UNIVERSITY OF TURKU

GEOENERGY AND SUSTAINABLE DEVELOPMENT

Perspectives on environmental challenges and governance of geoenergy installations

Pirjo Majuri

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 363 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2020

GEOENERGY AND SUSTAINABLE DEVELOPMENT

Perspectives on environmental challenges and governance of geoenergy installations

Pirjo Majuri

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA - SER. A II OSA - TOM. 363 | BIOLOGICA - GEOGRAPHICA - GEOLOGICA | TURKU 2020

University of Turku

Faculty of Science and Engineering
Department of Biology
Environmental Science
Doctoral Programme in Biology, Geography and Geology (BGG)

Supervised by

Docent Timo Vuorisalo
Department of Biology
University of Turku
Finland

Reviewed by

Professor Peter Bayer
Institute of Geosciences and Geography
Martin-Luther-University Halle-Wittenberg
Germany

Professor Peter Lund
Department of Applied Physics
Aalto University
Finland

Opponent

Professor Eva Heiskanen
Centre for Consumer Society Research
University of Helsinki
Finland

ISBN 978-951-29-7949-3 (PRINT)
ISBN 978-951-29-7950-9 (PDF)
ISSN 0082-6979 (Print)
ISSN 2343-3183 (Online)
Painosalama Oy, Turku, Finland 2020

UNIVERSITY OF TURKU
Faculty of Science and Engineering
Department of Biology
Environmental science
PIRJO MAJURI: Geoenergy and sustainable development – Perspectives on environmental challenges and governance of geoenergy installations
Doctoral Dissertation, 113 pp.
Doctoral Programme in Biology, Geography and Geology (BGG)
February 2020

ABSTRACT

Ground source heat pumps (GSHPs) are an established energy technology, and as such a noteworthy alternative to increase the share of renewable energy in the consumption. At present there are approximately 130 000 geoenergy systems in use in Finland, and in 2018 almost 8000 new GSHPs were sold and installed in the country. The growth rate highlights the significance of good installation practices and public governance of the installations.

So far there has been little research into either the construction practices and observed complications of ground heat exchangers (GHEs), or the permit procedures for geoenergy systems in Finland. Therefore, this thesis was designed to examine (1) the management of environmental and quality issues in the construction of GHEs in Finland; (2) the role of public regulation and governance, for example GHE permit systems, in promoting environmental protection and quality control of GHEs in Finland; and (3) ways to develop the capacities of both geoenergy practitioners and public authorities to respond effectively to the environmental and quality challenges.

The material for this thesis consisted of a questionnaire study among geoenergy practitioners, interview studies with geoenergy experts and municipal building control officials, heat pump statistics, legal texts, municipal regulations, and permit applications and decisions from municipalities and Regional State Administrative Agencies (AVIs).

The questionnaire study asked about the types of complications the practitioners had encountered in their geoenergy projects. The most common types were in order of frequency (1) borehole collapse, (2) discharge of artesian water, (3) harmful spreading of drilling dust and slurry, (4) heat exchanger pipes stuck during installation, (5) flooding caused by artesian water, and (6) heat transfer fluid leakages. Complications resulting from hydraulic connections between separate aquifers and other borehole-related issues were also reported.

Competition has been severe within the Finnish geoenergy sector in recent years. A large proportion of the questionnaire respondents referred to the consequent price competition at the expense of quality. Meanwhile, a third of the respondents expressed their concern about quality problems. At present, voluntary training is available for GSHP installers and borehole drillers in Finland, but there are no statutory qualification requirements. Additionally, there are no binding national regulations for the construction of GHEs and geoenergy systems in Finland either.

In the questionnaire study, 62% of the respondents were of the opinion that the municipal Action Permit should require BHEs to be built following certain standards.

Public authorities may contribute to the quality control of geoenergy systems for example through permit procedures. In Finland there are two permit procedures for GHEs. The municipal Action Permit scheme is applied to almost all geoenergy systems. The Water Permit scheme is administered by the AVIs and it is applied to geoenergy systems on designated groundwater areas. Municipalities have diverse practices in promoting quality control throughout the Action Permit procedure. For example, they may have criteria for the location of the GHE, they possibly require a site manager to be nominated, and building inspectors may control certain details at inspections. The level of expertise varied among building control officials depending on their personal interests and experience. The same applied to the AVIs so that the reasoning in the Water Permit decisions was diversified.

As the number of operative geoenergy systems grows, the success and acceptability of the industry depend increasingly on the quality and environmental safety of installations. To promote these, national standards need to be developed for both the construction of GHEs and the Action Permit procedure. Qualification requirements for geoenergy practitioners need to be incorporated into these standards. Sector specific regulations are also needed to clarify the legislation in relation to the Water Permit scheme. Additionally, technical and geological instructions need to be developed to promote geologically sound reasoning in the handling of permits.

KEYWORDS: building regulation, geoenergy, ground heat exchanger, ground source heat pump, groundwater protection, legislation, qualification, quality control

TURUN YLIOPISTO
Luonnontieteiden ja tekniikan tiedekunta
Biologian laitos
Ympäristötiede
Pirjo Majuri: Maalämpö ja kestävä kehitys – Näkökulmia maalämpöasennusten ympäristöhaasteisiin ja hallintaan
Väitöskirja, 113 s.
Biologian, maantieteen ja geologian tohtoriohjelma
tammikuu 2020

TIIVISTELMÄ

Maalämpöpumput ovat vakiintunutta energiateknologiaa ja siten varteenotettava menetelmä lisätä uusiutuvan energian osuutta kulutuksesta. Suomessa on käytössä arviolta 130 000 maalämpöjärjestelmää, ja vuonna 2018 myytiin ja asennettiin lähes 8000 uutta maalämpöpumppua. Järjestelmien nopea yleistyminen korostaa hyvien asennuskäytäntöjen ja asennusten valvonnan merkitystä.

Suomessa on tehty niukasti tutkimusta maalämpöjärjestelmien keruupiirien rakentamiskäytännöistä, niissä ilmenneistä ongelmista tai maalämpöjärjestelmien lupamenettelyistä. Käsillä oleva väitöskirja tarkastelee näitä kysymyksiä seuraavien kysymysten valossa: (1) Miten maalämpöjärjestelmien lämmönkeruupiireihin liittyviä ympäristö- ja laatuhaasteita käsitellään Suomessa? (2) Mikä rooli julkisella sääntelyllä ja hallinnalla, kuten lupajärjestelmillä, on ympäristönsuojelun ja laatukontrollin edistämisessä? (3) Miten voidaan kehittää maalämpöalan toimijoiden ja viranomaisten mahdollisuuksia vastata tehokkaasti ympäristö- ja laatuhaasteisiin?

Väitöskirjan aineistona olivat maalämpötoimijoiden keskuudessa tehty kyselytutkimus, maalämpöasiantuntijoiden ja kuntien rakennusvalvonnan henkilöstön haastattelut, lämpöpumpputilastot, lakitekstit, kunnalliset säännökset sekä kuntien ja Aluehallintovirastojen (AVI) käsittelemät maalämpölupahakemukset ja -päätökset.

Selvitin kyselytutkimuksella muun muassa sitä, minkä tyyppisiä komplikaatioita maalämpötoimijoiden kohteissa on esiintynyt. Yleisimpiä ongelmia olivat (1) energiakaivon sortuminen, (2) paineenalaisen (tai muutoin runsastuottoisen kaivon) pohjaveden purkautuminen porauksen yhteydessä, (3) porauspölyn tai -lietteen haitallinen leviäminen (4) lämmönkeruuputkien jumiutuminen kaivoon asennuksen yhteydessä, (5) paineenalaisen pohjaveden tulviminen, sekä (6) lämmönsiirtonesteen vuoto. Toimijat raportoivat myös tapauksista, joissa eri pohjavesikerrosten sekoittuminen tai muut porareikään ja sen poraukseen liittyvät seikat aiheuttivat ongelmia.

Maalämpöalan sisäinen kilpailu on viime vuosina ollut ankaraa Suomessa. Lähes puolet kyselyyn vastanneista maalämpötoimijoista viittasi rajuun hintakilpailuun, jota käydään laadun kustannuksella. Kolmannes vastaajista ilmaisi huolensa laatuongelmista. Tällä hetkellä maalämpöasentajille ja kaivonporareille on Suomessa tarjolla vapaaehtoista koulutusta ja sertifiointiohjelmia, mutta lakisääteisiä pätevyysvaatimuksia ei ole. Lämmönkeruupiirien ja maalämpöjärjestelmien rakentamiselle ei myöskään ole sitovia kansallisia määräyksiä. 62 % kysely-

tutkimuksen vastaajista oli sitä mieltä, että toimenpideluvan pitäisi edellyttää lämpökaivon rakentamista tiettyjen standardien mukaisesti.

Suomessa viranomaisilla on mahdollisuus vaikuttaa maalämpöjärjestelmien laatutasoon kahden lupamenettelyn kautta. Kunnallinen toimenpidelupa vaaditaan suurimmalta osalta maalämpöjärjestelmiä. AVI:n myöntämä vesilupa edellytetään pohjavesialueille rakennettaessa. Kunnilla on vaihtelevia käytäntöjä laatukontrollin edistämiseksi toimenpidelupamenettelyn yhteydessä. Esimerkiksi lämmönkeruuputkistojen sijoittamiselle on kriteerit, osa kunnista edellyttää vastaavan työnjohtajan nimeämistä maalämpöurakalle, ja joissakin kunnissa rakennusvalvonta tarkastaa tiettyjä urakan osia katselmuksien yhteydessä. Rakennusvalvontaviranomaisten asiantuntemuksen taso vaihteli riippuen omakohtaisesta kiinnostuksesta ja kokemuksesta. Sama koskee myös AVI:en henkilökuntaa, joten vesilupapäätösten perustelut olivat tasoltaan vaihtelevia.

Käytössä olevien maalämpöjärjestelmien määrä kasvaa jatkuvasti. Alan menestys ja hyväksyttävyys riippuvat enenevässä määrin siitä, että asennukset tehdään laadukkaasti ja ympäristö huomioiden. Näiden turvaamiseksi tarvitaan kansalliset standardit sekä lämmönkeruupiirien rakentamiselle että toimenpidelupamenettelylle. Näihin standardeihin pitää sisällyttää pätevyysvaatimukset maalämpöalan toimijoille. Vesilupiin liittyvää lainsäädäntöä pitää selkeyttää maalämpöä koskevilla alakohtaisilla säännöksillä. Lisäksi teknisiä ja geologisia ohjeistuksia tulee kehittää asiantuntevan lupakäsittelyn edistämiseksi.

ASIASANAT: ammattipätevyys, geoenergia, laadunhallinta, lämmönkeruuputkisto, maalämpöpumppu, lainsäädäntö, pohjavesien suojelu, rakentamismääräys

Table of Contents

Abbreviations

AVI	Regional State Administrative Agency (Aluehallintovirasto)
BHE	Borehole heat exchanger
ELY Centre	Centre for Economic Development, Transport and the Environment (Elinkeino-, liikenne- ja ympäristökeskus)
GHE	Ground heat exchanger
GSHP	Ground source heat pump

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Majuri P. Ground source heat pumps and environmental policy – the Finnish practitioner's point of view. *Journal of Cleaner Production*, 2016; 139: 740 – 749.

