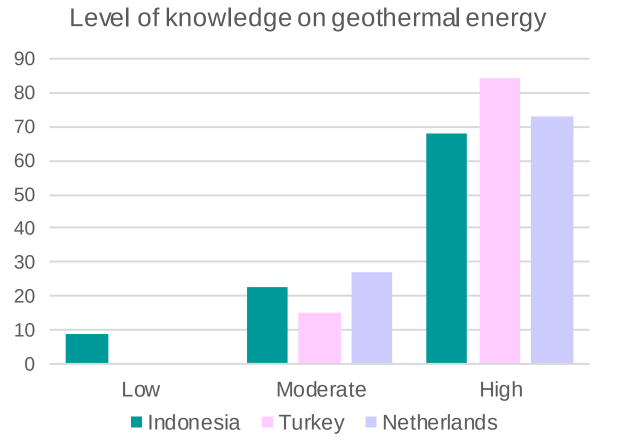


Figure 4.3.1 Level of knowledge on geothermal energy as the survey respondents indicated themselves in the survey

General perception of geothermal energy

To study the general perception on geothermal energy among the respondents, they are asked to indicate to what extent they agree with the two statements. These are *"I am concerned about the future development of geothermal energy in my home country"* and *"Geothermal energy is suitable as an alternative energy source for the future."* The responses to these questions are used to calculate the average value and standard deviation through the Likert scale that was implemented, and these results are presented in Table 4.3-2. For the first statement the numbers that were assigned to the Likert scale are inversed, because of the positive note in the statement. This means that for the calculations with this statement, '1 = strongly agree' and '5 = strongly disagree'.

Table 4.3-2 Responses to two statements in the survey to which the respondents had to indicate whether they agree or not. The value of n is the number of times the answer was selected, avg stands for the average of all responses and st.dev stands for the standard deviation defines the spread of the responses.

	All countries			Indonesia			Turkey			The Netherlands		
	n	mean	st.dev	n	mean	st.dev	n	mean	st.dev	n	mean	st.dev
Statement 1: "Geothermal energy is suitable as an alternative energy resource for the future."	88	1.59	0.94	21	1.37	0.96	26	1.85	1.19	41	1.54	0.71
Statement 2: "I am concerned about the future development of geothermal energy in my home country."	88	2.49	1.21	22	2.95	1.15	25	2.68	1.41	41	2.15	1.01

From the table it is clear that the majority of the respondents agrees with this statement. This trend is stronger among the Indonesian respondents, where the mean is 1.37. In Turkey and the Netherlands the means are respectively 1.85 and 1.54. The respondents from these countries agree less strongly with the statement, but the majority is still very convinced that geothermal energy is a suitable alternative energy resource for the future.

The responses to the second statement are less concentrated, with a mean value of 2.49. 40% of the respondents chose 'somewhat disagree', and the other answers were chosen by 8% to 20% of the respondents. This trend is similarly spread among the Indonesian responses, but the mean is somewhat higher with 2.95. The mean is somewhat lower among the Turkish respondents, with 2.68, and the standard deviation is much wider with 1.41. This indicates that they agreed less with the statement than the Indonesian respondents. The Dutch respondents overall agreed least with this statement with a mean of 2.15 and low standard deviation of 1.01.

Following these statements, the respondents were asked to indicate how important they consider a range of factors on their perception of geothermal energy. These factors are the sustainability, pollution, nuisance, energy produced per area of land, costs and the continuity of energy supply. The responses to each of these are presented in Table 4.3-3. To study the trends in the three countries separately, the factor ratings are also visualized in Figure 4.3.2 to Figure 4.3.6. In these figures Indonesia is plotted in green, Turkey in pink and the Netherlands in purple.

Table 4.3-3 Responses to 'Indicate how important each factor is in your opinion on geothermal energy." The value of n is the number of times the answer was selected, avg stands for the average of all responses and st.dev stands for the standard deviation defines the spread of the responses.

	All countries			Indonesia			Turkey			The Netherlands		
	n	mean	st.dev.	n	mean	st.dev.	n	mean	st.dev	n	mean	st.dev
Sustainability	89	3.66	1.50	22	4.10	1.41	26	2.19	1.41	41	4.41	0.72
Pollution	88	3.65	1.18	22	3.90	0.97	25	3.24	1.3	41	3.79	1.15
Nuisance	89	3.25	1.05	22	3.35	1.04	26	3.62	1.02	41	2.95	1.00
Land area	88	3.19	1.23	22	3.70	1.08	25	2.60	1.35	41	3.31	1.08
Costs	88	3.35	1.23	22	3.90	1.25	25	2.68	1.22	41	3.49	1.05
Continuity of energy supply	89	3.48	1.30	22	4.20	0.89	26	2.54	1.48	41	3.74	0.97

The respondents reactions are divided in the rating of the factor sustainability. Only 3% chose 'moderately important', while 17% and 38% of them chose 'not at all important' and 'extremely important'. The majority of the Indonesian respondents (50%) think sustainability is extremely important to consider in the development of geothermal energy. The general trend in the plot (Figure 4.3.2) is going upwards towards the more important side for the Indonesian responses. A similar trend is observed among the Dutch respondents, but it is much different among the Turkish respondents. The majority of the Turkish respondents (>70%) think sustainability is a 'not at all important' or 'slightly important' factor to consider.

The majority of all the respondents (80%) think pollution is 'moderately important', 'very important' or 'extremely important'. Between the three countries the trends differ slightly (Figure 4.3.3). Among the Indonesian respondents there is a clear peak (31%) on the right side of the figure, at 'very important'. This increasing trend is even clearer than the one in the sustainability plot for Indonesia. The trend is similar among the Dutch respondents, of whom the majority (88%) chose the three answers on the right side of the figure. The Turkish responses to this factor are more divided, with percentages between 8% and 28% for each of the ratings. Therefore, the average rating of the pollution aspect is lower in the Turkish data than it is in the Indonesian and Dutch ones.

The majority of the respondents (86%) rate nuisance as 'slightly important' to 'very important'. This nuisance includes sight, noise and scent pollution. The responses are divided around the central three ratings of this question. In Figure 4.3.4 the Indonesian and Turkish data show increasing peaks at 'Very important' of around 40%. The Dutch data show a similar trend, but with a slightly less strong peak at 'Slightly important'. Therefore, the Dutch respondents consider nuisance a less important factor than the Indonesian and Turkish respondents.

The rating of energy production per land area shows a divided trend, with 10 to 28% of each rating. The Indonesian data in Figure 4.3.5 show a roughly increasing trend towards the right side of the figure. These have 25 to 30% of the ratings. The Dutch ratings are approximately equal, with a peak at 'moderately

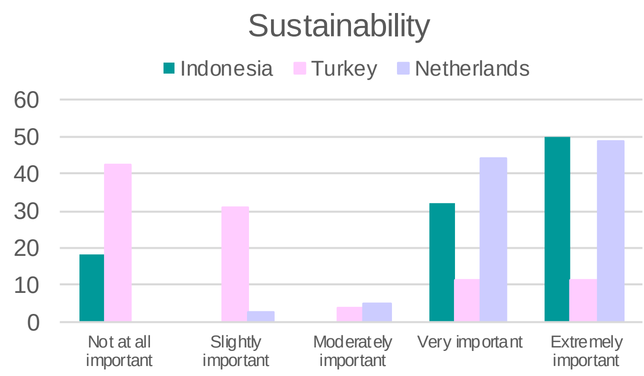


Figure 4.3.2 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Sustainability.'

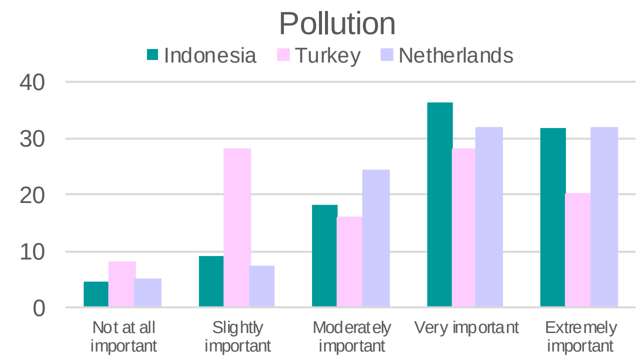


Figure 4.3.3 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Pollution.'

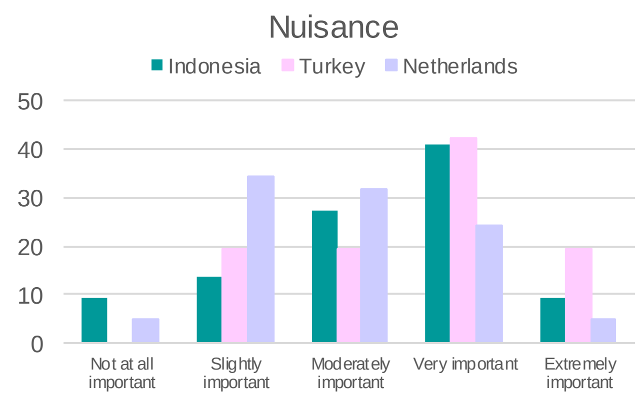


Figure 4.3.4 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Nuisance.'

important' of 37%. An opposite and scattered trend is seen in the Turkish data. There is a peak of 32% at 'Slightly important', and the right three ratings received 16% or less.

The costs show a scattered trend in the overall data set, with 24% among the central three ratings. In the Indonesian responses there is a clearly increasing trend towards the right side of the figure, with over 75% at 'very important' or 'extremely important' (Figure 4.3.6). The peak in the Turkish data is less strong and located on the left side of the figure, with over 50% of rankings at 'Not at all important' or 'Slightly important'. The Dutch data set show a peak of 37% in the central part of the figure, around 'Moderately important'. The remaining data points are scattered among the remaining ratings.

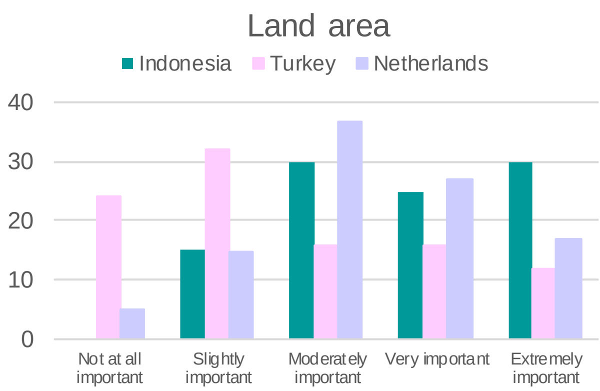


Figure 4.3.5 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Energy production per

The overall data set for the factor 'continuity of energy supply' is centered around 'very important'. In the Indonesian plot there is an increasing trend towards the right side of the figure. 80% of the Indonesian respondents chose this factor to be 'Very important' or 'Extremely important'. The Turkish data show a majority of ratings on the other side of the figure, with over 60% at 'not at all important' and 'slightly important'. The Dutch data set shows a peak on the right side of the figure that is less strong than in the Indonesian one. Over 90% of the Dutch respondents chose at least 'Moderately important' as ranking for this factor.

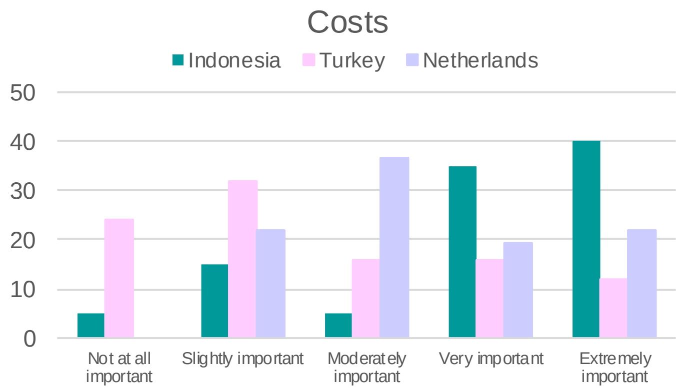


Figure 4.3.7 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Costs.'

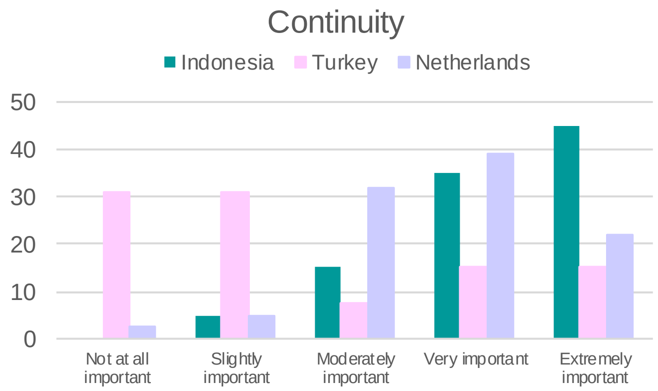


Figure 4.3.6 Percentage of each answer given to question 'Rate how important each factor is on your opinion on geothermal energy: Continuity of power supply.'

Risk perception on geothermal energy

The respondents were asked to indicate their level of concern about five potential risks related to geothermal operations. These risks are groundwater contamination, air pollution, nuisance, seismicity and sight pollution. The means and standard deviations of the responses to this question are presented in Table 4.3-4 and the trends for the different risks are visualized in histograms in Figure 4.3.8 to Figure 4.3.12. In these figures, Indonesian data are plotted in green, Turkish in pink and Dutch in purple.

Table 4.3-4 Responses to 'Indicate your level of concern about each potential risk.' The value of n is the number of times the answer was selected, avg stands for the average of all responses and st.dev stands for the standard deviation defines the spread of the responses.

	All countries			Indonesia			Turkey			The Netherlands		
	n	mean	st.dev.	n	mean	st.dev.	n	mean	st.dev	n	mean	st.dev
Groundwater contamination	89	2.79	1.18	22	3.70	1.08	26	2.42	1.02	41	2.56	1.10
Air pollution	88	2.20	1.32	22	3.25	1.45	25	2.32	1.22	41	1.59	0.91
Nuisance	88	2.26	1.11	22	2.90	1.02	25	2.08	1.29	41	2.05	0.92
Seismicity	88	2.60	1.21	22	3.55	1.19	25	2.12	1.13	41	2.41	1.02
Sight pollution	89	1.81	1.07	22	2.45	1.19	26	2.12	1.21	41	1.28	0.56

Among the ratings for groundwater contamination there is a divided trend in the overall data set because each level of concern has between 18% and 37% of the responses. In the Indonesian data (Figure 4.3.8) is a clearly increasing trend towards the right side of the figure. Each of the right three answers was chosen by over 25% of the Indonesian responses. The Turkish data show a strong peak of around 'Moderately concerned' with over 45% of the responses, but only less than 5% of the Turkish respondents chose 'Very concerned' or 'Extremely concerned'. The Dutch data set contains a similar peak that is less steep (34%) and a smoother trend towards the left and right side of the figure.

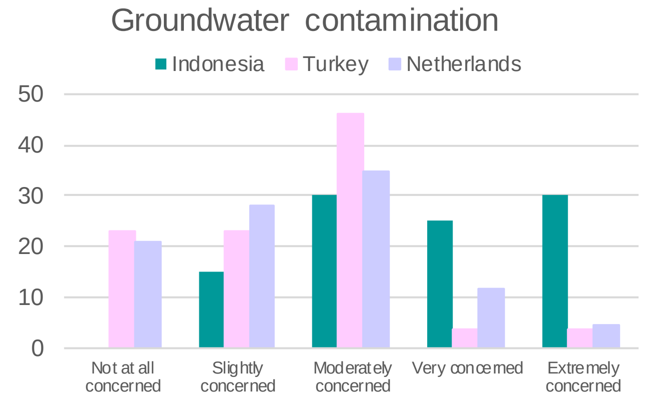


Figure 4.3.8 Percentage of each answer given to question 'How concerned are you about the following potential risks: Groundwater contamination'

The overall ratings of air pollution are concentrated around 'not at all concerned'. From Figure 4.3.9 the differences between the three countries are studied. The Indonesian responses are divided over the graph width, as each rating scored between 14 and 32%. There are two small peaks at 'Slightly concerned' and 'Extremely concerned'. In the Turkish data there is decreasing trend towards the right side of the figure. This runs from 32% at 'Not at all concerned' to 5% at 'Extremely concerned'. In the Dutch data there is a strong peak at 'Not at all concerned' with over 65%. The remaining values show a decreasing trend with 17% or less. Therefore, the Dutch respondents show the least concern about air pollution from geothermal operations.

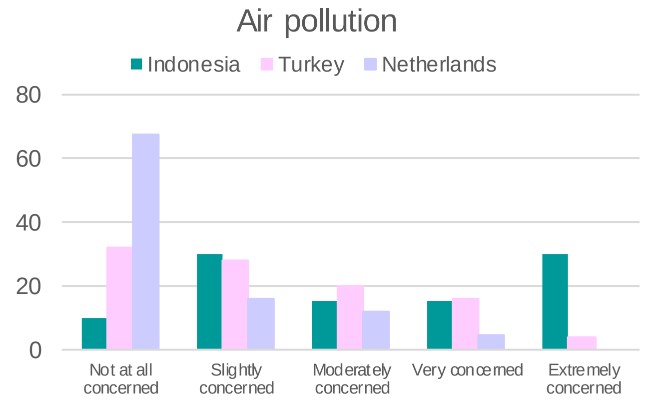


Figure 4.3.9 Percentage of each answer given to question 'How concerned are you about the following potential risks: Air pollution'

Most respondents (77%) indicated that they are 'not at all concerned' or 'slightly concerned' about the risk of nuisance from geothermal operations. Among the Indonesian responses the majority is 'Slightly concerned' to 'Very concerned'. Each of these 3 ratings were chosen by more than 23% of the respondents. The Turkish data show a decreasing trend towards the right side of the figure, where almost 50% of the respondents indicates they are 'Not at all concerned' and less than 10% is 'Very concerned' about nuisance. The Dutch responses also show a decreasing trend towards the right, where 'Not at all concerned' and 'Slightly concerned' were both chosen by 37%.

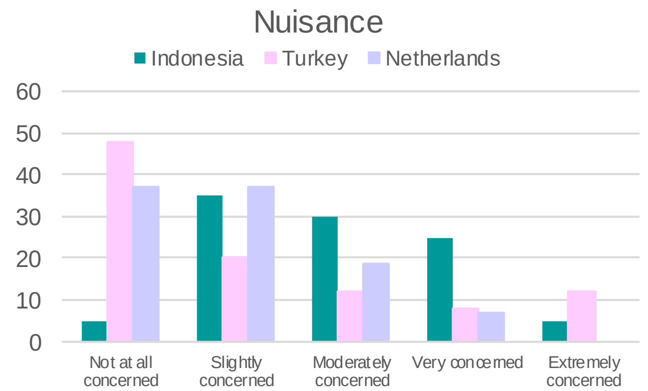


Figure 4.3.10 Percentage of each answer given to question 'How concerned are you about the following potential risks: Nuisance'

In the overall data set, 24% to 31% of the respondents rated the risk of seismicity as 'not at all concerned' to 'moderately concerned'. The trend among the Indonesian responses looks slightly different than the Turkish and Dutch ones. The Indonesian trend is increasing towards the right side of the figure, as the right three ratings each received over 23% of the responses. The Turkish data show a decreasing trend towards the right side of the figure, with two peaks at the right and center of the figure. The Dutch data also show a decreasing trend and has a peak of 41% at 'Slightly concerned'.

Finally, the majority (56%) of all the respondents indicate that they are 'not at all concerned' about sight pollution. Among the Indonesian responses, this trend is decreasing towards the right side of the figure, with ratings that differ from 32% at 'slightly concerned' to 5% at 'extremely concerned'. A similar trend was observed in the Turkish data. This data set decreases from 38 to 4%. The Dutch data show a very clear peak of 80% at 'Not at all concerned' and less than 5% for each of the right most three ratings. Therefore, the Dutch respondents are least concerned about the risk of sight pollution from geothermal operations.

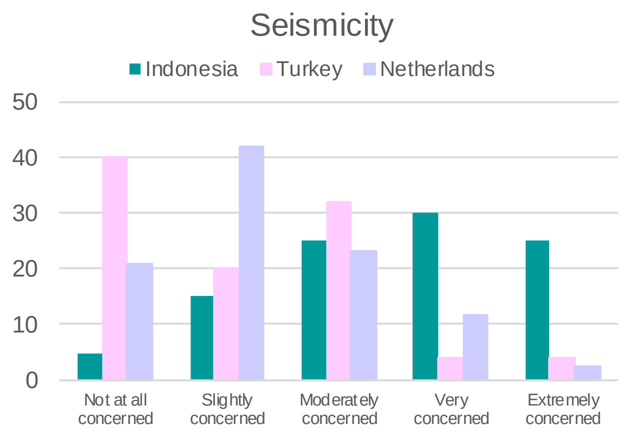


Figure 4.3.11 Percentage of each answer given to question 'How concerned are you about the following potential risks: Seismicity'

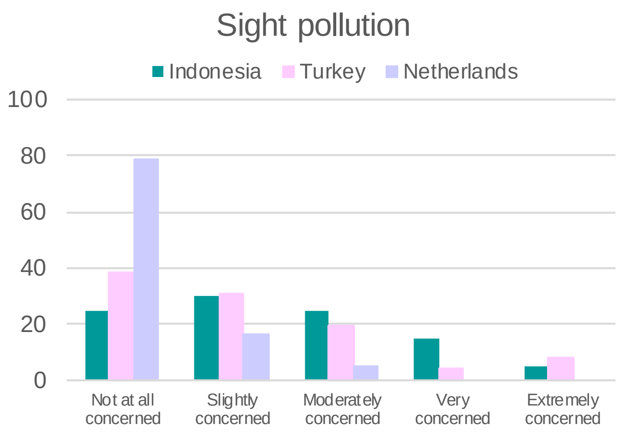


Figure 4.3.12 Percentage of each answer given to question 'How concerned are you about the following potential risks: Sight pollution'

Correlations

Correlation coefficients are calculated to study the relation between the (risk) perception and a population their demographic properties and prior knowledge on geothermal energy. This is done in SPSS for four data sets: the total collection and the separate Indonesian, Turkish and Dutch response collections. The correlation calculations were implemented for four parameters: the level of education, self-rated level of knowledge on geothermal energy, the trust in geothermal energy and the concerns about geothermal energy. Correlation coefficients could not be calculated for the region of residence nor the professional expertise, because these parameters cannot be quantified as numbers in SPSS. Also the regional variety of the respondents was too small to observe the differences between the regions.

The results of the data set from all countries together are presented in Table 4.3-5 and detailed numbers from the different countries can be found in Appendix 6. Most of the calculated correlations are either insignificant (sig. > 0.05) or zero (correlation coefficient < 0.1). Therefore, we only discuss a limited selection of correlations. The correlations of the (risk) perception to the level of education and the overall trust in geothermal energy are mostly insignificant and/or zero. The only significant correlation is between the concerns about sight pollution and the level of education of the respondents, and it is classified as weak. Both responses to these questions are concentrated at specific responses (Figure 4.3.1 and Figure 4.3.12), which are low concerns about sight pollution and a high level of education.

The level of knowledge and general concerns about geothermal energy have a significant correlation to the concerns about potential risks from geothermal operations. This is a weak to moderate negative correlation for the level of knowledge, and weak to moderate positive for the general concerns about geothermal energy developments. For the level of knowledge in four of the five risks there is a negative correlation between -0.27 and -0.41, which means that generally the respondents are less concerned about the potential risks when they are more knowledgeable about geothermal energy. The correlation is insignificant for sight pollution, the risk with the strongest concentration of responses at 'not at all concerned' (Figure 4.3.12).

For the general concerns the correlation is slightly stronger and positive, between 0.34 and 0.46 for each of the assessed risks. This means that people are more concerned about the potential risks when they are more concerned about the future development of the geothermal energy sector in general.

Table 4.3-5 Spearman correlation coefficients for the total data set. The value of N is the number of times the question was answered, Sig. is the significance of correlation and the third value in each column is the correlation coefficient.

		Level of education			Knowledge on geothermal energy			Trust in geothermal energy			Concerns about geothermal energy		
		N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient
Factors	Sustainability	89	0.581	-0.059	89	0.379	-0.094	89	0.117	-0.168	89	0.915	-0.012
	Pollution	89	0.289	-0.114	89	0.884	0.016	89	0.199	-0.139	89	0.136	-0.161
	Nuisance	89	0.761	0.033	89	0.469	0.078	89	0.223	-0.131	89	0.232	-0.129
	Land area	89	0.125	-0.165	89	0.488	-0.075	89	0.402	-0.091	89	0.518	-0.07
	Costs	89	0.652	0.049	89	0.488	-0.075	89	0.590	-0.059	89	0.865	0.018
	Continuity of energy supply	89	0.470	-0.078	89	0.237	-0.127	89	0.158	-0.152	89	0.695	0.042
Risks	Groundwater contamination	89	0.462	0.079	89	0	-0.377	89	0.887	0.015	89	0.000	0.364
	Air pollution	89	0.817	0.025	89	0	-0.405	89	0.875	-0.017	89	0.001	0.352
	Nuisance	89	0.995	-0.001	89	0.007	-0.286	89	0.974	0.003	89	0.000	0.459
	Seismicity	89	0.566	0.062	89	0.008	-0.279	89	0.308	-0.111	89	0.001	0.345
	Sight pollution	89	0.035	0.223	89	0.184	-0.142	89	0.067	-0.196	89	0.000	0.398

5. Integration and discussion

To improve understanding of the geothermal energy systems and the environmental risks related to them, an interdisciplinary approach was implemented to study the risks from multiple perspectives: the natural sciences and the social sciences perspective. This approach was used to distinguish between the perceived risks and the actual risks in geothermal fluids in three different country settings. The combination of these perspectives makes the study unique. Equally unique is the extensive geochemistry data set that was worked with. This chapter will first discuss the different aspects separately and conclude on the findings on each of the aspects. Finally, the findings of all sections are integrated to bring the natural and social perspectives together.

Interpretation of results

Geochemical analysis by country

Indonesia

The geochemistry in Indonesia differs largely in locations throughout the country and there is a wide variety of chemical properties in terms of equilibrium level, fluid origin, pH and salinity. There is a clear difference between the well and spring waters. The well waters are predominantly Cl waters of variable equilibrium conditions and the spring waters are immature HCO_3 waters. Next to these water types, both the well and spring sample sets contain waters that have a high concentrations of SO_4 and a low pH, both indications of volcanic activity.

The Na-K-Mg diagrams for Indonesian well and spring waters show very different trends. Where the well waters are found as both immature waters and in partial to full equilibrium, the spring waters all have high Mg concentrations and are therefore non-equilibrated waters. This means that the spring waters experience active mixing with different waters (98). Since the well waters are found on this broad range of equilibration levels, it is assumed that they experience low to high levels of mixing.

The Cl-SO_4-HCO_3 diagrams also show a clear difference between the well and spring waters. The well water samples are predominantly found as Cl waters. Cl waters are typically present in deep geothermal fluids in most high-temperature systems. Systems with high Cl concentrations are fed more directly from the deep reservoir, and identify permeable zones (19). Fluids that have high Cl contents often also contain Na and K as their main constituents and they are found in partial to full equilibrium with their host rock. The pH range of the well waters is typically around the neutral pH. The combination of these properties explains that they are mature waters fed from the deep reservoir that have experienced less mixing (74). In the Indonesian well samples there is generally a strong correlation between the Cl concentrations and that of other elements. This is in line with the high Cl content in well waters that relate to the water origin in a deep geothermal reservoir. Correlations with F and SO_4 are stronger in well samples than in spring samples. These elements are a result of volcanic activity, so this indicates that the inflow from volcanic systems is higher in the well waters and the volcanic activity originates from the deeper subsurface.