II Majuri P. Technologies and environmental impacts of ground heat exchangers in Finland. *Geothermics*, 2018; 73: 124 – 132.

III Majuri P., Kumpula A., Vuorisalo T. Diverse geoenergy permit practices in Finnish municipalities as a stakeholder challenge. Submitted manuscript.

IV Majuri P., Arola T., Kumpula A., Vuorisalo T. Geoenergy permits in Finnish regional administration – Contradictory practices and inadequate judicial regulation. Submitted manuscript.

1 Introduction

Many countries are currently tuning up their energy policies to promote renewable energies. This has been further inspired by the IPCC's Special Report on Global Warming of 1.5°C in late 2018 (IPCC, 2018 & 2019; Ge et al. 2019). In many parts of the world ground source heat pumps (GSHPs), as an established energy technology, are in a good position in the redistribution of the energy market. Since heat pumps are an efficient technology for power-to-heat conversion, they may also have a prominent role in energy storage when the share of variable renewable electricity, such as wind power and photovoltaics increases (Pilpola & Lund 2018).

GSHPs are devices that process energy collected from the ground with ground heat exchangers (GHEs). This energy is then used for heating e.g. buildings and domestic water. In Finland and in other Nordic countries the term geoenergy has in recent years been adopted to refer to shallow geothermal energy that consists of the Earth's heat flux and solar energy stored in the ground. This energy source has rapidly gained popularity in Finland.

The idea of ground source heat pumps was first presented and patented in 1912 by a Swiss turbine engineer Heinrich Zoelly. The basis for GSHPs is in refrigeration technology, which was researched and put into practice already in the 1800s. Ambitious heat pump schemes with for example river water as the heat source were successfully installed in Switzerland in the 1930s and 1940s. In the 1940s installations with ground as a heat source were explored and constructed for example in the United States (Zogg, 2008; Anon., 1948). In Finland, experimental GSHP systems were installed in the 1950s (Karjalainen, 1959).

The commercialization of GSHPs on a large scale has occurred in two waves: During the 1970s the world experienced two oil crises that launched a global interest in alternative energy sources, including GSHPs. In the 1990s, after a decade in the doldrums, geoenergy started to gain increasing attention due to for example rising energy prices. Growing climate concern and increasing need for energy security prompted also governments in different countries to design policies in favour of renewable energies (I).

Currently there are approximately 130 000 geoenergy systems in use in Finland, and in 2018 alone almost 8000 new GSHPs were sold and installed in the country

(SULPU, 2019). GSHPs are installed in new buildings and retrofitted in place of oil burners, electrical heating, wood furnaces and district heating.

The rapid growth of the geoenergy industry has raised questions about the environmental benefits and costs of GSHPs. For instance, the renewable energy production and carbon footprint of GSHP systems as well as geothermal potential of aquifers have been intensively studied (e.g. Arola et al. 2014; Arola & Korkka-Niemi 2014; Bayer et al. 2012; Laitinen et al. 2014; Mattinen et al. 2014). The current growth rate highlights the significance of good installation practices and public governance of the installations.

This thesis investigates the policies, regulation, environmental and technical challenges, and permit procedures related to geoenergy systems in Finland. The aim is to find out and propose solutions to issues that may cause conflicts between different stakeholders in geoenergy projects. These stakeholders include (potential) owners of geoenergy systems, neighbours, geoenergy practitioners, the public administration and, notably, the environment.

1.1 Policy and governance – public administration of geoenergy

In Finland heat pumps became a part of national energy policy in the 1970s (I). Finland's Energy Policy Programme from 1979 mentioned heat pumps alongside solar and wind energy and stated that the utilization of and research into these alternative energy sources will be promoted (Energy Policy Council, 1979: 9). The next Energy Policy Programme (1983: 18) declared that efforts will be made to develop more economical heat pumps for small- and large-scale applications. However, these efforts never materialised, and research funding was terminated. Heat pumps were not even mentioned in the Finnish energy strategies and energy committee reports in the late 1980s or in the 1990s (Energy Committee, 1989; MTI, 1992 & 1997). The Climate Strategy of 2001 stated that "The use of heat pumps, inter alia geoenergy, will be promoted" (MTI, 2001).

In the Finnish Advancement Programme for Renewable Energy 2003–2006 heat pumps received more attention than in the earlier programmes. Heat pumps were already considered a noteworthy source of renewable energy, and a tool for reduction of CO_2 emissions, and an investment subsidy was suggested (Working Group on Renewable Energy, 2003: 43, 50). In 2005 the National Strategy to Implement the Kyoto Protocol stated that "the utilisation of heat from the environment… through the use of heat pumps has proceeded positively" (MTI, 2005: 26). The Long-term Climate and Energy Strategy of 2008 set a 5 TWh target for renewable energy production by heat pumps in 2020 (MEE, 2008: 48). Interestingly, a much earlier report had presented a scenario of 5–6 TWh of GSHP energy for the period 2020 –

2030 in Finland (Joensuun korkeakoulu, 1983: 25). The National Energy and Climate Strategy of 2013 listed heat pumps as one of the tools in decreasing the use of fossil fuels in heating (MEE, 2013: 19, 51). The Energy and Climate Roadmap 2050 stated that “geoenergy can be utilised much more than at present” but did not set any targets for geoenergy production (PCECI 2014:13).

The National Energy and Climate Strategy for 2030 (MEE, 2017) saw continued growth potential for heat pumps due to for example decreasing use of light fuel oil in heating and increasing use of large heat pumps in district heating. The report also listed deep geothermal energy as a potential source for district heating. This was inspired by a pilot plant project in Espoo, southern Finland. On the other hand, the report defined (building-specific) geoenergy as the greatest challenger to district heating. In this report, the scenario calculations for renewable energy production by heat pumps were 6 TWh in 2020 and 7 TWh in 2030 (MEE, 2017: 46, 106, 119; Hansen, 2017). Notably, the figures were the same for the base scenario and the policy scenario, so the strategy presented no policies that would have influenced the heat pump market.

A new sense of urgency was added to discussions about energy policies after IPCC’s Special Report on Global Warming of 1.5°C was published in 2018 (IPCC, 2018, 2019). In Finland the Programme of Prime Minister Antti Rinne’s Government (2019) declared to aim at a carbon neutral Finland by 2035 and a phase out of fossil fuel oil in heating by the beginning of the 2030s. The programme proposed numerous measures with implications for the geoenergy industry. These include development of a smarter electricity and district heating network; ensuring that heat pumps do not cause spikes in electricity consumption; energy subsidies for housing companies; changes in the tax deduction for domestic help work; promotion of large-scale renovation and energy efficiency projects; a sector-specific plan to achieve carbon neutrality in the construction sector; and development of procurement expertise within the public sector.

While energy policies aim at increasing the use of renewable energies, policy targets may be further supported by permit schemes that monitor and regulate the quality of renewable energy installations. In the case of geoenergy and GHEs, possible benefits of permit schemes include avoidance of problems for adjoining properties, possibility of including building specifications in the permit regulations, improved risk management, registration of new GHEs and the possibility for mapping project areas in relation to patterns of regional land use (I; III; IV). Finnish legislation contains two permit procedures that are applied to geoenergy projects (see Table 1 for details): (1) The Finnish land use and building legislation amendment in May 2011 introduced a building permit scheme, administered by municipalities, that applies generally to all new GHEs. (2) In some cases (primarily GHEs on designated groundwater areas and surface water heat exchangers in general), geoenergy projects also require a permit from the Regional State Administrative Agency, hereafter AVI

(AVI, 2018a). The Centres for Economic Development, Transport and the Environment (ELY Centres) have a central role in this procedure as providers of expert statements on each permit application. Their role is based on the fact that, according to the Water Act and the Environmental Protection Act, the ELY Centres supervise general environmental interests in the society (III; IV).

The ELY Centres are also responsible for categorizing aquifers that are suitable for drinking water extraction. These classified aquifers have a legal status (Arola, 2015) and are referred to as designated groundwater areas in this thesis.

Table 1. Permit schemes for ground heat exchangers in Finland

	Local administration	**Regional administration**
Legislation	Land Use and Building Act (Finnish statute 1999/132, section 126a)	Water Act (Finnish statute 2011/587, Chapter 3, section 2) Environmental Protection Act (Finnish statute 2014/527, section 17)
Competent authority	Municipal building control	Regional State Administrative Agency (AVI, Aluehallintovirasto)
Aim of legislation in relation to GHEs	Control installation of GHEs in relation to their potential impacts on natural conditions and surrounding land use	Groundwater protection
Application of legislation	In most municipalities each new GHE requires either (a) an Action Permit (a simplified building permit procedure applied to retrofits when only a geoenergy system is installed) or (b) a Building Permit (applies to larger projects, where the GHE is approved as a component of a construction project). However, a municipality may decide that permits are not needed, in which case (c) a notification procedure is usually applied.	If a planned GHE is located on a designated groundwater area, a permit from AVI is required. The municipal authority may request a statement on the need of a permit from the Centre for Economic Development, Transport and the Environment (ELY Centre).

In addition to the duties and regulations that follow from the Action Permit scheme, the Finnish Land Use and Building Act (Finnish statute 1999/132, section 119) directly assigns a duty to take care in building activities to the party engaging in a building project, i.e. the client: "*A party engaging in a building project shall ensure that the building is designed and constructed in accordance with building provisions and regulations and the permit granted.*"

In Finland local municipalities have traditionally had a strong and independent position for example in the form of administrative authority in certain activities with environmental impacts (Paloniitty & Kangasmaa, 2018). This enables rather great differences among municipalities in the practical procedures. Each municipality oversees for example land use planning, building control, and environmental protection within its borders. Municipalities in Finland may give binding regulations for construction in the form of municipal *land use plans*, *building codes* or *environmental protection regulations*.

Identifying and incorporating good permit practices is crucial when developing permit schemes for renewable energies. The Council of Europe has issued the 12 Principles of Good Governance (Council of Europe, 2019). According to the principles, any permit scheme should follow the national rules and regulations, and decision-making should be transparent and treat all citizens impartially (Principles 4 and 5). All public services should be delivered within a reasonable timeframe, and procedures should be adapted to the legitimate expectations and needs of citizens (Principle 2). Moreover, the professional skills of those who deliver governance should be continuously maintained and strengthened in order to improve their output and impact (Principle 7).

Haehnlein et al. (2010) discovered that environmental legislation related to geothermal energy varied significantly among the European countries, and most countries had no legally binding regulations or even guidelines for geoenergy systems. However, in the environmental legislation of most countries environmental permits are needed for activities that involve a risk of environmental degradation, and the construction of geoenergy systems is commonly classified as such an activity.