The spring waters typically have high HCO_3 concentrations and are immature waters. Spring waters that contain a high HCO_3 content are formed as a result of the condensation of steam or gas into groundwaters with low oxygen levels (19). When these fluids are from non-volcanic high-temperature systems, they may constitute the deep reservoir fluid. The dominant pH in Indonesian spring waters ranges from 5 to 8.5, which is around the neutral pH. The neutral pH is typical for HCO_3 waters because of their reaction with local rocks and the related loss of protons. After these reactions the principal constituents are typically Na and HCO_3, which explains the trends observed in the Na-K-Mg and Cl-SO_4-HCO_3 diagrams. In the spring samples there is generally a strong correlation between the HCO_3 concentrations and that of other elements. The salinity in the Indonesian spring waters (up to 1000 mg/L) is clearly lower than in the wells (up to 3500 mg/L). This can be explained by the age and depth of the geothermal water, as the spring waters are typically from shallower depths and have experienced less long-term mineral-fluid interactions.

Besides the high concentrations in the Cl and HCO_3 domain for the well and spring waters, in both data sets there are samples with high SO_4 concentrations. Acid SO_4 waters are formed by the condensation of geothermal gases from volcanic rock bodies, like H_2S, into near-surface groundwater that contains oxygen (19). This results in the following chemical reaction in which SO_4 is formed (Eq. 1).

$$H_2S\ (g)\ +\ 2O_2(aq)\ =2H^+(aq)+SO_4^{2-}(aq) \qquad \text{Equation 1}$$

Part of the data have a pH between 1.5 and 3.5. This low pH is proof of acidification of the geothermal water. The chemical reaction in Eq. 1 induces the condensation of CO_2 (Eq. 2), which leads to acidification of groundwater that commonly occurs near the surface. Through this reaction SO4 waters typically entail a decrease in pH, down to pH 2.

$$CO_2\ (g)\ +\ H_2O\ (l)\ \rightleftharpoons H^+(aq)+HCO_3^-(aq)=2H^+(aq)+CO_3^{2-}(aq) \qquad \text{Equation 2}$$

When acid SO_4 waters penetrate to deeper reservoirs, they can react with Cl waters and form Cl-SO_4 fluids (19). Cl-SO_4 waters can also form as a result of the absorption of magmatic gases in groundwater followed by close iso-chemical dissolution of the contact rock (74). The Cl-SO_4-HCO_3 shows a wide distribution of samples throughout all regions. Most of the samples in Java are peripheral waters, which relates to the high levels of mixing as seen in the Na-K-Mg diagram. The Javan data set also contains some Cl-SO_4 waters.

The samples from Sulawesi are predominantly found to be Cl waters that are in partial equilibrium, so they are fed from the deep reservoir. The North-Sumatran samples are predominantly found at high HCO_3 concentrations and are immature. Therefore, these samples experience high groundwater mixing. The samples from South-Sumatra are mature waters with a Cl concentration of 50-60%. These have experienced little groundwater mixing. The Javan samples are immature and contain a high HCO_3 concentration, with some high SO_4 concentrations. This means that they are samples that have experienced high mixing and some of them are fed more directly from volcanic rocks.

These findings are supported by other studies. For example, Deon *et al.* (99) describe numerous samples from Java, Sumatra and Sulawesi that contain Cl and HCO_3 waters, but especially high SO_4 waters that have a very low pH, between 1 and 2.5. Furthermore, Mahon *et al.* (100) studied the chemistry of geothermal fluids and their relationship to water and vapor dominated systems. Their study concluded that deep-seated chloride-dominated waters experience difficulty to reach the surface and therefore the shallow geothermal reservoirs are typically non-chloride waters.

Turkey

The differences between the well and spring waters in Turkey are less obvious than they are in Indonesia. The majority of the Turkish samples are immature HCO_3 waters of a pH that is slightly above the neutral pH. Besides these there is a variety of SO_4 and Cl waters found in specific regions throughout the country, some of which are close to equilibrium conditions.

The Na-K-Mg diagrams for the Turkish well and spring waters show similar trends. In both diagrams, the majority of the samples are immature and less densely spread throughout the partial equilibration zone. Among the well waters there are slightly more samples found in partial to full equilibrium than in the spring samples. This is also confirmed by the higher correlation coefficients in well waters than in spring waters of Na with other minerals. The large amount of immature waters in Turkey indicates that there is active mixing of subsurface fluids.

The Cl-SO_4-HCO_3 diagrams with Turkish well and spring data show similar trends. Bot have a majority of HCO_3 waters, and a minority of Cl, SO_4 and Cl-SO_4 samples. There are slightly more Cl, SO_4 and Cl-SO_4 waters among the spring samples than in the well samples. The origins of these fluids are typically in the deep reservoir or a result of H_2S leakage from the volcanic system into the geothermal reservoir. This volcanic activity is confirmed by the strong correlations found between F and other elements. The high concentration of HCO_3 is related to the rock type from which the geothermal fluids are produced. These are often high in calcite, and therefore HCO_3 dissolves from the rock into the groundwater when water flows into the reservoir (Eq. 3).

$$CaCO_3\ (s)+CO_2\ (g)\ +H_2O\ (l)=Ca^{2+}(aq)+2HCO_3^-(aq) \qquad \text{Equation 3}$$

The pH range in Turkish wells and springs is near-neutral and this corresponds to the near-neutral pH in HCO_3 waters as a result of their reaction with local rocks, as previously explained. The pH range is slightly lower in the spring waters than in the well waters, which can be related to the SO_4 concentration that is higher in these waters. The salinity is slightly higher in Turkish spring waters than in well waters. The spring waters with the highest salinity are samples near the coast of Western Anatolia. Close to these sampling locations, in Çeşme (Izmir), high salinity geothermal fluids were previously found to be a result of mixing with seawater that penetrates through faults into the reservoir (101).

By studying the graphs per region, it is visible that each region contains a sample of each type. Most of the chloride samples close to the equilibrium line are from the Menderes Massif, followed by the Kirsehir Massif, Sakarya Zone or Anatolide-Tauride Block. The samples from the Arabian Platform and Istanbul Zone are all immature waters. These regional differences depend on the geological settings, such as volcanic activity and reservoir sediment, but it also depends on the type of installation that is present. Since the Menderes Massif is the main production location of geothermal fluids, it also contains most deep, high-enthalpy geothermal wells and since these produce from the deeper geothermal fluid they are also more likely to produce Cl fluids.

The Netherlands

The variety of geothermal fluids in the Netherlands is small compared to Indonesia and Turkey. This is a result of the size of the country and geological variation. The geothermal fluids are Cl waters in partial to full equilibrium and have a neutral pH.

The Na-K-Mg diagram that shows the Dutch data contain samples in partial to full equilibrium, because they have a high Na concentration. From the Cl-SO_4-HCO_3 diagram it is clear that all Dutch samples have a maximum Cl concentration. The correlations are also strong in mixtures with Cl and Na. This indicates that they are mature waters that are fed from the deep geothermal reservoir (19). The geothermal fluids are stored in deeply buried, inactive geothermal reservoirs that are not actively deformed anymore and do not experience active mixing with fluids from surrounding rock. The samples have a pH between 6 and 6.5, which is in between the neutral pH for normal temperatures (pH = 7) and at high temperature (pH = 5.5). The geothermal fluids are found at depth and heated due to the geothermal gradient. The salinity is low compared to the other two countries, which is because of the different nature of the geothermal systems. The salinity in sedimentary reservoirs with temperatures below 100ºC is generally lower than in volcanic reservoirs producing at high temperatures (102). The strong correlation between Na and Cl in Dutch geothermal fluids is previously described by Antics & Hartog (103), the equilibrium with the host rock by TNO (104) and the relatively low brine concentration by Dijkstra (102).

The Cl-SO_4-HCO_3 graphs look similar for each of the production locations. The samples in full equilibrium are from the West and Central Netherlands Basins, and the majority of the ones in partial equilibrium are from the Roer Valley Graben. This difference between production locations can be related to the level of active mixing in the different formations that is produced from. In the Roer Valley Graben this is more active due to the production from a fault zone that stimulates subsurface fluid flow (59).

Environmental risk analysis

H_2S

High H_2S emissions are generally a result of volcanic activity in the subsurface. The sulfur that is emitted in this activity ends up in geothermal fluids in the form of H_2S (105). H_2S is a toxic gas that can have fatal health effects, mainly depending on its concentration. Short-term exposure to lower concentrations can result in headaches and nausea, but at higher concentrations it can result in serious damage to the eyes and lungs, and even death within a few hours to a few breaths (79). H_2S can be slowly converted into SO_2 under atmospheric conditions. When SO_2 reacts with water and air it forms sulfuric acid, which is the main component in the acid rain that results in deforestation, corrosion to buildings and infrastructure and the acidification of surface waters (106).

The environmental risk of excessive H_2S emissions from geothermal installations is highest in Indonesian samples. Here the concentration of H_2S in the gas emitted from the geothermal system reaches up to 90% and the average concentration is around 5%. In Turkey and the Netherlands, this concentration does not exceed 5% and is on average below 1%. The H_2S emissions from geothermal power plants in Indonesia were studied by Yuniarto *et al.* (107). They studied three locations in which the emissions varied between 0.14 and 2.54 g/kWh with an average value of 1.45 g/kWh. They concluded that the H_2S emissions in these power plants varied not only by the amount of steam supply but more with reservoir characteristics. This corresponds to the occasionally high H_2S concentrations in the Indonesian samples. It also confirms the importance of performing a close and accurate analysis of the reservoir settings for the risk assessment of H_2S emissions. The Turkish H_2S emissions were studied by Dumanoglu (108), by sampling two geothermal power plants. This study concluded that the H_2S safety limits were not exceeded in either of the plants.

In January 2021, a malfunction in a geothermal power plant in North Sumatra led to the exposure of civilians to H_2S gas and there were 40 people hospitalized and five fatalities as a result of this leakage (109). This accident is a clear example of the environmental risks that result from highly toxic H_2S emissions and can occur when a malfunction of the geothermal operation takes place. Therefore, areas where geothermal fluids have increased H_2S concentrations require extra attention on this aspect.

CO_2

The most abundant greenhouse gas (GHG) in geothermal fluids is CO_2, as was studied by Fridriksson *et al.* (110). The result of their analysis was that an average of over 95% of the steam composition was CO_2 and only a few percent CH_4. The CO_2 in geothermal gases most frequently originates from the host rock of the geothermal system, and only a small fraction has the same origin as the geothermal fluid itself. The CO_2 that originates from the geothermal source rock is derived from carbonate-bearing rocks. $CaCO_3$ precipitates at the flash point as waters with high HCO_3 concentrations are produced in the geothermal system (32). This leads to the inverse reaction in Eq. 2, which explains the CO_2 emissions from these carbonatic reservoirs. In this way, CO_2 emissions from carbonatic reservoirs can be much larger than from volcanic systems (111). High temperatures (and thus geothermal steam instead of liquid) are not common but they do occur in regions with carbonatic systems, such as in Western Turkey. CO_2 can also enter the reservoir from the geothermal heat source in volcanic geothermal systems, through e.g. magmatic intrusions mantle sources. Excessive concentrations of CO_2 in the atmosphere lead to an enhanced greenhouse effect, but can also result in a variety of health effects depending on the air concentration (107). This affects the lungs, skin and cardiovascular systems.

The Turkish CO_2 emissions determined in this study were always over 95% of the total gas solution that was emitted from geothermal operations. This makes the risk of excessive CO_2 emissions high. The CO_2 concentration was on average around 90% in the Indonesian samples, but this value varies more throughout the different systems, as some have a very high H_2S concentration and much lower (<5%) CO_2 concentrations. In the Dutch data set is one sample with a CO_2 concentration of almost 60%. Apart from this sample, the CO_2 concentration was no more than 25% of the solution, therefore the risk in the Netherlands is low.

The study by Yuniarto *et al.* (107) found that the CO_2 emissions from three Indonesian geothermal power plants they studied was mainly dependent on the steam supply type. Emissions were higher from dry steam reservoirs than those from two-phase systems. The CO_2 emissions ranged from 37 to 73 g/kWh with an average of 63 g/kWh. Different emission levels from Turkish systems were studied by Layman (112) and Aksoy *et al.* (32). The CO_2 emissions in their studies ranged from 400 to 1650 g/kWh, with an average of 1121 g/kWh. This is a factor of 9.2 higher than the weighted average in geothermal power plants worldwide, which is 122 g/kWh.

The emission of CO_2 from geothermal brines into the atmosphere has already led to heavy debate on the sustainability of geothermal energy in Turkey (32). Some Turkish geothermal fields already emit up to 1800gr/kWh of CO_2, which sums up to almost twice the emissions from coal burning plants (32). These high CO_2 levels are a result of the carbonate host rocks in, for example, the Büyük Menderes and Gediz Grabens, which are both major production locations of geothermal energy. These reservoirs contain CO_2-bearing rocks like marble and limestones. Lower enthalpy sites emit more CO_2 per kWh, because less geothermal brine is used per produced kWh of electricity as temperatures increase. However, the discussion on the sustainability of geothermal power plants in Turkey is still ongoing as some suggest that CO_2 emissions from geothermal sites are anthropogenic based and not re-generated, as is common in fossil fuels. Some suggest that natural CO_2 is embedded in the fluids and that the power plants convey it into the atmosphere (113). In these sites natural emissions have increased drastically after the installation of a geothermal power plant. Others state that some power plants increase CO_2 emissions (110), which makes it an anthropogenic environmental problem.

CH_4

Next to CO_2, CH_4 is a GHG that is generally present in geothermal fluids (110). Its global warming potential is 28 times stronger than that of CO_2, so CH_4 can contribute significantly to enhanced GHG emissions from geothermal energy production (111). This effect is stronger because CH_4 traps thermal radiation more efficiently than CO_2 does. CH_4 gases are most frequently hosted in sedimentary reservoirs that contain hydrocarbon resources, and less commonly in geothermal resources (114). The CH_4 in geothermal systems can have different origins, including organic carbon in rocks and sediments or high-temperature magmatic carbon in rocks (115). It was found from isotopic data that these magmatic CH_4-sources are often a result of mid-oceanic rifting, so they can be expected at locations that are (former) mid-oceanic rifting zones. The CH_4 that is of organic origin can be expected to occur more frequently in reservoirs where this organic carbon content in the source rock is higher.