1.2 Construction practices, climate and geology

A typical GSHP system in Finland consists of a ground heat exchanger (GHE) and a vapor compression heat pump with either an inbuilt or a separate domestic hot water tank. The GSHP system is connected to hydronic heat distribution, which is usually underfloor heating in new buildings and newer retrofit sites, or wall mounted water radiators in older retrofit sites (II).

Generally, three types of GHEs are used in Finland. In order of frequency, these are BHEs, horizontal GHEs, and surface water heat exchangers. All of them consist of a plastic pipe made of polyethylene, with diameter usually 40 mm (45 – 50 mm in BHEs deeper than 250 m). The heat transfer fluid is most commonly a 28 wt-% ethanol solution (freezing point -17°C) (II).

BHEs have been commonly built in Finland since the 1990s. BHEs are typically 100 – 250 meters deep (but may be 300–400 m in for example borehole arrays for large buildings). BHEs usually consist of a single U-pipe. Mostly groundwater filled (open-hole) boreholes are used, with no backfilling. Horizontal GHEs were the most commonly applied technology when the first wave of GSHPs entered Finland in the 1970s. In a horizontal GHE a single plastic pipe is typically installed in series at a depth of 1.0 – 1.5 meters, with a minimum distance of 1.5 meters between the parallel pipes. Compact collectors, such as slinky or multiple pipe systems (cf. Banks, 2012: 334, 338), have not been applied to any noteworthy extent in Finland. Surface water heat exchangers consist of a closed loop placed at the bottom of a lake, pond or the sea at a minimum depth of two meters. These have been built to a lesser extent since the 1970s (II). Open loop geoenergy systems, where groundwater or surface water is directly pumped to the heat exchangers, are very rare in Finland despite their existing potential (Arola et al., 2014).

Boundary conditions for the sizing and design of GHEs in Finland are set by the northern climate and distinctive geological conditions. The annual average ambient temperature in Finland varies from over 5°C on the south coast to below -2°C in parts of northern Finland, where the temperature may drop below -40°C in wintertime (FMI, 2019a, 2019b). Correspondingly, the annual average temperature of the ground surface varies from 8°C on the south coast to 2°C in the far north of Finland (GTK, 2019). The thermal conductivity of Finnish rocks is typically over 3 W/(m*K), and the geothermal gradient is 8 – 15 K/km (Kukkonen & Peltoniemi, 1998; Kukkonen, 2000).

The bedrock in Finland generally consists of hard crystalline rocks, and sedimentary rocks are rare. Practically all of Finland is located on the Fennoscandian Shield, which is relatively unbroken and tectonically stable (Korsman & Koistinen, 1998; Plant et al., 2005). Due to the hard rocks in Finland, a method known as down-the-hole (DTH) drilling is economically superior, and more efficient than any other method (cf. Rebouças, 2004). In practice, it is the only method applied to drill boreholes for BHEs in Finland. The rotating DTH hammer’s percussion is powered by compressed air (typical working pressure 35 bar), and the exhaust air is used to flush the drill cuttings out of the borehole (Jouni Lehtonen, personal communication 12 Nov 2016; Jimmy Kronberg, personal communication 24 May 2017). Another consequence of the hard rocks is that boreholes are mostly installed without backfilling and usually remain open (provided that a sufficiently long borehole casing has been installed and securely fitted with a well cap). The need for backfilling is also decreased by the fact that the groundwater table is in most cases within ten meters from the ground surface (Karro & Lahermo, 1999). A completely dry borehole indicates that the rock is solid enough to prevent groundwater movement, in which case the borehole is filled by pumping water into it (II).

Groundwater reservoirs in Finland are mostly found in Quaternary, glaciofluvial coarse-grained deposits, mostly eskers or ice-marginal end moraine complexes. The largest coarse-grained deposits in the country are the Salpausselkä end moraines. Aquifers are normally unconfined, but there are also semi-confined or confined aquifers, mostly in the southern parts of Finland. Semi-confined and confined aquifers are due to post glacial clay deposits that overlay sand or gravel sediments. The hydraulic conductivity of Finnish glaciofluvial sand and gravel aquifers is usually between 10^{-5} to 10^{-2} ms^{-1} (Hänninen et al., 2000; Rantamäki et al., 2009).

1.3 Research questions

In relation to geoenergy systems, groundwater protection and quality issues have been extensively discussed in Finland and internationally since the 1970s. Aittomäki and Wikstén (1978), and Aittomäki (1983) compared ground, surface water and air as heat sources for heat pumps in Finland and discussed possible ecological impacts of heat extraction on lake sediment fauna. Hähnlein et al. (2013) and Vienken et al. (2015) analysed the sustainability of ground source energy use in general. Environmental risks of heat transfer fluids in GHEs were discussed by e.g. Heinonen et al. (1997 & 1998), Klotzbücher et al. (2007), Ilieva et al. (2014) and Schmidt et al. (2016). Morofsky and Cruickshanks (1997) reviewed procedures for environmental impact assessment in underground thermal energy storage projects. Groundwater flow and potential cross-contamination between aquifers were studied by e.g. Lacombe et al. (1995) and Santi et al. (2006). Bonte (2013) investigated the hydrochemical and geomicrobial effects of GSHPs and aquifer thermal energy storage. Fleuchaus and Blum (2017), and Sass and Burbaum (2010) analysed damage events relating to BHE construction in Germany. Bleicher and Gross (2016) discussed the unpredictability of hydrogeology in general, and experimental strategies to cope with it in GSHP projects.

Several international projects have analysed the existing shallow geothermal legislation and GSHP standards at European level, and the need to develop and harmonise these regulations (e.g. Benou & Sanner, 2008; REGEOCITIES, 2013; Hähnlein et al. 2013; Tsagarakis et al., 2020). Topics related to geoenergy permits have been studied by for example Bleicher and Gross (2016), who discussed the different experimental strategies the German environmental officials may apply in permit decision making. Hähnlein et al. (2013) suggested a legal framework for the sustainable use of shallow geothermal energy; this framework is a workflow for the preparation of a permit decision in geoenergy projects. To harmonise administrative procedures and requirements among the European Union member countries, Tsagarakis et al. (2020) called for the EU to develop legislation and standards on geoenergy. Geoenergy permit schemes and their possible development needs have been examined in several countries (e.g. Karytsas & Chaldezos, 2017; Somogyi et al., 2017; Liu et al., 2015; Jardeby et al., 2013; Haehnlein et al., 2010). Park et al.

(2013) conducted a detailed study on the local authorities' planning processes in relation to micro-wind turbines in the UK.

Environmental risks and technical problems related to GHEs have been commonly discussed in public, and between authorities and GSHP practitioners in Finland. Yet, there has been little research into either the construction practices and observed complications of ground heat exchangers (GHEs), or the permit procedures for geoenergy systems in Finland. This thesis addresses the issue through the following questions:

(1) How are environmental and groundwater protection, and quality issues currently managed in the construction of GHEs in Finland?

(2) What is the role of public regulation and governance, for example GHE permit systems, in promoting environmental protection and quality control in Finland?

(3) What further steps should be taken to develop the capacities of both geoenergy practitioners and public authorities to respond effectively to the environmental and quality challenges?

2 Materials and Methods

The material for this thesis consisted of questionnaire and interview studies (I, II, III), heat pump statistics (I), legal texts (I, III, IV), municipal regulations (III), and permit applications and decisions (III, IV).

2.1 Sampling

In the questionnaire study relating to I and II, my aim was to reach as many practitioners as possible. To achieve a broad sub-sectoral and geographical coverage, six organizations associated with the heat pump industry were asked to deliver the questionnaire link to their members. The link was also e-mailed directly to 126 unorganized companies. Since the organisations and their members distributed the questionnaire link freely, the exact number of questionnaire recipients is not known. It is anyway reasonable to argue that nearly all practitioners in the field received the questionnaire (I, II).

For the thematic interviews used in I and II, the interviewees were chosen based on their long experience in the GSHP sector in Finland. Random sampling of interviewed persons was not possible due to the very small number of pioneers in the field in Finland (I, II).

The province of Southwest Finland (Varsinais-Suomi) was chosen as the study area for the study on municipal permit practices (III). The area comprises 27 municipalities (Lounaistieto, 2018) and nine randomly sampled municipalities (Table 2) were studied: three small (<5000 inhabitants), three medium sized (5000 – 15000 inhabitants) and three large municipalities (>15000 inhabitants). Concerning the small and medium-sized municipalities, all available permit applications and decisions, and notifications were studied from 2011, when the permit scheme came into effect, until the end of 2016. In relation to the large municipalities, I decided to concentrate on applications of the year 2014, since the numbers of geoenergy applications peaked in the small and medium-sized municipalities in 2014 (III).

Table 2. Study municipalities

	Population at end of 2016 (Statistics Finland, 2018)	**Land area km²** (RCSF, 2018)
Salo	53546	1986
Kaarina	32738	150
Lieto	19418	300
Somero	9027	668
Laitila	8520	532
Mynämäki	7842	520
Aura	3984	95
Pyhäranta	2075	143
Oripää	1363	118

For the study on the Water Permit procedure (IV), the databases of the Regional State Administrative Agencies (AVIs) were searched for geoenergy-related Water Permit applications. Covering the years 2011 – 2017, all available applications that had led to a permit decision were included in the analysis.

2.2 Questionnaire study

A questionnaire study (Appendix B in I) was conducted at the beginning of 2014 among GSHP professionals, utilizing the Webropol online survey software (www.webropol.com). The questionnaire made it possible to collect experiential knowledge and views from a large number of heat pump professionals. The target groups for the questionnaire were engineering offices, GSHP contractors and borehole contractors, and the aim was to gather company-specific information (I, II).

There were 64 respondents in total. The obtained data contained for example the practitioners' experience and views on the GSHP policies, legislation and control, and their implementation; percentage values of different GHE types in their geoenergy projects, applied technologies including construction phase practices of BHEs and properties of the completed BHEs; and the occurrence and frequency of complications and environmental problems related to GHEs (I, II).

2.3 Interviews

Two sets of interviews were used as material for this thesis: Thematic interviews were conducted with heat pump experts and a personal interview survey with building control officials.

The purpose of the thematic interviews was to collect the professionals' insights and in-depth information that has not been previously recorded. Seven Finnish heat pump experts representing different sectors of the heat pump industry and research were interviewed. The interviews recorded their views on the development of the geoenergy sector and policies in Finland. The interviewees' observations of the construction and potential complications of GHEs were also documented more broadly than was possible in the questionnaire responses. Since most of them were not contractors in active working life, they could also provide different perspectives compared to the questionnaire respondents (I, II). The interview outline is available as Appendix A in I.

Municipal permit practices for GHEs were studied by conducting a personal interview survey (Czaja & Blair, 2005) with municipal building control officials (III). The interview survey outline is enclosed as an appendix to III. One interviewee was contacted in each municipality. The questions were discussed with the interviewees and their responses were directly typed on the computer. The interview survey consisted of open-ended questions on the application processes and practices; preconditions for GHEs; quality control and permit regulations for GHEs; environmental impacts of GHEs; instructions and training the officials had received relating to geoenergy permits.