Whereas the concentration of CH_4 does not exceed 5% in the Indonesian and Turkish samples, its concentration is between 30 and 90% in the Dutch geothermal wells. This risk of enhanced emissions is therefore highest in the Netherlands. A detailed study was performed by TNO about the sustainability of geothermal energy in the Netherlands (58). This study showed a relation between the geothermal water and methane production, depending on the age of the producing formation. This relation differed from 1:3 in formations of Permian age to 1:1 in formations of Jurassic and Cretaceous age.

The emissions of methane are a major side effect of the production of geothermal energy in the Netherlands. This gas production has a significant effect on the sustainability of the geothermal systems (58). Currently most of this CH_4 gas is burned, which results in significant CO_2 emissions that range from 2.2 to 7.5 kg of CO_2 per GJ produced heat (58). Possible solutions to this problem are the conversion of the CH_4 gas into natural gas, or by pumping the CH_4 gas back to the reservoir.

Aluminum

Waters that are rich in Al are recognized as toxic for freshwater organisms and a major problem in agriculture because it can lead to fish extinction in combination with acid rains (116). For humans Al toxicity can have serious effects on blood, brain and bone health (84). Al is a major constituent of the earth's crust and is a common component of many principal minerals at surface and subsurface conditions (117). Excessive Al concentrations (> 0.1 µg/mL) are present in waters with a pH below 5 (118). These conditions typically occur in acid spring waters and volcanic regions (118).

The percentage of samples in which the Al guideline value was exceeded is 28% in Indonesia and here the guideline value is exceeded by up to 1500 times. Such high Al concentrations in Indonesian sites were studied previously by Rahayudin *et al.* (119). They found that the high Al concentration is a result of active interaction between acidic volcanic water and wall rock, mainly andesite. The guideline value in Turkish data is exceeded by 5.6% of the samples, which are a factor of up to 6 times too high. In the Dutch samples the guideline value was exceeded in one out of two samples by a factor of less than 2. The small number of samples makes it hard to draw any conclusions on the environmental risk of aluminum contamination, but does indicate a considerable environmental risk. Altogether, the risk of Al contamination is considered high in Indonesia, moderate in Turkey and low in the Netherlands.

Arsenic

Even though human beings are exposed to As through their food intake on a daily basis, the most adverse effects of As intake are seen after exposure from drinking water. Elevated levels of As in ground and drinking water can pose potential human health concerns and hazards, including cancer, vascular diseases and hyperkeratosis (80). As is a very common component of active and fossil geothermal systems. High As concentrations were found previously in geothermal fluids throughout the world (120).

The As guideline value is exceeded in 17% of the Indonesian samples, with one extreme value that is almost 2500 times the guideline value. A study on As concentrations in geothermal systems in West Java (121) shows that most thermal fluids contain low concentrations, but some contain higher concentrations of up to 2.6 mg/L, which is 260 times the guideline value. Here, it was typically found that Cl waters contain a high amount of As, and SO_4 and HCO_3 type waters contain low As concentrations. The authors concluded that boiling of the geothermal water increases the As content, and dilution by other fluids decreases it. A New Zealand study supports this positive correlation between high As and Cl content related to a geothermal reservoir (122).

The guideline value is exceeded in 13% of the Turkish samples, by a factor of up to 9. Different research studies on As contamination in Turkey recorded an increased As concentration related to geothermal activity (101) (123) (124). These were either observed in geothermal waters themselves, or in spring and shallow groundwater samples that are in direct contact with or influenced by geothermal fluids.

In one out of the two Dutch samples the guideline value is exceeded by only a small percentage. The limited data makes it challenging to assess the risk in the Dutch geothermal systems. According to the study by Stuyfzand *et al.* on As contamination in the Dutch drinking water supply, the current concentrations are well below the maximum concentration limits. They reported As concentrations in the range of <0.1 to 1.500 microg/L in Dutch groundwaters (125). Altogether, the environmental risk of As contamination related to geothermal fluids is high in Indonesia, moderate in Turkey and low in the Netherlands.

Cadmium

The toxic heavy metal Cd is known to be an environmental pollutant and inhalation of Cd has been related to kidney and respiratory diseases. In animals Cd has also shown to be a developmental toxicant that can result in fetal malformations, but no evidence of this exists in human studies yet (83). Cd concentrations are generally higher in sedimentary than in igneous or metamorphic rocks (126). Since Cd is one of the most mobile heavy metals in the environment, the Cd concentration in the host rock has a major effect the concentration in the geothermal fluids.

The guideline value for Cd is exceeded in 2% of the Indonesian samples by a maximal factor of 3. The number of Cd measurements in Turkey and the Netherlands is limited (only 2 and 1), but the guideline value is exceeded by factors 16 to 34 in these samples. Therefore, the environmental risk of Cd contamination is high in Turkey and the Netherlands, even though the limited amount of samples restrict a proper comparison. The risk in Indonesia is relatively low.

Fluoride

F in synthesized for intentional use such as dental products, but can also negatively affect flora and fauna. For humans F has beneficial effects on teeth and bones in low concentrations, but excessive exposure in drinking water can result in teeth decay, osteoporosis and damage to intestines, the nervous system and muscles (82). For example, F contamination in drinking water is considered a major health problem by the United Nations Development Program (127) because it causes fluorosis in different regions in Turkey. High F concentrations are likely supplied by HF gas that ascends from deep volcanic activity, because HF is one of the most abundant volatile gas elements from magma (128).

The drinking water guideline value for geothermal waters in Indonesia is exceeded in 43% of the samples by a factor of up to 14, therefore the risk is high. A previous study on an Indonesian site with high F concentration found that this high F concentration was directly related to volcanic activity on the site (119). The environmental risk from F in Turkey and the Netherlands could not be assessed because there were no data available.

Mercury

Hg tends to settle in water as methylmercury, a highly toxic mineral that mostly accumulates in fish (85). In humans, methylmercury toxicity is associated with damage to the nervous system and developmental neurotoxicity. Hg occurrence in geothermal systems is related to the vaporization of volcanic gases into the geothermal water (121).

The environmental risk of Hg pollution in Indonesia and Turkey is not assessed because there were no data available. However, Herdianita & Priadi (121) describe mercury concentrations of more than 125 ppb in the soil of a vapor dominated geothermal system in West Java, Indonesia. From the Dutch data it is clear that there is no risk, because the drinking water guideline value is not exceeded in any of the samples.

Lead

Pb is known to be present in many everyday products like cosmetics, batteries and jewelry, but is also toxic to humans and especially children (129). The effects on human health include developmental neurotoxicity, reproductive dysfunction and toxicity to kidneys and blood (81). Lead is the most abundant of the heavy metals and is known as a hydrothermal deposit. This means that it leaches from hot aqueous fluids in the subsurface (130).

In the Indonesian samples 7.7% exceed the drinking water guideline value for Pb by a factor of up to 15. In the Turkish samples this is the case in 83% of the samples up to a factor 100. From the Netherlands one of the three samples exceeds the guideline value for Pb by a few µg/L, so the environmental risk here is considered low. However, the limited number of samples restrict a proper comparison for the Netherlands. The risks in Indonesia and Turkey are respectively considered moderate and high.

The conclusions from this sections are summarized in Table 5-1 in terms of the relative environmental risk of each toxic gas and element that was studied. These risks can be prevented by operators through the employment of high quality drilling techniques and wells in which the risk of leakage is minimized. As the equipment and knowledge will continue to improve in the future, the aim is that this will also decrease the environmental risks. Another prevention method is through the implementation of reinforced law and employment by government institutions (8). These can base the grant of geothermal permits on a so-called prevention ladder, that needs to be set up prior to the permit application. An example of such a ladder is from the Dutch drinking water policy and consists of four stages that are respectively (1) risk prevention; (2) procedure at source; (3) contamination control and (4) enhanced purification (8). The policy and supervision of geothermal projects need to be implemented into this ladder in order to closely monitor environmental risks in geothermal operations.

Table 5-1 Relative risk assessment of toxic gases and elements. Each risk is assessed relative to the risk in the other two countries. Some risks are not assessed (n.a.) because there was no data available.

	Indonesia	Turkey	Netherlands
H_2S	High	Moderate	Low
CO_2	High	High	Low
CH_4	Low	Low	High
Al	High	Moderate	Low
As	High	Moderate	Low
Cd	Low	High	High
F	High	Low	n.a.
Hg	n.a.	n.a.	Low
Pb	Moderate	High	Low

Risk perception

Respondent profile

A general respondent profile is sketched from the questions in the first two sections of the survey. The majority of the respondents followed their education at master level and have their professional expertise in technology. On average, they rate their level of knowledge on geothermal energy moderate to high and they are from regions that are major geothermal energy production regions, which relates to their affiliation with the geothermal industry. These regions are Java and Sumatra in Indonesia, the Aegean in Turkey and the West of the Netherlands

General opinion on geothermal energy

The respondents general opinion on geothermal energy was studied through two statements about the trust in and concerns about the development of geothermal energy. From the responses to the first statement, it is concluded that the majority of the respondents agree that geothermal energy is suitable as an alternative energy resource for the future. This response was expected because the respondents are affiliated with the geothermal energy industry. The Indonesian respondents agreed slightly stronger to the first statement than the Turkish and Dutch did, but the potential capacity of geothermal energy in Indonesia is also one of the highest worldwide (43). On the contrary, the Indonesian respondents were much more divided on their overall concerns about the future development of geothermal energy in their home country, as they indicated in statement 2. On average these were higher than the concerns in Turkey and the Netherlands.

The general opinion on geothermal energy in the three countries can differ because of a broad range of factors. The local cultural dimensions can affect the way the respondents answer the survey questions. For example, a highly masculine culture can induce overestimation of the respondent's self-rated level of knowledge. This was observed among the Turkish respondents. Their country ranks highest on the masculinity dimensions, and the Turkish generally indicated to have low concerns about the risks (26).

Personal experiences and media framing of geothermal energy changes the public perception and thereby affect the way the public reacts to new and current projects (131). An accurate description of media framing in a country requires a detailed study on a broad range of local news articles and the popularity of geothermal energy, like the study by Stauffacher *et al.* (131).

What factors are considered important for the development of geothermal energy?

The respondents were asked to indicate how important they consider a number of factors in their opinion on geothermal energy. In the entire sample, the factor sustainability was rated the most important factor, but the responses also varied. This is because the trend clearly differs between the Indonesian, Turkish and Dutch respondents. Where the Indonesian and Dutch rate sustainability as very to extremely important, this was considered not at all to slightly important among the Turkish respondents. The lack of environmental awareness in the Turkish culture was previously found to be a related of the lack of future orientation, masculine management methods and survival concerns among individuals (132).

The rating of the factors pollution, production of energy per land area, costs and the continuity of energy supply have an increasing trend towards extremely important over the entire population. Though nuisance is considered a slightly to very important factor among the majority of the respondents, they hardly consider it an extremely important factor. When the ratings of these factors are studied separately for each country, the trends are similarly increasing in Indonesia and the Netherlands, but much more divided among the Turkish respondents. In contrast, the Turkish consider the factor nuisance relatively more important than the other respondents. Therefore, the general values in geothermal energy are different among the Turkish respondents compared to the Indonesian and Dutch.

The difference in perception on these factors can be a result of demographic or cultural aspects. Demographic aspects are, for example, the country's population density or economic wealth. The population density is related to the perception of the factor 'energy production per land area' (133), and this factor is considered least important in Turkey, which has a population density of 106 per km^2 (134). The land area is considered more important in Indonesia and the Netherlands, where the population density is considerably higher: 141 per km^2 in Indonesia, with 1121 per km^2 in Java specifically (135), and 424 per km^2 in the Netherlands (136). Another impact on the perception is the local economic wealth (25). The Indonesian respondents consider the costs a very to extremely important factor, and the country's economy is ranked the 104th of the world by The World Bank (137). The Dutch and Turkish respondents rate this factor as less important, and they are respectively ranked 13th and 52nd.

Cultural aspects are heavily affected by the local education programs and media framing. There is no correlation between the general perspective and level of education, but the local energy education through schools, media and forums can be a major influence on the public awareness of a renewable energy technology such as geothermal energy (138).

The type of geothermal system can affect the local perception of geothermal energy through their different risks. For example, shallow geothermal systems are known to have a higher risk of pollution (19) and for large-scale surface installations their visibility is criticized by some residents because of the disturbance of scenic or historical sites (133). Though the installation process might lead to nuisance, deep geothermal systems generally only have minor direct nuisance impacts on the surface when they are in operation. Also, alternative renewable energy resources that are already in place affect how the local people look at geothermal energy. In the Netherlands wind power installations are sometimes under debate because of their surface impact and sight and noise nuisance. Compared to wind power installations, the surface installations for geothermal energy in the Netherlands are hardly visible.

What risks are perceived strongest in geothermal energy development?

The respondents were asked to indicate how concerned they are about five potential risks in geothermal operations. In the statement about their concerns on the development of geothermal energy, the majority of the respondents indicated that they are generally not concerned about it. Besides, the majority of the respondents was 'not at all concerned' about the named potential risks. This is as expected because they are affiliated with the geothermal industry either through their professional careers, education or interest. From the correlation coefficients it became clear that there is a weak to moderately inverse correlation between the respondents level of knowledge on geothermal energy and their risk perception. This indicates that the concerns are lower when people are more knowledgeable about geothermal energy.

From the overall results, the concerns are lowest about sight pollution, and highest about groundwater contamination, but the trends differ between the three countries. The responses are most concentrated among the Dutch responses, with sometimes over 80% of the respondents that chose the same answer. Where the majority of the Dutch respondents have relatively low concerns for each potential risk, this trend is similar among the Turkish responses but there are larger concerns about groundwater contamination and seismicity. The levels of concern are most divided among the Indonesian respondents, whose concerns are most scattered (each between 5% and 37%). The difference in data concentration between the Indonesian and Dutch responses can be related to the country geography. Indonesia is approximately 46 times larger than the Netherlands is, so the cultural differences are presumably larger as well (26). Altogether, the concerns are lowest among the Dutch and highest among the Indonesian respondents.