2.4 Statistics and literature

The sales statistics were used to get an overview of the development of the GSHP industry. The statistics were supplied by the Finnish Heat Pump Association (SULPU, www.sulpu.fi). SULPU provided the Finnish sales statistics it started to collect from GSHP factories and importers after its establishment in 1999 and estimates on sales figures for the period 1976–1998 (I).

I also sought to obtain objective information about problems and accidents related to geoenergy projects, if possible, in the form of statistics on insurance claims. To this end eight Finnish insurance companies were contacted. Four of the companies could supply some kind of information whereas the rest of them notified that their data systems did not enable the identification of geoenergy related claims. Some of the insurance companies provided qualitative data. One company in particular was able to provide more detailed qualitative information and even some general statistics. None of the companies could provide detailed statistics of different kinds of geoenergy damage or accidents (II).

GSHP literature provided contemporary viewpoints to the development of the geoenergy industry and also some damage event reports. The Finnish National Library's article reference database Arto (https://arto.linneanet.fi) yielded 117 heat pump articles from Finnish professional and popular journals between 1960 and 2013. However, only a few of the articles proved useful from the viewpoint of this thesis (I, II).

2.5 Legislation and municipal regulations

Five sectors of legislation that have influenced the development of the GSHP industry in Finland were considered for this thesis: (1) qualification requirements imposed on the geoenergy trade; (2) the Action Permit scheme for ground heat exchangers; (3) legislation on groundwater protection and Water Permits; (4) the EU legislation that sets requirements and incentives with effects on the heat pump industry; and (5) public subsidies applied to the heat pump sector.

Municipal regulations and instructions were examined for the analysis of municipal permit practices. These included municipal environmental protection regulations and building codes, and GHE permit application instructions and GHE instructions in the studied municipalities (III).

2.6 Permit applications and decisions

To analyze the municipal permit practices for geoenergy, Building and Action Permit documents (419 cases) and notification documents (86 cases) were studied (III). For each permit application or GHE notification, the following data were collected:

- application's date of arrival, date of decision, and date of decision issue
- objective of application: for an Action Permit, or for a Building Permit
- type of GHE installation: BHE, horizontal GHE or surface water heat exchanger; number of loops
- permit decision, possible reasons (for rejection), and permit regulations
- decision maker: inspector's name, or building board

We analysed altogether 68 Water Permit documents relating to geoenergy projects (IV). These had been issued by four Regional State Administrative Agencies (AVIs): ESAVI (AVI Southern Finland), LSSAVI (AVI Western and Inland Finland), ISAVI (AVI Eastern Finland) and PSAVI (AVI Northern Finland) during the period 2011–2017. As for their size, the studied projects were in the range of 1 – 50 BHEs. Of the 68 analysed cases, 56 concerned ground heat exchangers planned on or near designated groundwater areas. Eleven cases were planned surface water heat exchangers and one open-loop groundwater heat pump (IV).

The permit documents are public and freely available on the website of the AVIs (AVI, 2018b & 2018c). A list of the analysed decisions and links to the documents are provided in IV, Appendix A. Each document contained:

- a summary of the contents of the permit application,
- a summary of the statement by the ELY Centre,

- summaries of possible statements and comments by municipal authorities, the water utility, neighbours etc.
- the permit decision by the AVI (permit granted or not), permit regulations if the permit was granted, and justifications for the decision

2.7 Analyses

Inductive qualitative content analysis (Silvasti, 2014; Elo & Kyngäs, 2008; Thomas, 2006) was used to analyse the qualitative data. For IV, NVivo 12 Pro software was used to conduct the analysis (https://www.qsrinternational.com/nvivo/nvivo-products). For I, II and III the analyses were conducted manually: Relating to each topic of interest relevant data were assembled from the questionnaire and interview responses, permit and notification documents, and written documents. These data were tabulated, and different themes were identified within these tables.

Statistical correlations were analysed using Fisher's exact test, a non-parametric statistical significance test, which can be applied to small sample sizes (Ranta et al., 2012).

2.8 Limitations of the study

When examining the questionnaire and interview data, some potential sources of bias are to be kept in mind. The interviewees' responses for example may be shaped by the phrasing of questions and by what they think the interviewer wants to hear (Hammersley & Gomm, 2008). To address the issue of phrasing, the interview outline was designed to be simple and neutral.

There is an element of uncertainty related to information that is based on the informants' memory and recollections. Relating to some of the numerical questions in the questionnaire, the respondents were asked to give estimates as they were not expected to remember exact numbers for incidents that may have occurred over a period of more than two decades. Moreover, it is possible that some respondents were reluctant to disclose full details of observed problems or of their companies' failures. It may even be that contractors with the worst problems were less likely to participate in the questionnaire (II).

The total number of studied Action and Building Permit applications and decisions in this study was rather large. However, in small and medium sized municipalities applications and decisions over a period of more than five years were studied, while in large municipalities only one year was studied. Thus, it is not possible to, for example, compare the absolute diversity of permit regulations between the studied municipalities.

3 Results

After the first energy crisis GSHP sales grew steadily in Finland from the mid-1970s to the early 1980s (Figure 1). In the early1980s there were at least 15 GSHP factories in Finland, most of them small "garage workshops" (Interviewee 2). Many of the GSHPs installed in those days proved to be durable and functioned well for decades, while others had problems with for example low-quality components, the design of GHEs and integration to the rest of the heating system (Interviewees 7 and 1). Failures affected the reputation of the whole industry. This was one of the central reasons that led to a rapid decrease in the demand for GSHPs, and by the end of 1983 the original 15 GSHP factories had all gone bankrupt or otherwise out of the heat pump business. Some new business activities emerged but GSHP trade remained at a very low level until the mid-1990s (I).

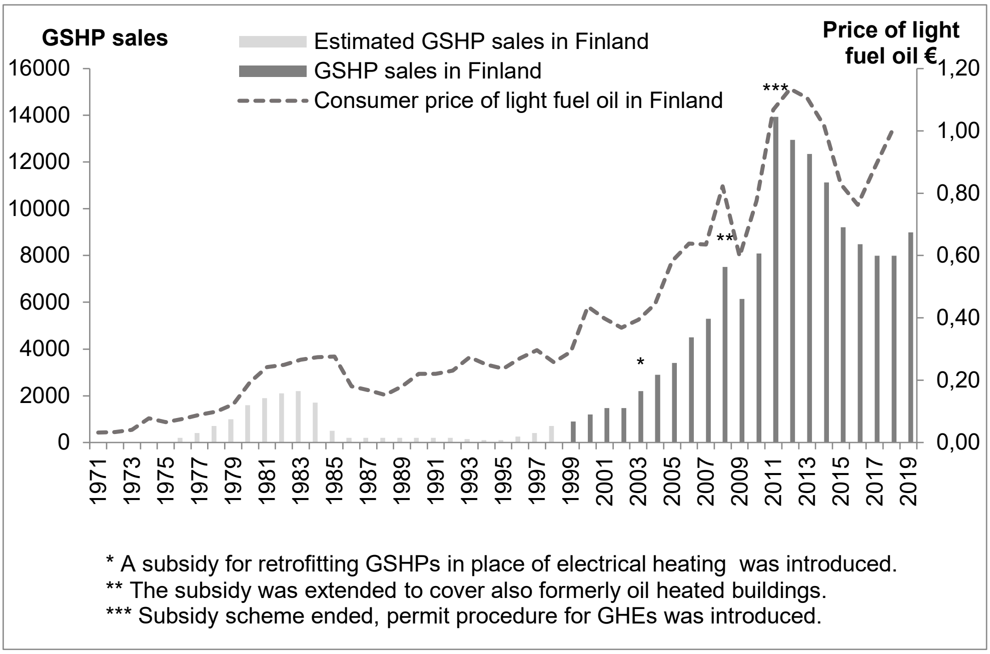

Figure 1. GSHP sales and consumer price of light fuel oil in Finland. Modified from I, data from the Finnish Heat Pump Association, Myllyntaus (1999), Statistics Finland (2019).

Towards the end of the 1990s the GSHP industry started to recover in Finland (Figure 1). This time the market growth was on a more solid foundation due to more advanced technology and distribution channels. Most of the heat pump suppliers began to build a retailer network of specialised contractors in the 1990s (Interviewee 6). The Finnish Heat Pump Association (SULPU) was founded at the end of the 1990s to distribute information, defend the interests of the industry, promote quality, and develop training. Construction of borehole heat exchangers increased markedly in the 1990s, which made the use of geoenergy possible on smaller and rockier building lots (I).

3.1 Environment, groundwater and quality issues in GHEs

The early problems of the geoenergy industry demonstrated the significance of delivering good quality. Environmental and groundwater safety has been a recurring theme in the quality discussions around geoenergy. This section describes the environmental and quality challenges of the geoenergy sector in Finland, and factors that influence them.

The questionnaire respondents reported approximately 850 cases of complications in their geoenergy projects, which were analysed in II (Figures 2 and 3). See sections 2.2 and 2.8 above for details on interpretation.

In BHEs the most commonly reported ground water related complications were discharge of artesian water during drilling, and flooding caused by artesian water (Figure 2). A number of the cases reported by the respondents may also be non-artesian boreholes with just a very high water yield (II).

Questionnaire respondents reported a total of 73 heat transfer fluid leakages (Figures 2 and 3; note that ‘Leakage from metal joints at the bottom of BHE’ is not included in the sum as these would be already included in the ‘leakages in the borehole’). Leakages are much more common in the horizontal header pipes (i.e. between the borehole and the heat pump) and in horizontal GHEs than in the boreholes. Interviewee 3 pointed out that if a ground loop or surface water heat exchanger leaks, not all the fluid escapes but only those parts of the pipes get drained that are above the groundwater or water level (II).

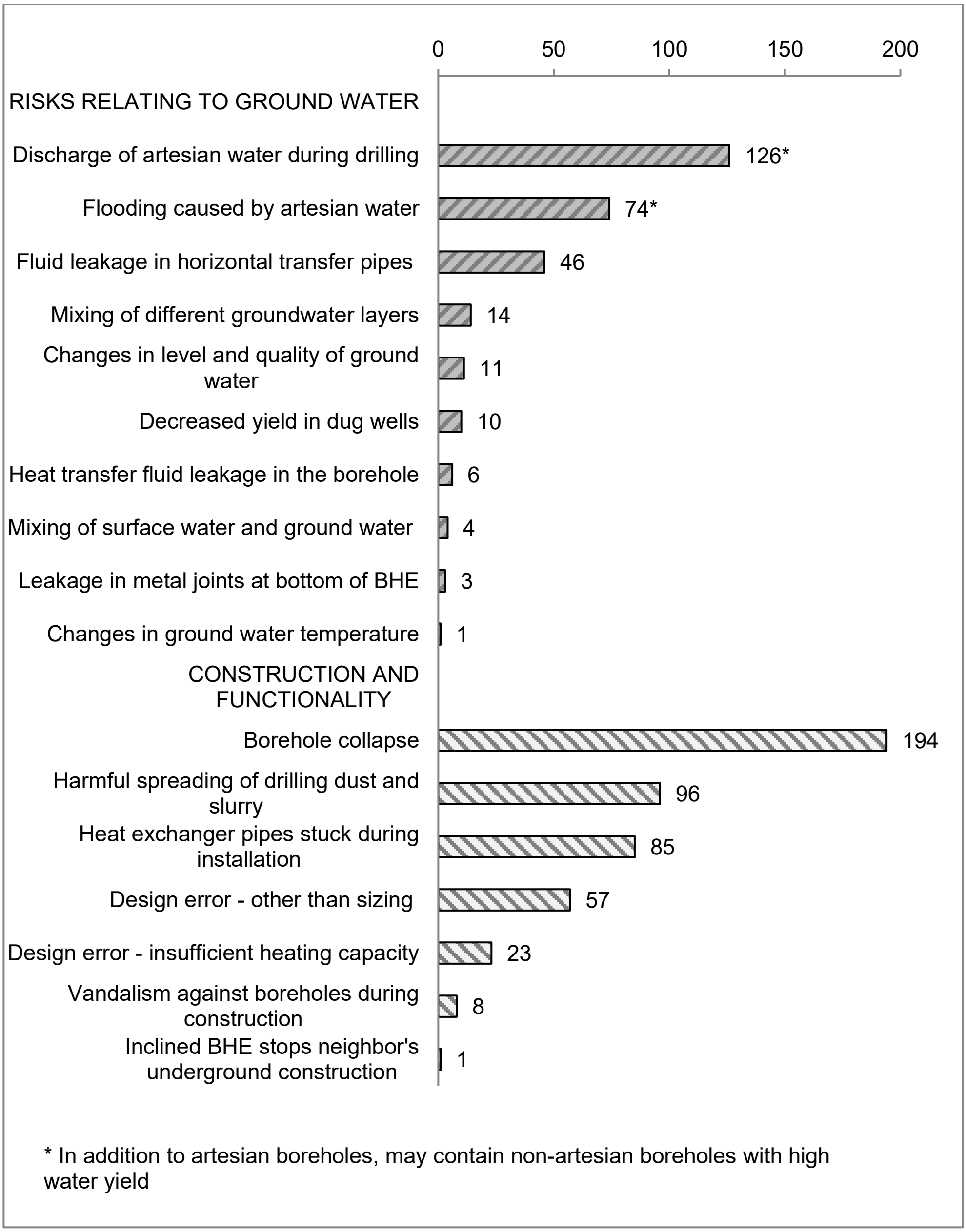

Figure 2. The numbers of different types of complications in questionnaire respondents' BHE projects. The respondents were asked to estimate the numbers of cases that had occurred in all the BHE projects of their company (the figures in brackets refer to the number of respondents reporting each type of complications). (II)

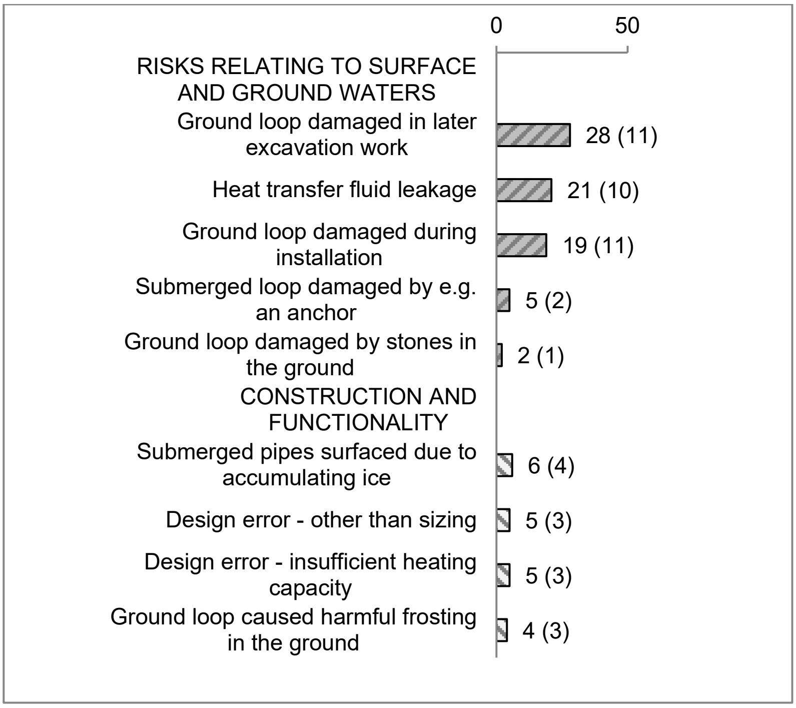

Figure 3. The numbers of different types of complications in horizontal GHEs and surface water heat exchangers reported by the questionnaire respondents (the figures in brackets refer to the number of respondents reporting each type of complications). (II)

The submerged pipes in surface water heat exchangers sometimes surface due to excessive ice accumulation (Figure 3), which is a constructional and functional problem as such, and may also cause leakages. Interviewee 3 described two cases in the 1980s that resulted in leakages in large surface water heat exchangers, comprising several kilometers of pipes. In both cases the problems resulted from excessive cooling, ice build-up around the pipes, consequent buoyance and partial surfacing of the pipes (II).

Four of the potential groundwater complications listed in the questionnaire were related to the borehole and drilling it: mixing of groundwater layers, mixing of surface water and groundwater, changes in level and quality of ground water, and decreased yield in dug wells. The respondents reported altogether 39 cases belonging to these categories (Figure 2). Eleven of these cases concerned changes in level and quality of groundwater. Two of the interviewed building control officials mentioned cases when water wells on neighbouring properties had dried up during BHE drilling. Possibly due to this, some Action Permit applications have been rejected based on the proximity of neighbours' water wells (III).

Interviewees 4 and 5 mentioned the risk of surface waters for groundwater deterioration. The pollution of groundwater is prohibited by the Finnish Environmental Protection Act (see section 3.2). Moreover, it is a business concern for companies that drill also water wells for their customers (II).

Since almost all BHEs in Finland are constructed without backfilling, surface water sealing is of utmost importance for groundwater safety. Of the questionnaire respondent companies 41% always and 16% often installed or required the installation of surface water sealing. Surface water sealing in the borehole may be implemented in different ways. These include plugs, plates, separate surface water casings and methods to improve the tightness of the borehole casing (II).

At the time of the questionnaire, 40% of the respondent companies used only 4½ inch (115 mm) boreholes, 24% 5½ inch (140 mm) boreholes and 4% 6½ inch (165 mm) boreholes. Over the past ten years the borehole diameters have increasingly shifted from 5½ towards 4½ inches, the latter being cheaper to drill (II). This has implications for the surface water sealing as not all the sealing methods are suitable for the 4½ inch boreholes.

In relation to groundwater issues in GHEs, it should be kept in mind that, apart from discharge and flooding of artesian water, most of the other problems with groundwater are rather difficult to detect. As one questionnaire respondent pointed out, for example mixing of surface water and groundwater, mixing of groundwater layers, or changes in the level and quality of groundwater are usually revealed only if there are water wells nearby (II).

A type of complication that certainly does not go unnoticed, is harmful spreading of drilling dust and slurry. Questionnaire respondents reported 96 of these cases (II).

In the questionnaire study, collapsed boreholes were clearly the most common type of complication in BHEs, with 194 reported cases (Figure 2). Geological conditions, in most cases fracture zones in the rock, were given as a reason for collapsed boreholes. The driller often observes signs of the borehole’s tendency to collapse already during drilling, but sometimes it is only revealed during pipe installation. In Finland collapsed boreholes are commonly handled by drilling the borehole open, although other measures may also be required (II).

To facilitate future inspections and repairs, it is practical to have the boreholes, and the connections between the collector pipes and the header pipes accessible by using a manhole instead of covering them directly with soil. A manhole here refers to a concrete or plastic ring with a cover of concrete, plastic or steel, placed on top of the borehole. When the questionnaire study was made, a clear majority of the respondent companies preferred to use a manhole (67 % always and 14 % often) (II).

The questionnaire respondents reported 23 design errors with insufficient heating capacity for BHEs, and 5 for horizontal heat exchangers (Figures 2 and 3). Interviewee 3 described the insufficient sizing of BHEs as a time bomb: he had encountered numerous boreholes that were frozen year-round. 13 respondents expressed their concern about the design practices of GSHP systems in general, or BHEs in particular (II).

Competition has been severe within the Finnish geoenergy sector in recent years. In the open-ended question “How does the competition present itself?”, 35 questionnaire respondents mentioned price competition, and 28 of them explicitly used the expressions ‘price dumping’, ‘under-pricing’ or ‘price competition at the expense of quality’. Meanwhile, 23 respondents expressed their concern about quality problems (I). Carelessness in the installation, such as neglecting pressure tests of pipes, inevitably leads to problems. As a general observation, Interviewee 6 underlined the importance of disseminating responsible environmental attitudes among the GSHP and borehole contractors (II).

3.2 Regulation and public governance

Environmental and quality issues are controlled by the public authorities through regulations and permit procedures. Also, financial incentives by the government may have an impact on how attitudes towards quality develop within the industry. The effects legislation has had on the GSHP industry in Finland, and the central statutes cited in this thesis are summarized in Table 3.

As for the significance of financial incentives, practitioners presented opposing views on the 2003–2011 direct subsidy scheme (I). The positive aspects of the subsidy were that it increased the demand for GSHPs, and GSHPs received publicity every year during the application period. On the other hand, some professionals criticized the 2003–2011 direct subsidy scheme for causing sharp fluctuations in demand (a) on a larger scale by its sheer existence and its ending, and (b) annually since there was only one application period per year. After the subsidy application, installations could not be initiated until the subsidy decisions had been made, which caused installations to pile up towards the end of the year. The periods of high demand brought new contractors into the trade within a short period of time. Many of them had little expertise, which led to defective installations. Overcapacity caused fierce and unhealthy price competition during times of low demand, and especially after the subsidy scheme had ended. At that stage some companies even went bankrupt. Another serious deficiency with the subsidy scheme was that it contained no requirements for the quality of installations or the qualifications of installers (I).

As a good way of subsidizing heat pump trade, the practitioners mentioned the tax deduction for domestic help work, which applies to retrofit geoenergy installations. The positive aspects of the tax deduction are that it has been reasonably predictable, and it has encouraged customers to choose companies that operate within the law instead of the black economy (Interviewees 5 and 6; I).

Table 3. Central geoenergy legislation in Finland (modified from I and Majuri, 2016b).