The potential risks were perceived differently in the three countries. For example, the concerns about groundwater contamination and seismicity are relatively high among the Indonesian respondents compared to the Turkish and Dutch ones. In the Netherlands, however, seismicity is the main risk that is assessed for improving he public perception on geothermal energy. This does not correspond with the survey results, but is likely related to the survey population. These are people affiliated with the geothermal industry, and therefore their opinion is affected less by media framing or previous events resulting from gas extraction in the Northern province of Groningen (139).

Figure 5.1 Protests in Jakarta in August 2017. They were held after the local community of the Karangtengah village in Central Java found out their main fresh water resource was contaminated from a nearby geothermal power plant. Modified from (134).

The concerns about air and sight pollution are relatively low among the Dutch respondents. In this discussion the main focus is on the risks of groundwater contamination and air pollution, because these are the environmental risks that are most closely related to the geochemical analysis that was performed previously. Therefore, these are considered most relevant.

The differences in risk perception can be a result of specific events that the local population was confronted with in the past, or the way an energy resource is framed in the media. For example, a fatal incident of H_2S leakage from a geothermal power plant in Sumatra, Indonesia, led to five deaths and 46 hospitalizations (33). Incidents like this can increase concerns about the risks in geothermal operations. An example of the influence of the media on public perception is the news about the protests in Jakarta, in August 2017 (140). This protest was organized after the people of the Karang Tengah in Central Java learned that one of their key freshwater resources was contaminated by debris from the installation of a geothermal power plant (Figure 5.1). Protests attract attention and can thereby alarm other people about the potential risks of a new energy resource such as geothermal energy. The public discussion on the sustainability of Turkish geothermal operations due to high CO_2 emissions (32) can also result in increasing concerns among the population.

The difference in risk perception of geothermal energy can be related to the type of geothermal systems that are in place. The Dutch installations are all deep geothermal systems whose surface installations are relatively small and that have no steam discharge into the atmosphere or large converter installations. This decreases the perceived risk of sight pollution in the Netherlands, whereas the shallow and surface geothermal systems in Indonesia and Turkey increase the risk of landscape pollution. Active water and steam discharges from high-temperature geothermal systems have a higher environmental risk that is directly visible at the surface. This visibility in turn also affects the risk perception on sustainability and pollution of the geothermal systems.

Integration of all results

There are several interesting trends observed when integrating the natural and social disciplines of the study. Overall, the public concerns are stronger with increased environmental risks, but there are numerous exceptions and outliers to this relationship that will be discussed in this section.

In Indonesia concerns about the development of geothermal energy are strongest, especially on groundwater contamination and air pollution. The Indonesian population has a strong value of sustainability, related to previous incidents and the visibility of geothermal energy in the landscape, which negatively affect the risk perception. Their concerns are reasonable, because the geochemical analysis showed that the active volcanic systems in the country can induce increased levels of pollutants in the geothermal fluids. This is for example seen in the high risk of H_2S emissions from the geothermal power plants. The concentrations of toxic elements in Indonesia more frequently exceed the guideline values by the WHO (86) than in Turkey and the Netherlands and these exceeding values are typically found in recurring fluids. By studying the fields with high H_2S emissions more in-depth, it becomes clear that these samples are from both springs and wells, and typically found at low pH, which indicates the volcanic source. An example of such a well sample is well 12 on Lahendong. The gas from this well contains 72% H_2S, has a pH of 4.6 at the depth of 1625 meters. At depth more chloride waters are common, but the volcanic activity clearly has an effect on its geochemical properties and environmental risks. In contrast, the spring Ciater on Java has an even lower pH of 2.26 and a salinity of 4365 mg/L. The high salinity of the fluid induces an increased amount of pollutants and thereby increases its environmental risk.

The Turkish population indicated that their general values of sustainability and pollution in geothermal operations are low to moderate, and also their concerns about most potential risks are low. They have moderate concerns about groundwater contamination and about pollution. The samples with a high environmental risk of the toxic elements As, Cd and Pb have a neutral pH and of a salinity ranging from 100 to 3500 mg/L. Therefore, the pollution from these samples is not as clearly related to the volcanic system type as they are in Indonesia. The Turkish population is also less concerned about air pollution than the Indonesian population is, whereas the CO_2 production per kWh of energy produced is 10 to 25 times higher in the Turkish geothermal operations. However, CO_2 is more indirectly dangerous to the environment than H_2S is, because H_2S has shown fatal results within seconds after exposure and excessive CO_2 emissions are mostly related to the enhanced greenhouse effect.

The Dutch population generally does not have high concerns about the potential risks from geothermal operations. Their concerns about air pollution are very low, whereas the risk of CH_4 production is much higher than in Turkish and Indonesian geothermal operations. The Dutch population is most concerned about groundwater contamination, and this concern was found to be righteous by the 2021 report on drinking water quality threats as a result of geothermal drillings in the Netherlands (8). This report was also shared in the Dutch national news (141), and therefore it is possible that this report affects the Dutch risk perception on geothermal energy, specifically on groundwater contamination. The risk perception can differ largely from Indonesia and Turkey because there are only deep geothermal systems in place in the Netherlands and the surface installations for heating systems are generally smaller than they are for electricity generation. Besides, leakage from deep geothermal reservoirs has a less direct effect on groundwater and air pollution simply because of the longer pathway. However, the Dutch Court of Audit (Algemene Rekenkamer, (8)) describes their concerns about the pollution of subsurface drinking water reserves.

The integrated approach in this research offered the opportunity to study the environmental risks from a new, innovative perspective in which two disciplines are integrated. By studying a large data set with samples from three countries, it is possible to provide an accurate description of the differences in fluid types, to make generalizations in the fluid characterization, but also to calculate percentages and factors by which the environmental pollution limits are exceeded. As the geochemical analysis is combined with the local perception on geothermal operations and the risks involved, the three countries can be compared in terms of whether the risk assessment and perception are equal or not. The type of geothermal system that is in place has a direct effect on the environmental risks from geothermal operations, but also on the perceived risks in different cultures. This relation is altered in specific settings due to media framing and previous incidents, like the difference in risk perception and assessment of air pollution between Indonesia and the Netherlands.

Limitations and recommendations

This study faced numerous limitations over the course of the research, which mainly concern the data sets and research methods. The data collection phase was carried out through literature and contacts that assisted in setting up an extensive data set. The data set is limited by the different amounts and types of data from the three countries, which also influenced the quantification of the environmental risk assessment. When performing a geochemical analysis of geothermal fluids, some properties are practically always measured, like the pH and temperature. However, the concentrations of specific elements, like Hg, or of specific valence types, are hardly measured because this information is not essential for the production report of the operator and owner and they require relatively expensive measurement tools. However, polluting gases, elements and their valence types are essential in the risk assessment because for example arsenite (As^{+3}) is more toxic than arsenate (As^{+5}) (125). Therefore, a more detailed approach to the geochemical sampling can help improve our understanding of environmental risks in future research. This approach can be improved by performing a similar risk analysis on more detailed sample measurements.

Though the samples are from locations from throughout each country, these are still a selection of samples that are not completely representative of the entire country. This can be improved by equally dividing the geochemical samples across the country.

This study analyzes the environmental risks in different locations, but it is also possible to analyze the seasonal changes of the environmental risks by studying samples that were measured at different times. Especially in shallow and surface geothermal systems large variations in environmental pollution can occur over the seasons (142). Besides the geochemistry of the geothermal fluids, we can continue to study the external effects on the fluid composition. This is for example affected by the influx of sea water through faults (101), or as a result of anthropogenic activities, like is the case for Pb contamination in the Turkish Salihli geothermal field as a result of the local agriculture (143).

To assess the environmental risks in Chapter 0, the concentrations from the data samples were compared to drinking water guideline values set by the World Health Organization (86). These guidelines are a major influence on the results of this study because different guideline values would result in a different environmental risk assessment. The WHO drinking water guideline value focuses on preventing threats to human health but do not specifically focus on plant and animal health, which are often more vulnerable than humans. This is either because they are exposed more continuously to the pollutant or because their defense system is less strong. Some countries set their own drinking water guideline values instead of using the one set by WHO. This could be improved by studying the relation to different guideline values, and thereby performing the risk analysis under different conditions.

Another opportunity to further explore the environmental risks from geothermal fluids is the correlation between different pollutants. Something similar is done in West Java, by a study on As and Hg concentrations in geothermal systems (121). Here, an exponential relationship was found between the As and Hg concentrations. However, the study also mentioned that this finding needs to be confirmed through further studies, especially on the Cl type thermal waters. Therefore, the relations between different pollutants in geothermal fluids can be confirmed by studying more geothermal fluid samples with complete data sets.

In the social perspective, the data obtained through the survey contain the answers from 89 respondents, but the sample size of 30 responses was not reached for Indonesia and Turkey. This decreases the reliability of the results in these countries. Although biased language was avoided in the survey, the questions can still be misinterpreted depending on the translations or the reader his interpretation. Besides, the explanatory text in the survey contains an example from Turkey. This can lead to biased opinions among the Turkish respondents, because the example is closer to their direct environment.

The anonymity of the survey makes this method easy to perform in terms of privacy regulations, but also decreases the control on who the respondents are. The respondents were selected by the organizations and contacts by snowball sampling. Therefore, these contacts had a major influence on the selection bias of the respondents and it cannot be completely certain that they are part of our population. Besides sampling a broader or more specific audience, future research can be improved by combining different research techniques. Quantitative research can be supplemented by qualitative research, for example by carrying out individual interviews. This qualitative research can create a more detailed understanding of the risk perception and minimizes the limitations to the quantitative research. Furthermore, the population of the social study can be extended to people that are not affiliated with the geothermal sector, so that one can also study the external effects on the public perception in more detail. This kind of research will also contribute to an improved interpretation of this study's survey results.

To perform an interdisciplinary research, extensive knowledge on the different study domains is required. This can be challenging, but also opens up for new research opportunities. In this study, the main discipline of the author is in the natural sciences domain, which means there was no formal training in the social domain. Therefore, other choices could have been made in the surveying if there was more experience in the social domain. This could have led to the formulation of different questions or a different approach to the survey distribution methods. However, since the combination of the natural and social sciences in this study are what makes it unique, it is recommended for future research to form a larger research group that combines experts in both domains. In that way, one can perform more extensive and detailed studies in the interdisciplinary field of understanding risks in geothermal operations.

Since the most important factor on the acceptance of geothermal energy is landscape and environmental protection, the public needs to be assured that this is under control (144). This can be achieved by more actively involving local communities in geothermal projects and by communicating the risk management plan to them in a concise and comprehensive manner. This risk management plan should contain detailed information about the scope of environmental risks and how these are mitigated, and it can thereby create an active debate in which all stakeholders can take place (145). This asks for active participation of operators in setting up these plans, but also in involving the local community. They can achieve this by sharing results in a transparent way, by holding preliminary meetings with community leaders or community meetings that are open to the public (146). Local governments play a role in this process as well, since they are in closer contact to the local community. Besides, the national government needs to implement closer environmental regulations for operators and to inspect whether these are followed by operators. These regulations have to include limits for the toxic gases and elements that are measured in the geothermal fluids, but also has to describe how the environmental risk is controlled in terms of well integrity and pressurization of the geothermal fluids and how large the risk of groundwater contamination or air pollution is in case of an incident.

6. Conclusions

The objective of this research is to provide a demonstration of the environmental risks related to geothermal energy production and to correlate these to the perceived risks among the local geothermal community. The environmental risks are therefore studied from both the natural and social sciences perspective in three different country settings. The combination of disciplines and study areas allows this research to offer an innovative perspective to understanding environmental risks, more specifically groundwater contamination and air pollution. Though the environmental risks from geothermal operations mainly depend on the integrity of the installations, they vary largely in different geothermal systems as well. The types of systems in place have a direct effect of the environmental risks from geothermal operations, but also on the perceived risks in different cultures.

Research findings

The active volcanic geothermal systems in Indonesia contain a broad range of fluid types that are strongly correlated to the sample types, which are well and spring samples. The spring samples are immature HCO_3 fluids and the well samples are mature Cl fluids. Besides this general trend, a number of SO_4 samples are found throughout the country. Their occurrence is related to volcanic activity and results in a low pH and high risk of excessive H_2S emissions. The high-temperature systems in Indonesia induce a high risk of the contamination of a number of toxic elements: Al, As, and F. The occurrence of these elements is closely related to volcanic activity. The high environmental risks are familiar among the Indonesian geothermal community, whose concerns about groundwater contamination and air pollution are high compared to the other two countries.

The majority of the Turkish carbonate systems host HCO_3 fluids and minor amounts of SO_4 and Cl fluids. The HCO_3 fluids are dominant among both well and spring samples, but slightly more dominant in the spring samples due to increased groundwater mixing. The high concentration of HCO_3 in produced geothermal fluids increases the risk of CO_2 pollution because it is released in the precipitation reaction that occurs in the installation. Toxic elements also increase the environmental risks in the Turkish geothermal operations, because relatively high concentrations of Cd and Pb are measured. The Turkish geothermal community is, compared to the other countries, least concerned about the potential environmental risks in geothermal operations. Their main concern is groundwater contamination and the least is air pollution. The low concerns about air pollution are in contrast with the high risk of CO_2 pollution in Turkey. This is potentially a result of the community their low value of sustainability in geothermal operations and the fact that there are no previous incidents in which CO_2 pollution had fatal results.

The sedimentary systems in the Netherlands show a uniform trend of Cl fluids that are in partial to full equilibrium with their host rock. The trend here is relatively uniform due to the inactive tectonics in the region and the small country size. The risk of CH_4 pollution from the Dutch geothermal systems is very high compared to the other countries, whereas the Dutch community is not at all concerned about the air pollution risk. The risk of pollution from toxic elements is low in most samples, but the community is moderately concerned about groundwater contamination.

Environmental risks can differ largely among locations and times, especially in locations with active deformational events or high regional variability. Therefore, the behavior of the geothermal system types that are described in this study can only be adopted for other locations to some extent. Assessing the geothermal system type for other locations will always require a thorough desk and field study on the site specifics.

The integrated approach in this research offers the opportunity to study environmental risks from an innovative perspective. The extensive geochemical data set makes it possible to perform a country-wide analysis of geothermal systems, but also requires generalizations and detailed studies on specific samples. By combining the geochemical data set with the data gathered in the survey, the two disciplines can be integrated to a detailed understanding of environmental risks; from the source of concerns about environmental risks to whether the risk perception and assessment are equal.

In conclusion, the geological settings of a geothermal system are a major control on the geothermal fluid type and environmental risks. Perceived risks increase with higher environmental risks, but they are also largely dependent on previous events, media framing and the level of knowledge on the subject. Generally, respondents with a higher level of knowledge on geothermal energy were less concerned about the risks in geothermal operations. It is essential to equalize the actual and perceived risks when upscaling geothermal energy to a major worldwide energy resource.

Opportunities for the future

To achieve an equalized risk assessment and perception, a close cooperation between operators, local community and government institutions is required. As the operators continue to implement high-quality drilling techniques and equipment, they need to actively involve local communities in the public debate. This will make the public risk perception closer to the risk assessment. Besides, the government needs to ensure that the geothermal permits are conform the environmental safety limits. These require a special focus on the risk source, because prevention is better than cure.

The environmental risks in geothermal operations can be prevented through a comprehensive assessment of the geothermal fluid composition, geological settings and the target and surrounding subsurface formations. The more is known about the fluid that is produced, the better the environmental risks can be predicted. Important properties of the produced fluid are the fluid source and pathway, state of the fluid and production process. The fluid source and pathway are major controls on the dissolved (toxic) elements that are present in the geothermal fluids. These either result from the fluid source or they have dissolved from surrounding rocks that are passed along the fluid pathway. The state of the geothermal fluid is a major influence on the pollution risk, because gases and volatile liquids escape and pollute their environment more easily. As pressures and temperatures alternate throughout the geothermal installations, the state of the geothermal fluid can change in the different stages of the production process. If fluids become more volatile when they are produced to surface conditions, the pollution risk will increase there. Once production commences the pollution risk from the installation can be decreased by the implementation of high-quality production techniques and equipment. These make the geothermal installation a fully closed-loop system in which the leakage of gases and liquids from the geothermal fluids is minimized.

The risk perception in this survey was measured among a population that is affiliated with the geothermal industry already. Even though this population is relatively well aware of the environmental risks, there is a clear difference between the risk perception in each of the three study areas. This is predominantly a result of cultural values, prior incidents and media and educational framing, but also by the visibility of the environmental effects. Where the consequences of the environmental risks in geothermal operations are more visible, like in Indonesia, people are more aware of the risks. On the contrary, the indirect environmental risk of CO_2 pollution in Turkey or CH_4 pollution in the Netherlands, are experienced less strongly by the survey population. If these pollution risks will have severe or fatal effects on our future health or climate goals, they will require additional media or educational attention.

As the geothermal industry is upscaled further throughout the world, environmental risks will become more visible to the public. For example, the risk of groundwater contamination is most severe and under heavy public debate in Indonesia, a country that is producing electricity from geothermal power plants on the large scale already. The local experience with groundwater contamination here is a potential forecast for other locations that will be upscaled in terms of geothermal capacity in the future. This will require additional attention in future research, both on the specific regional settings and on the pollution trends from large-scale geothermal operations.

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Appendices

Appendix 1. Geological maps

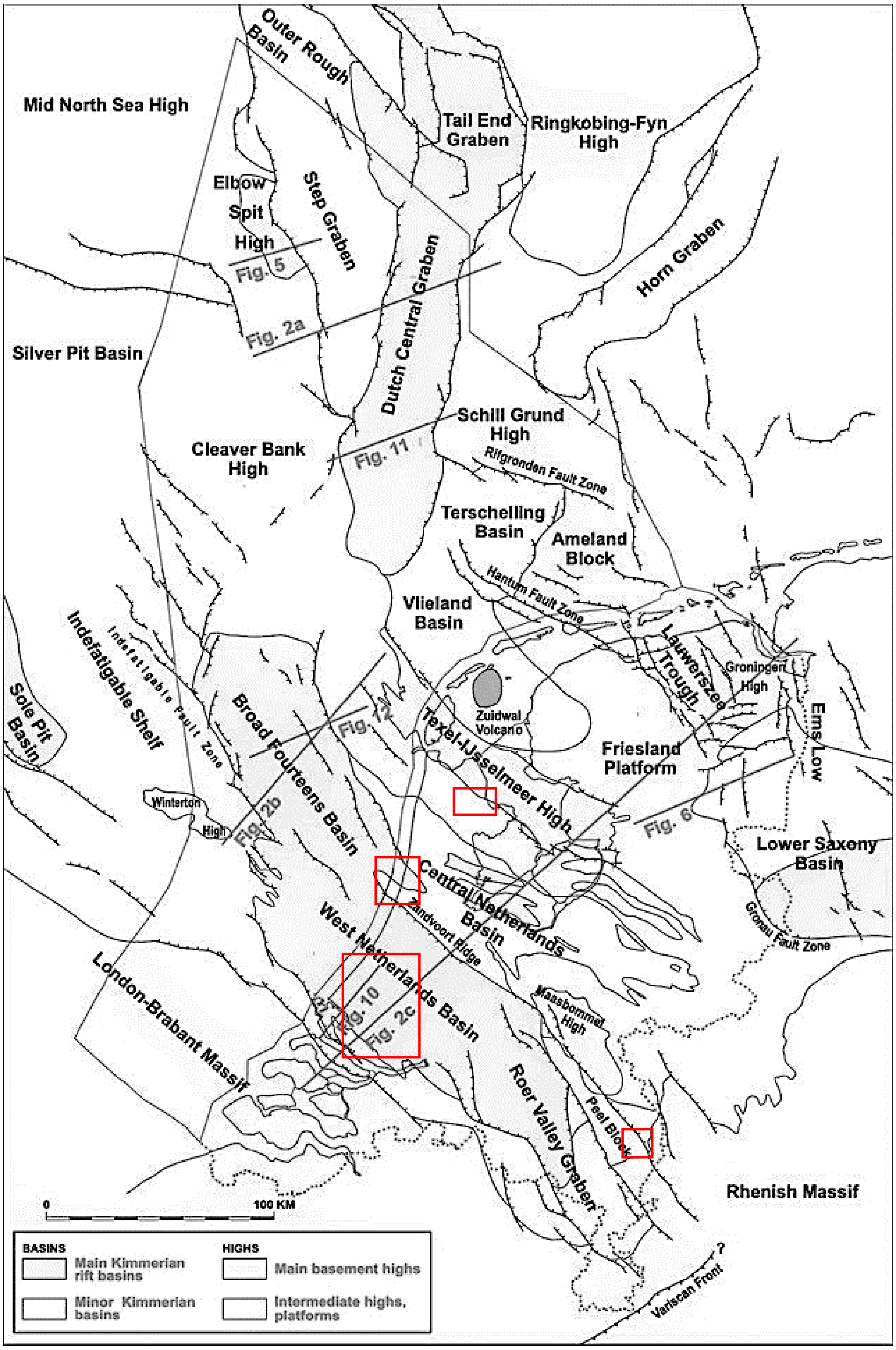

Figure 1A Geological structures in the Netherlands with the main geothermal production regions indicated in red. Modified from (38).

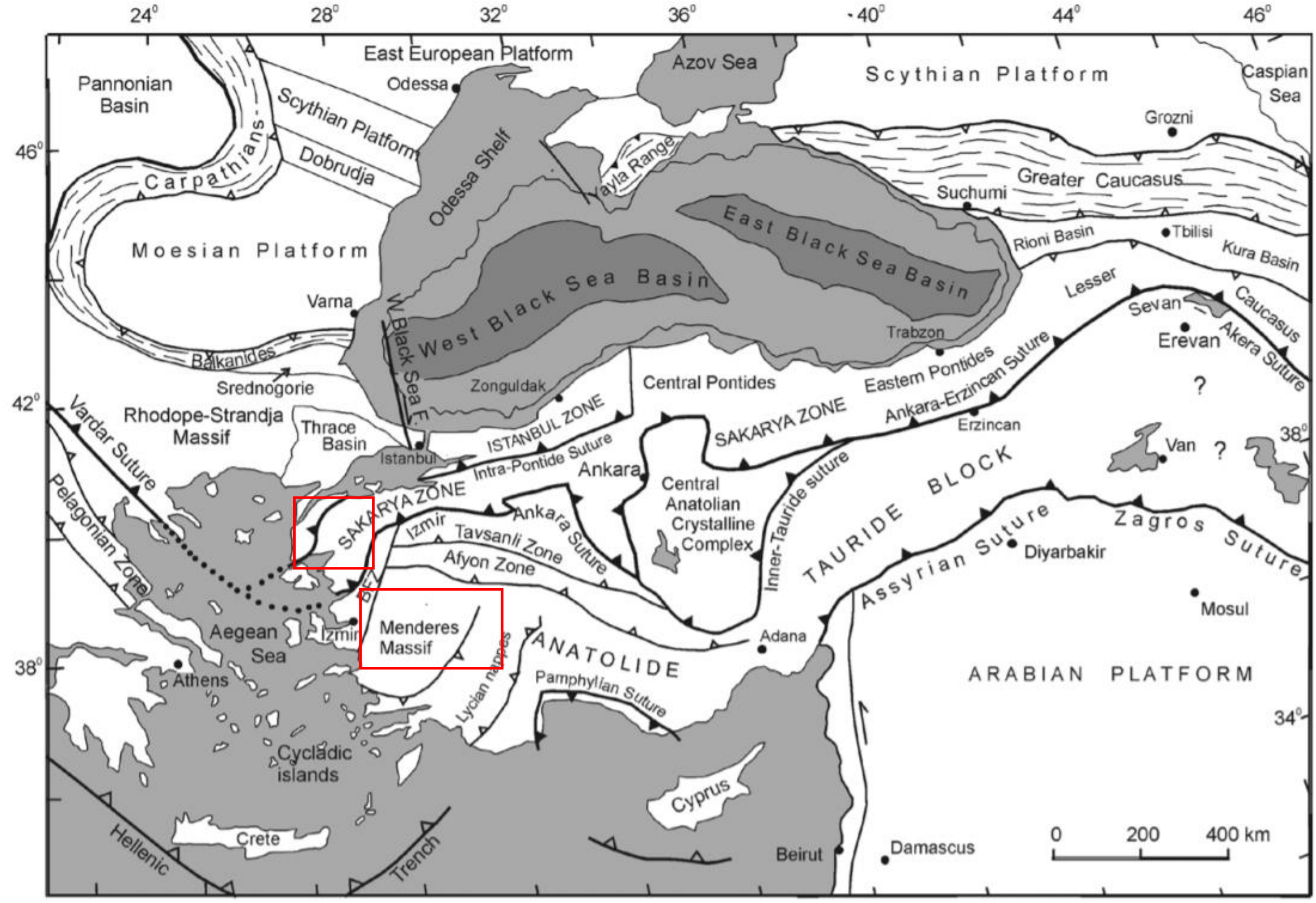

Figure 1B Crust map of Turkey with the main geothermal production regions indicated in red. Modified from (41)

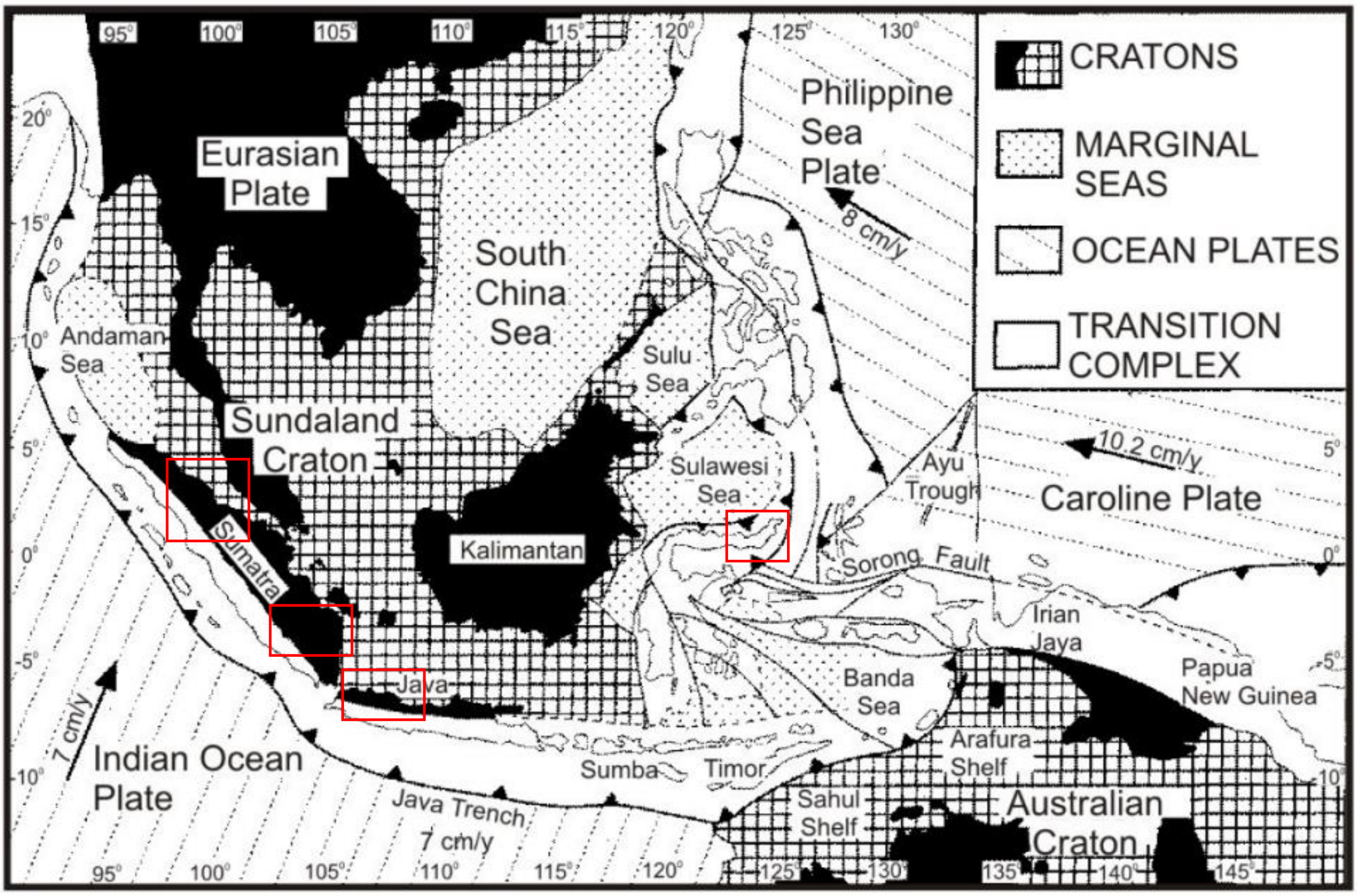

Figure 1C Crust map of Indonesia with the main geothermal production regions indicated in red. Modified from (147)