Topics and statutes	Contents	Notes
Qualification		
Finnish statute 2009/452 (servicing and maintenance of devices containing ozone depleting substances or certain fluorinated greenhouse gases)	GSHP installers must have a **refrigerant qualification**. Contractors must hire a foreperson with a qualification. For GSHPs with > 3 kg refrigerant, the foreperson must have a degree in refrigeration technique.	In force 2009–2016
Finnish statute 2016/766 (qualification requirements for handling devices containing fluorinated greenhouse gases or ozone depleting substances)	Only installation of heat pump systems assembled on-site requires a refrigerant qualification; installation of hermetically sealed GSHP units no longer does.	
Directive 2009/28/EC (promotion of use of energy from renewable sources, '**the RES Directive'**)	Certification or qualification must be available (not necessarily obligatory) for GSHP installers. Guidance must be offered for planners and architects.	
Note: For GSHP installations qualification requirements are no longer in force, for borehole construction they never existed. Voluntary training is available: Finnish Heat Pump Association introduced certification schemes for GSHP installers, and Finnish Well Drillers Association established a degree program for well drillers.		
Action Permit for ground heat exchangers		
Finnish statutes 1999/132, 1999/895 (Land Use & Building Act, and Decree), amendment 2011/283	Building a GHE requires an Action Permit, unless otherwise stated in municipal building code.	In force since 2011
Directive 2009/28/EC (promotion of use of energy from renewable sources, '**the RES Directive'**), Article 13	Licensing procedures are proportionate & necessary: procedures are streamlined & expedited; rules for licensing are objective, transparent, impartial & consider the particularities of individual technologies; simplified procedures for smaller projects.	
Groundwater protection		
Finnish statute 2011/587 (Water Act)	On designated groundwater areas, Water Permit is generally required for GHEs.	Acts contain no explicit regulations on temperature change etc.; permits may contain regulations
Finnish statute 2014/527 (Environmental Protection Act)	The pollution of groundwater with substances or energy is prohibited.	
Note: No binding national regulations exist for GHE construction or geoenergy systems in Finland.		
Financial incentives for GSHP deployment		
Finnish statute 2000/995 (amend. Income Tax Act **1992/1535**),	Tax deduction for costs of person and machine work in GSHP retrofit installations	
Finnish statutes 2002/1021, 2003/57 (residential renovation and energy saving grants)	State subsidy of up to 10% towards a retrofit GSHP system available to home-owners with electrical heating	Subsidy scheme began in 2003. Subsidies mostly ended in 2011, last subsidies in 2012.
Finnish statute 2008/115 (Amendment / grants for residential renovation, energy saving etc.)	Retrofit GSHP systems subsidised also if house previously had e.g. oil heating.	
Finnish statute 2010/1255 (Amendment / grants for residential renovation, energy saving etc.)	GSHP installations were removed from the list of subsidised measures.	

3.2.1 Municipal governance and the Action Permit scheme

Many geoenergy practitioners approved of the need for a control mechanism concerning GHEs: in built-up areas the positioning of BHEs should be carefully considered so that heat is not extracted from adjoining properties, and the safety zones between for example boreholes and small-scale sewage treatment should be ensured. The municipal permit procedure has been designed to achieve this, but it also received criticism from the questionnaire respondents relating to, for example, ambiguous permit practices and differences between municipalities, and the inadequate expertise of permit issuing authorities (I).

The municipalities indeed have varying practices regarding for example distances between BHEs and property borders. Most municipalities require neighbour hearings (or in some cases neighbour's consent) if distance between the BHE and property border is less than a defined limit. However, this limit varies from 4 to 50 meters. Several municipalities apply a limit of either 7.5 or 10 meters (III).

Municipalities have diverse approaches to quality control during the application phase. While some municipalities require an attachment form to the application that describes the construction methods of the GHE, others may only require that, for example, the BHE's location, depth and possible inclination are marked on the site plan (III).

Some municipalities handle the quality control of geoenergy installations by requiring that a site manager, i.e. a responsible foreperson to direct the work, is nominated. However, the effectiveness of this measure is limited because few of the municipalities have specified competence requirements for the site manager. In the other municipalities for example the clients themselves may act as forepersons (III).

In terms of post-installation quality control, some building inspectors may control certain details at inspections, such as pipe connections, floor drains, pipe insulations, and whether the client has received user guidance. As for the registration of GHE systems, most of the studied municipalities have a map or a GIS where they enter the GHEs with some degree of accuracy (III).

3.2.2 Regional governance and the Water Permit scheme

The geoenergy practitioners did not comment on the Water Permit scheme in the questionnaire (I). However, one respondent emphasised the importance of proper surface water sealing on designated groundwater areas. His or her opinion was that if this cannot be guaranteed, drilling on designated groundwater areas should be completely prohibited.

The Water Permit decisions were to a certain extent connected to the current use of the groundwater reserves. Permit decisions (i.e. whether granted or rejected) correlated with the distance between a planned construction site and the nearest water intake plant. On the other hand, there was no statistically significant difference in permit decisions in relation to groundwater flow direction between the construction site and the nearest water intake plant (IV).

The permit policies of the AVIs became significantly stricter since the early 2014 (Figure 4). While studying the permit decisions in search of reasons for this change, my attention was caught by repeated references to an instructions letter dated in October 2012 ('Uusimaa ELY instructions letter'). The ELY Centre at Uusimaa Province had targeted it at the municipal environmental protection authorities and building control authorities in the Uusimaa Province. This legally non-binding instructions letter aimed to (1) draw the municipal authorities' attention to groundwater protection and the risks of geoenergy systems when processing BHE Action Permits, (2) clarify conditions in which a Water Permit is needed, and (3) present principles and construction procedures that would benefit groundwater protection (IV).

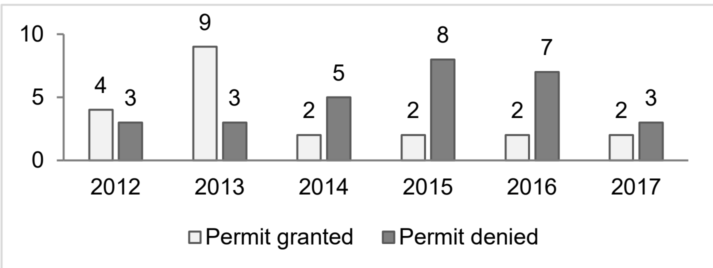

Figure 4. Annual permit decisions for borehole heat exchangers by all AVIs. Note that in 2015 one permit and in 2016 two permits were granted due to annulment of AVIs' earlier permit denials at Administrative Courts (IV).

The instructions letter was also sent to some other ELY Centres and ESAVI for their information (Timo Kinnunen, Uusimaa ELY Centre, personal communication 12 February 2019). In the subsequent years, from late 2013 on, the regional authorities especially in southern and central Finland frequently referred to the Uusimaa ELY instructions letter in their statements and decisions (a summary in IV, Appendix B). I identified 23 permit decisions with references to the instructions letter, and in 10 of these the instructions letter was explicitly mentioned (IV).

A direct result of the Uusimaa ELY instructions letter was that the principle of equality emerged as a justification for permit rejection in permit decisions made by ESAVI (others do not use this). Other topics that appeared in the AVI decisions and ELY statements as a result of the instructions letter were (IV):

- The unpredictability of the subsurface conditions: "*The ground and bedrock structure, and the groundwater conditions of designated*

groundwater areas are so complicated and variable at local scale that --- the possibility of damage to groundwater or neighbours' water wells can never be completely ruled out."
- "*[F]rom the groundwater protection perspective, it is not desirable that large* [residential] *areas are formed on designated groundwater areas on which heating is based on geoenergy.*"
- An interpretation about the nature of heat transfer fluids: "[The heat transfer fluids used in geoenergy systems] --- *are harmful to groundwater in the same way as for example fuel oil or solvents, and thus they must not end up in the groundwater under any circumstances."*

In addition to the references to the Uusimaa ELY instructions letter, the reasoning in ESAVI decisions changed also otherwise since 2014. Risks that in earlier permit decisions were covered by requiring safety precautions in the permit regulations became justifications for denying the permits (e.g. intrusion of lower-quality or salty water into the clean aquifers, and oil leaks from drilling equipment). ESAVI also adopted the view that there are few (if any) technologies available to reduce BHEs' adverse effects on groundwater. Nevertheless, some AVI decisions and ELY statements have placed technical requirements to improve groundwater safety, such as protective sleeves, borehole backfilling and surface water sealing. Since 2015 ESAVI also adopted the precautionary principle as an additional reason for rejecting permits (IV).

Many permit applications highlighted the environmental benefits of replacing oil heating with geoenergy, namely the possibility to reduce risks for groundwater from fuel oil tanks and to decrease CO_2 and particulate emissions. However, the AVIs mostly did not regard the ending of oil heating as a benefit in their permit decisions (IV).

3.3 The capacities of practitioners and permit authorities

3.3.1 Qualifications

Currently no qualification requirements are in effect for geoenergy practitioners after the refrigerant qualification requirement for GSHP installers was abolished from the Finnish legislation at the end of 2016 (Table 3; II). The questionnaire study was conducted in 2014 when the refrigerant qualification requirement was still in force. Even at that time ten questionnaire respondents either expressed their concern about the unqualified installers in the GSHP sector or called for better training or qualification requirements for the practitioners. Several respondents also criticised the limited and mostly irrelevant content of the refrigerant qualification, and the lack of enforcement of this decree (I).

Finland's Environmental Administration (2017) emphasizes in its instructions that "The writer of a [Water Permit] application must have sufficient expertise to write the application". The application process is indeed complicated and somewhat challenging for non-expert clients, and it has been recommended (e.g. in the Uusimaa ELY instructions letter) that these applications should be written by professionals. We do not know how often this is the case, but the quality of the permit applications varied considerably. More than ten applications gave deficient or false information about the amount or composition of the heat transfer fluid to be used in the system. The permit applications disagreed on sufficient safety measures. The Energywell handbook (Juvonen & Lapinlampi 2013: 27) and its instructions relating to building geoenergy systems on designated groundwater areas received varying degrees of attention. The permit applications proposed varying solutions for surface water sealing. Surprisingly, several applications included no plans whatsoever for a surface water sealing method, although they were seeking to gain a permit to build on a designated groundwater area (IV).

In the questionnaire study, some geoenergy practitioners expressed doubts about the municipal permit authorities' competence to handle GHE permits (I). It seems that there is variation between the officials in their level of knowledge, depending on their own interest and experience. Regarding instructions they had received for handling municipal Action Permits for GHEs, three interviewees mentioned the Energywell handbook published by the Finnish Ministry of the Environment (Juvonen & Lapinlampi, 2013). All the interviewees were asked for suggestions to improve the Energywell handbook, whereupon they mentioned for example instructions on how to prevent and handle problematic situations and special cases, and more detailed instructions for new inspectors. Courses and training days offered by the Finnish Society of Building Inspectors were also mentioned as a source of information. One interviewee mentioned the municipality's own instructions for GHE systems. One interviewee simply pondered that "It probably wouldn't hurt to get some more information" (III).

The regional administration seems to need further resources to deal with the scientific side of the Water Permit processing. Several AVI decisions and ELY statements contained elements that contradict with groundwater geology and chemistry. These were related to the hazardousness of heat transfer fluids, the probability and potential quantity of leakages as well as the movement of fluid in the ground in case of a leakage (IV).