Appendix 2. Classification of geothermal systems

Table 2A Classification of geothermal systems by Sanyal (50)

Class of Resource	Reservoir Temperature	Mobile Fluid Phase in Reservoir	Production Mechanism	Fluid State at Wellhead	Well Productivity and Controlling Factors other than Temperature	Applicable Power Conversion Technology	Unusual Development or Operational Problems
1. Non-electrical Grade	< 100°C	Liquid water	Artesian self-flowing wells; pumped wells	Liquid water	Well productivity dependent on reservoir flow capacity and static water level	Direct Use	
2. Very Low Temperature	100°C to < 150°C	Liquid water	Pumped wells	Liquid water (for pumped wells); steam-water mixture (for self-flowing wells)	Typical well capacity 2 to 4 MWe; dependent on reservoir flow capacity and gas content in water; well productivity often limited by pump capacity	Binary	
3. Low Temperature	150°C to < 190°C	Liquid water	Pumped wells; self-flowing wells (only at the higher-temperature end of the range)	Liquid water (for pumped wells); steam-water mixture (for self-flowing wells)	Typical well capacity 3 to 5 MWe; dependent on reservoir pressures, reservoir flow capacity and gas content in water; productivity of pumped wells typically limited by pump capacity and pump parasitic power need; productivity of self-flowing wells strongly dependent on reservoir flow capacity	Binary; Two-stage Flash; Hybrid	Calcite scaling in production wells and stibnite scaling in binary plant are occasional problems
4. Moderate-Temperature	190° to < 230°C	Liquid water	Self-flowing wells	Steam-water mixture (enthalpy equal to that of saturated liquid at reservoir temperature)	Well productivity highly variable (3 to 12 MWe); strongly dependent on reservoir flow capacity	Single-stage Flash; Two-stage Flash; Hybrid	Calcite scaling in production wells occasional problem; alumino-silicate scale in injection system a rare problem
5. High Temperature	230°C to < 300°C	Liquid water; Liquid-dominated two-phase	Self-flowing wells	Steam-water mixture (enthalpy equal to or higher than that of saturated liquid at reservoir temperature); saturated steam	Well productivity highly variable (up to 25 MWe); dependent on reservoir flow capacity and steam saturation	Single-stage Flash; Hybrid	Silica scaling in injection system; occasionally corrosion; occasionally high NCG content
6. Ultra High Temperature	300°C+	Liquid-dominated two-phase	Self-flowing wells	Steam-water mixture (enthalpy equal to or higher than that of saturated liquid at reservoir condition); saturated steam; superheated steam	Well productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity and steam saturation	Single-stage Flash	High NCG content; silica scaling in injection system; occasionally corrosion; silica scaling potential in production wells at lower wellhead pressures
7. Steam Field	240°C (33.5 bar-a pressure; 2,800 kJ/kg enthalpy)	Steam	Self-flowing wells	Saturated or superheated steam	Well productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity	Direct steam	Occasionally high NCG content or corrosion

Appendix 3. Growth of local geothermal sectors over time

Table 3A Past developments and future ambitions of the geothermal sector in the three countries based on country updates presented at the World Geothermal Congress

Years	Indonesia	Turkey		Netherlands
	MWe	MWe	MWth	MWth
Estimated potential	**29000**	**4500**	**60000**	**31700**
1975		0.5	0	
1980				0
1983	0			
1986		20	0	0
1995	310			
2000	527	20	0	0
2005	807			
2009	1187			
2010		82		
2013				40
2015	1439	400	2886	103
2016		721		127
2018	1949			
2020	2131	1549	3488	317
Future ambitions				
2021		1650		
2025	4000	2600	7000	
2030				1585
2050	1000			6341

Appendix 4. Geographical regions

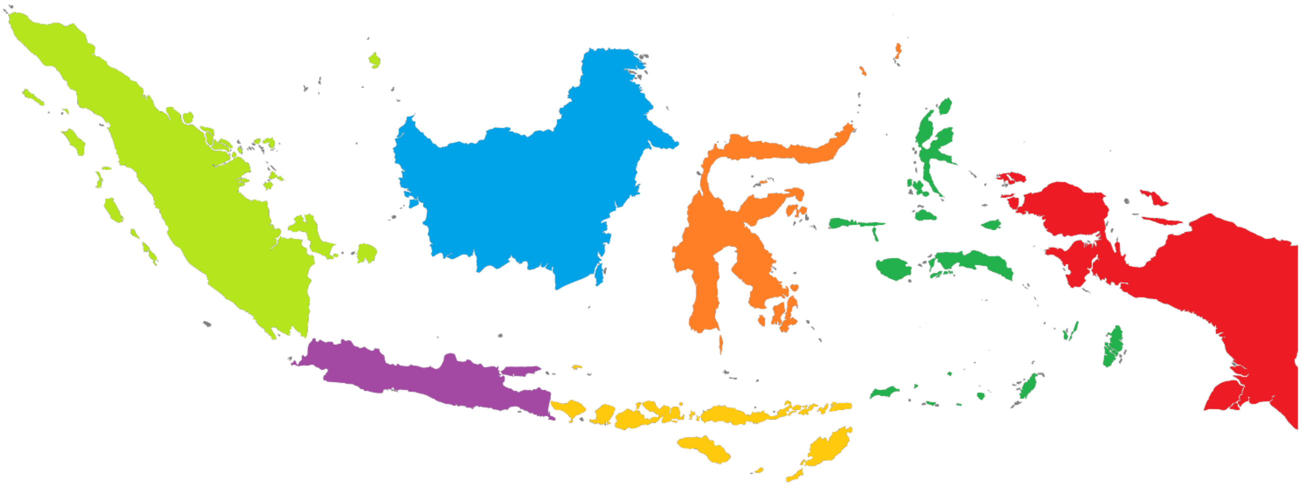

Figure 4A Regions in Indonesia according to ISO 3166-2:ID. The different regions are called Sumatra (in light green), Java (in purple), Kalimantan (in blue), Sulawesi (in purple), Nusa Tenggara (in yellow), Maluku (in dark green) and Papua (in red)

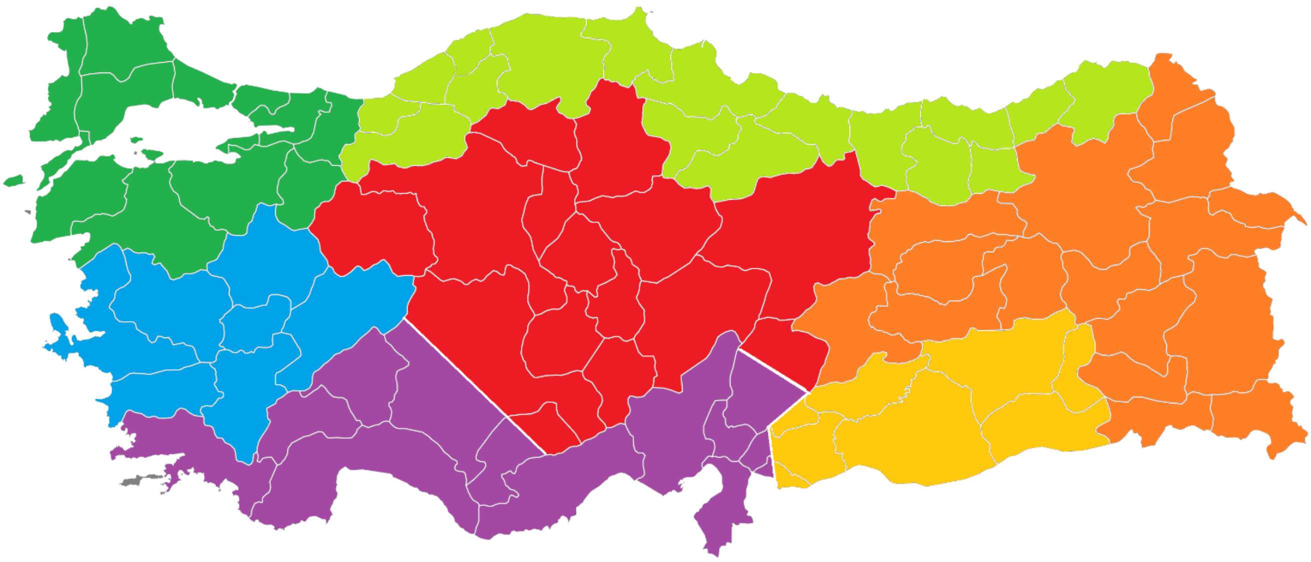

Figure 4B Regions in Turkey as presented at Turkey its First Geography Congress in 1941, in correspondence with NUTS regions (148). The different regions are called Marmara (in dark green), Aegean (in blue), Mediterranean (in purple), Black Sea (in light green), Central Anatolia (in red), Eastern Anatolia (in orange) and Souteastern Anatolia (in yellow).

Figure 4C Regions in the Netherlands according to NUTS-1 classification (148). The different regions are called North (in purple), East (in red), West (in yellow) and South (in green).

Appendix 5. Survey

Introduction statement

Dear participant,

Hereby I invite you to participate in a research study titled 'Risk perception on geothermal energy in Indonesia, Turkey and the Netherlands'. It is part of my graduation thesis at TU Delft and with this research I wish to contribute to the development of geothermal energy as a major future energy source.

The purpose of this research study is to compare Indonesia, Turkey and the Netherlands in terms of risk perception on geothermal energy. Your participation in this study is entirely voluntary, completely anonymous and you can withdraw at any time. You are free to omit any question. The survey will take you approximately 5 minutes to complete. The data collected from this survey will be stored in a private database to which limited people have access. The purpose of this research is purely research-based.

In case there are any questions about the research, feel free to contact me.

Jeanne Steijn, MSc student Geo-Energy Engineering
Delft University of Technology
German Research Center for Geosciences GFZ Potsdam

E-mail: j.a.steijn@tudelft.nl
Phone: +31 6 23 77 76 75

Section 1

The following questions are asked to find demographic information about the respondents. These questions include nationality and location of residence, level of education and expertise.

Q1 Nationality
o Indonesian
o Turkish
o Dutch
o Other, namely: ________

Q2 Country of residence
o Indonesia
o Turkey
o The Netherlands
o Other, namely: ________

Q3 Region of residence
If Indonesia is selected in Q2
o Sumatra
o Kalimantan
o Java
o Sulawesi
o Nusa Tenggara
o Maluku
o Papua
o Other, namely: ________

If Turkey is selected in Q2
o Marmara region
o Aegean region
o Mediterranean region
o Central Anatolia region
o Black Sea region
o Eastern Anatolia region
o Southeastern Anatolia region
o Other, namely: ________

If the Netherlands is selected in Q2
o North (Friesland, Groningen, Drenthe)
o West (North Holland, South Holland, Utrecht, Zeeland)
o East (Overijssel, Gelderland, Flevoland)
o South (North-Brabant, Limburg)

Q3 Background of education
o High school
o Bachelor
o Master
o PhD
o Other, namely: ________

Q4 Professional expertise
o Technology
o Science
o Policy
o Business
o Other, namely: _______

Section 2

Q5 How would you rate your level of knowledge on the following subjects?

	1 **Low**	2 **Moderate**	3 **High**
Global warming			
Renewable energy			
Geothermal energy			

Section 3

The following text gives an explanation about geothermal energy. After reading this, please indicate your answers to the statements below.

Today's energy transition calls for alternative energy sources. One of these is geothermal energy, which is produced from heated fluids that are stored in the Earth's subsurface. It can be used to generate electricity or directly for heating. Like many energy sources, there are advantages to geothermal energy but also potential risks involved. This survey is part of a technical research on the potential risks and will study how these risks are perceived.

Geothermal energy is gaining popularity due to its renewability and sustainability. Its carbon emissions are comparable to solar or wind energy, which makes it an energy source that is well preferred over fossil fuels. The amount of waste that results from geothermal energy extraction is minimal, and noise levels are only exceeded during installation, not during operation. The high efficiency of geothermal energy adds up to the limited use of land area that is needed for the installation. These advantages make geothermal energy a well preferred energy source. Worldwide there are hundreds of projects in place and over 15.000 MWe produced.

However, just like for other energy sources, it is important to study the potential risks closely. All potential risks are rated as low compared to alternative energy sources, except for noise levels during installation and potential water and air pollution. The pollution risk is correlated to the chemical composition of the extracted geothermal fluids. This chemistry depends on the local geological settings and therefore also differs per country and region. For example, marine carbonate rock reservoirs in Turkey combined with a high steam discharge has led to an increase in CO2 pollution. Likewise, the risk of groundwater contamination is reduced to a minimum in non-faulted reservoir systems in which the geothermal fluid is reinjected into the reservoir.

In conclusion both the advantages and disadvantages need to be taken into account carefully when implementing a new energy source like geothermal energy. The following questions will focus on your trust in geothermal energy and how you perceive the potential risks.

Q6 Please indicate your opinion on the statements below.

	1 **Strongly diagree**	2 **Somewhat disagree**	3 **Neither agree nor disagree**	4 **Somewhat agree**	5 **Strongly agree**
"Geothermal energy is suitable as an alternative energy resource for the future."					
"I am concerned about the future development of geothermal energy in my home country because of the potential risks."					

Q7 In the following table, please indicate how important each factor is on your opinion on geothermal energy.

	1 **Not at all important**	2 **Slightly important**	3 **Moderately important**	4 **Very important**	5 **Extremely important**
Sustainability					
Pollution					
Nuisance					
Energy production per land area					
Costs of installation and operation					
Continuity of energy supply					
Other, namely: ________					

Section 4

The survey aims to find out how the different risks are perceived in geothermal energy generation. Therefore, the following question asks you to indicate how concerned you are about each risk. Please rate your concerns about each risk in the following table.

	1 **Not at all concerned**	2 **Slgihtly concerned**	3 **Moderately concerned**	4 **Very concerned**	5 **Extremely concerned**
Groundwater contamination					
Air pollution					
Nuisance					
Seismicity					
Sight pollution					
Other, namely: ________					

Appendix 6. Survey results

Table 6A Table with answers to demographic and knowledge questions in the survey. The value of n is the number of times the answer was selected, which is calculated into a percentage (%) of all possible answers to that question.

	All countries		Indonesia		Turkey		The Netherlands	
	n	%	n	%	n	%	n	%
Country of residence	89	100	22	25	26	29	41	46
Region of residence	80	100	14	17	25	31	41	51
Java (IN)	-	-	10	71	-	-	-	-
Sumatra (IN)	-	-	4	29	-	-	-	-
Aegean (TR)	-	-	-	-	16	64	-	-
Central-Anatolia (TR)	-	-	-	-	4	16	-	-
Marmara (TR)	-	-	-	-	3	12	-	-
Mediterranean (TR)	-	-	-	-	2	8	-	-
West (NL)	-	-	-	-	-	-	31	76
North (NL)	-	-	-	-	-	-	2	5
South (NL)	-	-	-	-	-	-	5	12
East (NL)	-	-	-	-	-	-	3	7
Level of education	89	100	22	100	26	100	41	100
High school	1	1	0	0	0	0	1	2
Bachelor	13	15	2	9	5	19	7	17
Master	53	60	17	77	10	38	27	66
PhD	22	25	3	14	11	42	6	16
Professional expertise	88	100	22	100	25	100	41	100
Technology	70	80	18	82	17	68	35	85
Science	12	14	4	18	6	24	2	5
Policy	3	3	0	0	0	0	3	7
Social	2	2	0	0	2	8	0	0
Business	1	1	0	0	0	0	1	2
Level of knowledge	-	-	-	-	-	-	-	-
Global warming	88	100	21	100	26	100	41	100
Low	3	3	2	10	1	4	0	0
Moderate	40	45	13	62	10	38	17	41
High	45	51	6	29	15	58	24	59
Renewable energy	88	100	21	100	26	100	41	100
Low	0	0	0	0	0	-	0	0
Moderate	30	34	11	52	8	31	11	27
High	58	66	10	48	18	69	30	73
Geothermal energy	88	100	22	100	26	100	41	100
Low	2	2	2	9	0	0	0	0
Moderate	20	23	5	23	4	15	11	27
High	66	75	15	68	22	85	30	73

Table 6B Responses to two statements in the survey to which the respondents had to indicate whether they agree or not. The value of n is the number of times the answer was selected, which is calculated into a percentage (%) of all possible answers to that question.

	All countries		Indonesia		Turkey		The Netherlands	
	n	%	n	%	n	%	n	%
Statement 1: "Geothermal energy is suitable as an alternative energy resource for the future."	88	100	21	100	26	100	41	100
Strongly disagree	3	3	1	5	2	8	0	0
Somewhat disagree	2	2	0	0	1	4	1	2
Neither agree nor disagree	3	3	0	0	1	4	2	5
Somewhat agree	29	33	3	14	9	35	17	41
Strongly agree	51	58	17	81	13	50	21	51
Statement 2: "I am concerned about the future development of geothermal energy in my home country."	88	100	22	100	25	100	41	100
Strongly disagree	18	20	2	9	4	16	12	29
Somewhat disagree	35	40	6	27	12	48	17	41
Neither agree nor disagree	12	14	4	18	2	8	6	15
Somewhat agree	16	18	8	36	2	8	6	15
Strongly agree	7	8	2	9	5	20	0	0

Table 6C Responses to ‘Indicate how important each factor is in your opinion on geothermal energy.” The value of n is the number of times the answer was selected, which is calculated into a percentage (%) of all possible answers to that question.

	All countries		Indonesia		Turkey		The Netherlands	
	n	%	n	%	n	%	n	%
Sustainability	89	100	22	100	26	100	41	100
Not at all important	15	17	4	18	11	42	0	0
Slightly important	9	10	0	0	8	31	1	2
Moderately important	3	3	0	0	1	4	2	5
Very important	28	31	7	32	3	12	18	44
Extremely important	34	38	11	50	3	9	20	49
Pollution	88	100	22	100	25	100	41	100
Not at all important	5	6	1	5	2	8	2	5
Slightly important	12	14	2	8	7	28	3	7
Moderately important	18	20	4	15	4	16	10	24
Very important	28	32	8	31	7	28	13	32
Extremely important	25	28	7	27	5	20	13	32
Nuisance	89	100	22	100	26	100	41	100
Not at all important	4	4	2	9	0	0	2	5
Slightly important	22	25	3	14	5	19	14	34
Moderately important	24	27	6	27	5	19	13	32
Very important	30	34	9	41	11	42	10	24
Extremely important	9	10	2	9	5	19	2	5
Land area	88	100	22	100	25	100	41	100
Not at all important	9	10	1	5	6	24	2	5
Slightly important	17	19	3	14	8	32	6	15
Moderately important	25	28	6	27	4	16	15	37
Very important	20	23	5	23	4	16	11	27
Extremely important	17	19	7	27	3	12	7	17
Costs	88	100	22	100	25	100	41	100
Not at all important	6	7	2	9	4	16	0	0
Slightly important	21	24	3	14	9	36	9	22
Moderately important	21	24	1	5	5	19	15	37
Very important	21	24	8	36	5	19	8	20
Extremely important	19	22	8	36	2	8	9	22
Continuity of energy supply	89	100	22	100	26	100	41	100
Not at all important	10	11	1	5	8	31	1	2
Slightly important	11	12	1	5	8	31	2	5
Moderately important	18	20	3	14	2	8	13	32
Very important	28	31	8	36	4	15	16	39
Extremely important	22	25	9	41	4	15	9	22

Table 6D Responses to 'Indicate your level of concern about each potential risk.' The value of n is the number of times the answer was selected, which is calculated into a percentage (%) of all possible answers to that question.

	All countries		Indonesia		Turkey		The Netherlands	
	n	%	n	%	n	%	n	%
Groundwater contamination	89	100	22	100	26	100	41	100
Not at all concerned	16	18	1	5	6	23	8	20
Slightly concerned	24	27	4	18	6	23	12	29
Moderately concerned	33	37	6	27	12	46	14	34
Very concerned	20	22	5	23	1	4	5	12
Extremely concerned	18	20	6	27	1	4	2	5
Air pollution	88	100	22	100	25	100	41	100
Not at all concerned	40	45	3	14	8	32	27	66
Slightly concerned	21	24	7	32	7	28	7	17
Moderately concerned	13	15	3	14	5	20	5	12
Very concerned	9	10	3	14	4	16	2	5
Extremely concerned	7	8	6	27	1	4	0	0
Nuisance	88	100	22	100	25	100	41	100
Not at all concerned	30	34	2	9	12	48	15	37
Slightly concerned	29	33	8	36	5	20	15	37
Moderately concerned	17	19	6	27	3	12	8	20
Very concerned	10	12	5	23	2	20	3	7
Extremely concerned	4	5	1	5	3	75	0	0
Seismicity	88	100	22	100	25	100	41	100
Not at all concerned	21	24	2	9	10	40	8	20
Slightly concerned	27	31	4	18	5	20	17	41
Moderately concerned	23	26	5	23	8	32	10	24
Very concerned	12	14	6	27	1	4	5	12
Extremely concerned	7	8	5	23	1	4	1	2
Sight pollution	89	100	22	100	26	100	41	100
Not at all concerned	50	56	6	27	10	38	32	78
Slightly concerned	22	25	7	32	8	31	7	17
Moderately concerned	12	13	5	23	5	19	2	5
Very concerned	4	4	3	14	1	4	0	0
Extremely concerned	3	3	1	5	2	8	0	0

Appendix 7. Correlation coefficients

Table 7A Spearman correlation coefficients for 'level of education' with significant correlations in purple

		All countries			Indonesia			Turkey			The Netherlands		
		N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient
Factors	Sustainability	89	0.581	-0.059	22	0.286	0.238	26	0.953	0.012	41	0.993	0.002
	Pollution	89	0.289	-0.114	22	0.983	-0.005	26	0.805	-0.052	41	0.36	-0.147
	Nuisance	89	0.761	0.033	22	0.996	0.001	26	0.504	-0.137	41	0.662	0.07
	Land area	89	0.125	-0.165	22	0.21	0.278	26	0.533	-0.131	41	0.049	-0.309
	Costs	89	0.652	0.049	22	0.599	0.118	26	0.768	0.062	41	0.46	-0.119
	Continuity of energy supply	89	0.47	-0.078	22	0.625	0.11	26	0.578	-0.114	41	0.958	0.009
Risks	Groundwater contamination	89	0.462	0.079	22	0.173	0.301	26	0.215	0.252	41	0.544	-0.097
	Air pollution	89	0.817	0.025	22	0.824	0.05	26	0.684	-0.086	41	0.751	0.051
	Nuisance	89	0.995	-0.001	22	0.509	-0.149	26	0.604	-0.107	41	0.195	0.206
	Seismicity	89	0.566	0.062	22	0.55	0.135	26	0.959	0.011	41	0.304	0.164
	Sight pollution	89	0.035	0.223	22	0.441	0.173	26	0.402	0.172	41	0.102	0.259

Table 7B Spearman correlation coefficients for 'knowledge on geothermal energy' with significant correlations in purple

		All countries			Indonesia			Turkey			The Netherlands		
		N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient
Factors	Sustainability	89	0.379	-0.094	22	0.148	-0.319	26	0.486	-0.143	41	0.128	0.242
	Pollution	89	0.884	0.016	22	0.098	-0.362	26	0.029	0.436	41	0.537	0.099
	Nuisance	89	0.469	0.078	22	0.268	0.247	26	0.561	0.12	41	0.371	-0.144
	Land area	89	0.488	-0.075	22	0.914	-0.025	26	0.707	0.079	41	0.833	-0.034
	Costs	89	0.488	-0.075	22	0.784	0.062	26	0.432	0.164	41	0.365	-0.145
	Continuity of energy supply	89	0.237	-0.127	22	0.862	-0.039	26	0.52	-0.132	41	0.867	-0.027
Risks	Groundwater contamination	89	0	-0.377	22	0.033	-0.456	26	0.132	-0.303	41	0.029	-0.341
	Air pollution	89	0	-0.405	22	0.016	-0.505	26	0.001	-0.634	41	0.019	-0.365
	Nuisance	89	0.007	-0.286	22	0.264	-0.249	26	0.001	-0.619	41	0.748	-0.052
	Seismicity	89	0.008	-0.279	22	0.178	-0.298	26	0.006	-0.532	41	0.533	-0.1
	Sight pollution	89	0.184	-0.142	22	0.372	-0.2	26	0.637	-0.097	41	0.181	-0.213

Table 7C Spearman correlation coefficients for 'trust in geothermal energy' with significant correlations in purple

		All countries			Indonesia			Turkey			The Netherlands		
		N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient
Factors	Sustainability	89	0.117	-0.168	22	0.739	-0.077	26	0.223	0.248	41	0.018	-0.368
	Pollution	89	0.199	-0.139	22	0.816	0.054	26	0.35	-0.195	41	0.763	-0.048
	Nuisance	89	0.223	-0.131	22	0.123	-0.347	26	0.593	-0.11	41	0.901	0.02
	Land area	89	0.402	-0.091	22	0.209	-0.286	26	0.348	0.196	41	0.535	-0.1
	Costs	89	0.59	-0.059	22	0.391	-0.198	26	0.857	0.038	41	0.233	0.19
	Continuity of energy supply	89	0.158	-0.152	22	0.059	-0.419	26	0.376	0.181	41	0.32	-0.159
Risks	Groundwater contamination	89	0.887	0.015	22	0.807	0.057	26	0.279	0.22	41	0.711	0.06
	Air pollution	89	0.875	-0.017	22	0.641	0.108	26	0.539	0.129	41	0.682	0.066
	Nuisance	89	0.974	0.003	22	0.614	-0.117	26	0.485	0.143	41	0.586	0.088
	Seismicity	89	0.308	-0.111	22	0.62	-0.115	26	0.901	0.026	41	0.958	-0.008
	Sight pollution	89	0.067	-0.196	22	0.177	-0.306	26	0.456	-0.153	41	0.916	-0.017

Table 7D Spearman correlation coefficients for 'concerns about geothermal energy' with significant correlations in purple

		All countries			Indonesia			Turkey			The Netherlands		
		N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient	N	Sig.(2-tailed)	Correlation coefficient
Factors	Sustainability	89	0.915	-0.012	22	1	0	26	0.03	0.435	41	0.436	-0.125
	Pollution	89	0.136	-0.161	22	0.916	-0.024	26	0.094	-0.349	41	0.578	-0.089
	Nuisance	89	0.232	-0.129	22	0.134	-0.33	26	0	-0.725	41	0.136	0.237
	Land area	89	0.518	-0.07	22	0.868	-0.038	26	0.263	0.233	41	0.031	-0.337
	Costs	89	0.865	0.018	22	0.608	-0.116	26	0.299	0.221	41	0.793	-0.042
	Continuity of energy supply	89	0.695	0.042	22	0.283	-0.239	26	0.084	0.352	41	0.83	0.035
Risks	Groundwater contamination	89	0	0.364	22	0.182	0.295	26	0.02	0.461	41	0.151	0.228
	Air pollution	89	0.001	0.352	22	0.213	0.276	26	0.024	0.46	41	0.396	0.167
	Nuisance	89	0	0.459	22	0.326	0.22	26	0.006	0.538	41	0.002	0.46
	Seismicity	89	0.001	0.345	22	0.65	-0.102	26	0.001	0.603	41	0.074	0.282
	Sight pollution	89	0	0.398	22	0.256	0.253	26	0.001	0.641	41	0.631	0.077