3.3.2 Regulation of geoenergy construction and permit procedures

In Finland there are no national building regulations for geoenergy systems or GHEs. In the questionnaire study, 62% of the respondents (N=63) were of the opinion that the municipal Action Permit should require BHEs to be built following certain standards. 16% were against standards, and 22% had no opinion. Some respondents called for qualified official supervision of GSHP installations in general, and sizing of GHEs in particular to promote quality and functionality (I).

In addition to national legislation, municipal regulations guide the Action Permit procedures for GHEs in the municipalities (III). The same applies to Water Permits: Both national legislation and municipal regulations are legally binding and must be observed. In practice, the Water Act and the Environmental Protection Act provide minimal guidance in relation to geoenergy permit decisions. There were only some isolated cases in which the AVI had found the geoenergy project to conflict with the town plan or the municipal building code legally in force. However, in four of the studied permit decisions, AVIs referred to a *protection plan for a designated ground water area* (IV). Such protection plans are not legally binding but serve as guidelines for municipal land use planning and building codes as well as for processing permit applications (Finnish statute 2004/1299; Finland’s Environmental Administration, 2019).

4 Discussion

This thesis deals with (1) environmental and technical issues that are central for the future development of the geoenergy industry in Finland, especially groundwater protection and quality of installations, (2) the role of public regulation and governance in promoting these, and (3) how to better deal with these issues, that is targets for development as regards the GHE permit schemes, qualification requirements and building regulations for GHEs in Finland.

It seems that in the 1970s and 1980s the development of the GSHP industry in Finland was mostly directed by the energy price and internal factors of the industry, while legislation still had a minor role. The GSHP industry rose in the 1970s aided mainly by the energy crises that led to high oil prices and public research funding (I).

In the 1980s the downturn of the industry resulted from a combination of lost reputation and decreasing energy prices. The GSHP factories' fate was sealed when wholesalers sold their large GSHP stocks out at a cheap price and caused the prices to collapse (Lauttamäki, 2018: 121). Quality issues were behind the fall of the industry also in Switzerland and Sweden (Rognon, 2008; Nilsson et al., 2005). However, Lauttamäki (2018: 122) suggested that, of the more than 10 000 geoenergy systems sold in Finland by 1984, the majority (presumably 2/3 or more) functioned well, and the owners of geoenergy systems had for the most part positive views on geoenergy. Yet, geoenergy had a poor reputation among the general public.

In the 1990s the market situation, the societal atmosphere and public attitudes began to develop in a more favourable direction for the heat pump industry in Finland. This was in part caused by the strong emergence of sustainable development and climate policies that emphasized the role of alternative energy sources (Kivimaa & Mickwitz, 2011). The positive development in Sweden encouraged and directed the Finnish GSHP sector. Important success factors were at least (I):

(1) Developing technologies: technically more reliable GSHPs, and the emergence of borehole heat exchangers

(2) Rising energy prices in the 1990s and the beginning of the 2000s (Figure 1)

(3) Improving distribution channels and familiarity of the technology: At first the specialised retailer networks improved the credibility and reliability of the technology since the 1990s. Later on, heating and plumbing contractors have increased the installation capacity. Meanwhile the expertise and credibility of the industry have been improved by the training and certification schemes introduced by the Finnish Heat Pump Association since the beginning of the 2000s.

(4) In the 2000s environmental policy and legislation have had a double role in shaping the GSHP industry in Finland: On the one hand they have contributed to the deployment of GSHPs through subsidies. On the other hand, regulations have been introduced to control the expanding industry (Table 3).

In addition to the above-mentioned factors, the general economic trend in Finland has strongly influenced the GSHP industry in recent years (I). However, although sales in absolute numbers decreased after 2011, GSHPs continued to increase in relative popularity, and since 2013 more than 50% of new single-family homes in Finland have had a GSHP installed (Motiva, 2019).

4.1 Environment, quality and the future of geoenergy in Finland

As the number of operative geoenergy systems grows, the success and acceptability of the industry depend increasingly on the environmental safety of installations, such as groundwater protection. More broadly, keeping in mind the development of the 1980s, the general quality of installations is essential for the success of the industry.

Quality issues have been widely addressed in several geoenergy projects and studies (e.g. Benou & Sanner, 2008; Geotrainet, 2011; Dehkordi & Schincariol, 2014). Yet, in our data on the geoenergy industry in Finland, many practitioners were concerned about the unhealthy price competition at the expense of quality (I). Also, in many cases the regional authorities did not trust the contractors' abilities to build safe geoenergy systems in designated groundwater areas (IV).

Internationally there are a few examples of large-scale damage events with geoenergy systems. Fleuchaus and Blum (2017) analysed nine such events in Germany, each of them exceeding 500 000 € in damages. The Finnish geoenergy sector has been spared from unfortunate events of this magnitude. The Finnish geology that mostly consists of solid crystalline bedrock safeguards BHE projects from many of the risks described by Fleuchaus and Blum (2017), such as upheaval caused by swelling of anhydrite-bearing layers or subsidence resulting from drilling into karst structures. Also, the geological conditions in Finland do not favor very high pressure and yield in artesian bedrock aquifers. Thus, usually cases involving artesian water cause moderate damage at most (II).

In the questionnaire study, the respondents reported approximately 850 cases of complications in their GHE projects. Figure 5 illustrates roughly, how the effects of these cases could fall upon different stakeholder groups.

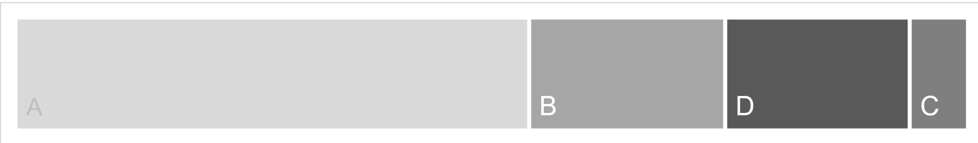

Figure 5. An estimate of how different stakeholders could have been affected by the complications (850 cases) reported in the questionnaire study. The estimate was made based on a discussion with a geoenergy expert. For each type of complications an estimate was made as to how many of the reported cases could possibly affect each of the listed stakeholder groups. The estimate refers to numbers of cases, not for example the amount of inconvenience or damage caused by these cases. Note that the estimate was made based on the responses to this questionnaire study; it was not possible to consider its applicability to all possible geoenergy complications in Finland
A – cases that likely cause problems only for the contractor
B – cases that potentially cause problems for the client and the contractor
C – cases that potentially cause problems for neighbours (and client and contractor)
D –cases that may involve a risk for the environment (and neighbours, client and contractor)

The horizontal header pipes, as well as horizontal GHEs are prone to damage by stones in the ground and excavation work, and consequent leakages. To prevent the latter, a warning tape is commonly placed in the ground above the pipes. In the Nordic climate conditions, upfreezing moves stones vertically in the ground (Anderson, 1988) so that the pipes may be at risk even if stones around the pipe have been removed during installation. Surface water heat exchangers are the most susceptible type since they have no protection against anchors, moving ice or other external factors in the water (II).

Central issues relating to heat transfer fluid leakages are for example toxicity of the fluid constituents or their degradation products, and oxygen depletion caused by biodegradation of the fluid constituents. These questions have been studied in relation to glycol-, betaine- and potassium formate -based fluids (Klotzbücher et al., 2007; Ilieva et al., 2014; Schmidt et al., 2016). Similar studies have not been conducted on the ethanol-based heat transfer fluids commonly used in Finland. In their studies Klotzbücher et al. (2007) and Schmidt et al. (2016) discovered that the commercial glycol-based heat transfer fluids are less biodegradable and more ecotoxic, than glycol solutions without additives. This implies that further research is needed also on the environmental impacts of the ethanol-based heat transfer fluids (II).

Lankia and Kleiman (2009) described a heat transfer fluid leakage in southern Finland. The case had serious consequences for a neighbour's water well and exemplifies problems that may follow from oxygen depletion when heat transfer fluid leaks. The anoxic conditions considerably increased the iron and manganese concentrations of the water. Also, iron sulphide (which is oxidized into e.g. sulphuric acid) appeared in the water. Large corrosive damage developed in the water pipes and the water became unusable.

Problems arising from the actual borehole connect to issues like handling difficult geologies and creating an artificial conduit between separate, superposed aquifers. Hydraulic connections between aquifers have been commonly discussed in environmental geoenergy studies (e.g. Hähnlein et al., 2013; Haehnlein et al., 2010; Dehkordi & Schincariol, 2014; Buday, 2014). The main concerns are changes in the level of groundwater and deterioration of groundwater quality due to intrusion of either surface water or low-quality groundwater from different aquifers with saline or polluted water.

To avoid problems with boreholes, the driller should master the drilling techniques and be able to interpret the geological clues conveyed by the drilling equipment. One of the interviewees, a retired borehole contractor, emphasized the significance of expertise and experience in borehole drilling: "*You can learn to operate the drill rig in a relatively short time, but learning to really drill, to know what happens down inside the rock, that takes time. --- And managing the more challenging situations is a whole different story. If someone else must try and fix them afterwards, it is incredibly difficult.*" With difficult geologies the driller should be able to diagnose the geological situation and, based on this, decide for example how fast and with what air pressure drilling may be continued, how long the casing should be and should the fracture zones be injected with concrete before continuing drilling.

Methods to prevent intrusion of low-quality water into aquifers include surface water sealing and backfilling of the borehole. Surface water sealing should be a standard practice and several methods involving different casing solutions, or plug- and plate-like structures are applied in Finland. Borehole backfilling may be used for surface water sealing and to prevent aquifer cross-contamination. Backfilling is not commonly used in Finland (see section 1.2 above for details), but on designated groundwater areas it has sometimes been required. The tightness of the backfilling is a potential challenge (Riegger et al., 2012; Bucci et al., 2018). Thus, using this method requires proper training and caution, even more so as there is relatively little experience of the method in Finland.

When drilling on designated groundwater areas, Juvonen & Lapinlampi (2013) recommended regular monitoring of chloride concentrations or electrical conductivity of the water to detect possible saline aquifers. Apart from this, there are no instructions on monitoring the impacts of BHE construction. Moreover, subsequent inspections and monitoring of the borehole are possible only if it has been constructed with a manhole (II).

Currently there are some geoenergy pilot projects under way in Finland involving boreholes that are approximately two kilometers deep. Several of the challenges depicted in Figure 2 may apply also to these deeper boreholes, such as issues with artesian water and abundant water yields, borehole collapse and the installation of pipes. On the other hand, the development of these technologies is in its early stages, and the magnitude of risks relating to for example fluid leakages and aquifer cross contamination will depend on the choice of heat transfer fluids, types of heat exchanger pipes, casing and possible backfilling.

4.2 Targets for development

4.2.1 Qualification requirements for practitioners and national regulations for GHEs

Stern (1992) highlighted the concept of problem avoidance in the context of promoting the diffusion of energy-efficient technologies. From the users' point of view this involves high quality of the systems, and simple shopping processes. In Finland a lot remains to be done in both respects. In their analysis of heat pump users in Finland, Heiskanen et al. (2014) pointed to "limited standards and the early stage of certification systems and advice by the public sector". They continued by listing the challenges these circumstances present for users: the users should, for example, make sure the products and service providers are competent and their plans are realistic, monitor the installation, and monitor and adjust their heat pump systems.

Thus, in line with the notions of Heiskanen et al. (2014), practical ways to advance system quality and to assist the clients in fulfilling their duties in supervising geoenergy projects are (1) placing qualification requirements for professionals involved in geoenergy projects and (2) designing comprehensive national building regulations for GHEs (I, II, III). Qualification requirements are commonly applied for example in the United States (Liu et al., 2015), and also in some Swedish municipalities using a certified driller is a prerequisite for a geoenergy permit (Jardeby et al., 2013).

The value of trained and qualified GSHP installers and drillers, as well as designers and architects has been highlighted in international reports (Benou & Sanner, 2008; REGEOCITIES 2013) and EU legislation (the RES Directive 2009/28/EC, Article 14). The importance of training for securing quality emerged also in many questionnaire responses in this study (I).

Since no qualification requirements are in force for Finnish geoenergy installers and well drillers, their competence relies on work experience, possible training by suppliers and voluntary training and qualification programs that have been set up for well drillers in Finland (Poratek, 2015), and for heat pump installers at the European level (EHPA, 2019).

HVAC designers' geoenergy expertise also varies significantly. This becomes an issue in larger projects with complicated geoenergy configurations and their integration to the heating system. As designing geoenergy systems is quite different from for example traditional oil heating systems, designers need to be trained for it and a certification system to verify their competence would be appropriate.

Instead of improving the quality of installations, the public subsidy scheme that was in place in Finland until 2011 aggravated the quality problems (I). An essential deficiency in the subsidy program was that no quality requirements were incorporated, unlike in e.g. Norway and Denmark (Bjørnstad, 2012; Nyborg & Røpke, 2015). In order to receive the subsidy for a geoenergy project in Finland, no requirements were imposed on the construction of the system, quality of the components, or qualification of the installers. This lack of quality incentives together with the overcapacity, which was also fuelled by the subsidy scheme, contributed to the unfolding of the unhealthy price competition at the expense of quality. In this respect the subsidy failed as a policy measure (I).

Regarding the qualifications of site managers, the current Land Use and Building Act distinguishes between demanding, ordinary and minor supervision work, and defines the qualification requirements for each category separately (Finnish statute 1999/132, section 122c). For *ordinary supervision work*, requirements are placed on the training and experience of the site manager. To undertake *minor supervision work*, no degrees are required but anyone who "may be seen as having sufficient prerequisites" is accepted. Thus, most of the studied municipalities have placed GHE installations into this latter category by accepting for example lay clients as site managers, which may be considered a non-optimal solution (III).

Incorporating national BHE building standards or regulations into the Action Permit scheme was supported by most respondents in the questionnaire study, which suggests that practitioners have commonly perceived the deficiencies in quality and inconsistent building practices as a problem (I). In the market of intense competition, the lack of statutory requirements encourages many contractors to neglect anything that is not necessary for the immediate functioning of the system. This eventually jeopardises environmental safety and system quality. For example in Sweden many municipalities have incorporated building standards into their BHE permit system (Jardeby et al., 2013; SGU, 2016).

Issues to be covered in the national building regulations are for example the placement of GHEs, proper installation of the borehole casing, acceptable methods for surface water sealing, handling of drill cuttings, quality and handling of heat transfer fluid, the backfilling procedure, and the installation criteria for the manhole. To design adequate regulations, technical, scientific as well as administrative expertise must be utilized. Further research would also be useful, for example the various methods of surface water sealing, their effectiveness and functionality should be researched (II, IV).

EU-level legislation and standards, as suggested by Tsagarakis et al. (2020), is one way forward. Since regional geologies vary significantly across Europe, listing detailed specifications at the EU-level may not be feasible, so that national governments should still develop their own regulations. The efforts at both national and European level could be assisted by for example a current international effort titled ‘Quality Management in Design, Construction and Operation of Borehole Systems’ (BoreSysQM, 2019), which compiles information on national procedures, and develops precautionary measures and recommendations for national and international guidelines and standards.

4.2.2 Governance

Finnish geoenergy practitioners expressed concerns about the heterogeneous Action Permit practices in different municipalities and municipal officials’ inadequate competence regarding geoenergy systems (I). Also previous research and reports have discussed the divergent permit practices in Finnish municipalities regarding small-scale renewable energy generation (Tarasti et al., 2015; MEE, 2014; Ruggiero et al., 2015). They have recommended for example simplifying, speeding up and harmonizing the permit processes with nationally standardized procedures, which would also be better in line with Principle 5 (impartial enforcement of rules and regulations) of the Council of Europe’s (2019) good governance guidelines (III).

Earlier studies have observed that heterogeneous permit practices complicate the adoption of renewable energies, for example in the UK regarding micro-wind turbines (Park et al., 2013) and in California in relation to small-scale solar and wind installations (Jacobson et al., 2014). From the perspective of both good governance and efficient adoption, a relatively uniform permit scheme would be recommendable.

Measures to promote quality control vary between municipalities. Principle 2 of the Council of Europe’s (2019) good governance guidelines states that procedures should be adapted to the legitimate needs of citizens. Considering this principle, the ‘duty to take care in building activities’ (Finnish statute 1999/132, section 119) is challenging for non-expert clients. Indeed, the Ministry of the Environment has given (non-binding) instructions that the extent of supervision by the municipal building control should be adapted to the level of expertise of the client, and that the need for public supervision increases when public interests are involved (ME, 2015: 5). In the case of GHEs, groundwater protection is such an important public interest (III).

Geoenergy practitioners identified preventing uptake of heat from adjoining properties as one of the positive effects of the Action Permit scheme (I). Some municipalities require 4 – 5 meters between a BHE and property border, which is too little in this respect. The recommended distance between two BHEs intended to be thermally independent is 15 m in Finland and 20 m in Sweden (Juvonen & Lapinlampi, 2013: 25; SGU, 2016: 25). If the distance is below 20 meters, it is recommended that this is compensated for by building a deeper BHE. Neighbour hearings are essential here to chart the locations of existing BHEs and to consider the neighbours' future needs. Neighbours must also be informed about the GHEs' possible influence on their property for example through heat extraction (III).

In many municipalities, clients receive useful information during the permit procedure regarding environmental issues and adjoining properties, such as (1) distances that should be left between GHEs and various other objects, (2) groundwater protection, (3) quality and handling of heat transfer fluid, and (4) handling of drill cuttings and sludge (III). One municipality has instructed a procedure for handling old oil tanks when oil heating is replaced with geoenergy and reminded of the asbestos regulations if asbestos insulation has been used in the old plumbing (III).

The building control may also offer quality control support for the client. By requiring the nomination of a qualified site manager (e.g. a drilling contractor with verified qualifications), the building control promotes a professional quality approach. If the final inspection is conducted on site, a variety of details may be covered (III).

With the permit or notification procedure, the public administration is now able to keep track of the locations and abundance of GHE systems. Unlike for example in Sweden (SGU, 2015), there is no borehole register in Finland. Thus, before the permit scheme took effect, the public authorities had little information regarding the constructed boreholes and geoenergy systems, or their locations. Maintaining a GIS or a map of GHE systems benefits, in addition to the building control, also the environmental authorities, surrounding property owners, future property owners and geoenergy practitioners (III).

There is a need for clarified legislation in relation to the GHE permit schemes. Since there are no binding regulations for the construction of GHEs in Finland (I), and since the Environmental Protection Act or the Water Act do not provide a clear enough foundation for making permit decisions, decisions are made based on soft law, i.e. non-binding instructions and recommendations. The lack of adequate binding judicial regulation for geoenergy permits explains, for example, why the

Uusimaa ELY instructions letter became a guideline for regional authorities in many parts of the country, which it was probably not originally meant to be (IV).

Furthermore, Principle 7 in the Council of Europe's (2019) good governance guidelines states that the professional skills of those who deliver governance should be continuously maintained and strengthened to improve their output and impact. Thus, in addition to judicial regulations, also further technical and geological instructions are needed for the permit authorities so that they can make scientifically sound and well-founded permit decisions.

5 Conclusions

Quality control has so far not been at the forefront when planning Finnish geoenergy policies. Although quality is an essential factor for user satisfaction, environmental protection, and the success of the industry, quality requirements were omitted for example from the former public subsidy programme for geoenergy systems.

Permit schemes are the link between legislation and installation practice. To develop the Action Permit scheme and improve governance, earlier studies and reports have called for a national standard to simplify, speed up and harmonize the permit processes. In addition to speed and simplicity, other objectives to be kept in mind are promoting environmental and groundwater protection, safeguarding the neighbours' interests, and supporting the clients in quality control. These objectives are also a top priority for the geoenergy industry in maintaining its reputation and credibility. To advance all these goals, national standards need to be developed for both the Action Permit procedure and the construction of GHEs. National standards set the qualitative and environmental goals and describe the means how to reach them, allowing for different geological and environmental conditions. The standards simplify the permit process for clients, authorities and practitioners as each building inspector does not need to formulate their own building regulations. Qualification requirements for geoenergy designers, installers and drillers need to be incorporated into these standards.

As for the Water Permit scheme, geoenergy issues were not considered when enacting the Water Act and the Environmental Protection Act, which thus provide meagre support for making permit decisions. Correspondingly the role of soft law documents is more prominent. Field specific regulations are needed to clarify the legislation. Additionally, technical and geological instructions need to be developed to promote geologically sound reasoning in the handling of permits.

Table 4 summarizes, how policy and practice could be developed for geoenergy construction. This development could be supported by further research, and several topics emerged in the course of this project. These include for example the ecotoxicity and biodegradation of ethanol-based heat transfer fluids; frequency and consequences of undersized BHEs in the Nordic countries; and comparison of different borehole designs (e.g. surface water sealing and its design, borehole diameter) and their functionality in an experimental setup.

Table 4. Goals and recommendations for developing geoenergy policy and practice in Finland

Goals	Recommendations
Simplify, speed up and harmonize permit processes in municipalities	National standards for the Action Permit procedure regarding geoenergy
Harmonize permit processes in regional administration	Geoenergy-specific regulations into the Water Act and Environmental Protection Act
Ensure technical and geological expertise of permit authorities	Advanced technical and geological instructions material and training for authorities
Environmental and groundwater protection	National standards for the construction of GHEs and boreholes
Safeguard neighbours' interests	Qualification requirements for geoenergy practitioners
Support clients in quality control	Quality requirements incorporated in subsidy schemes

The quality and environmental safety of installations have a decisive role for the future success and acceptability of the industry. Promoting these requires cross-sectoral expertise in formulating the national standards, and commitment to their implementation by both the industry and the public administration.

Acknowledgemets

I have had the opportunity to work within and around the geoenergy industry in Finland since the end of the 1990s, while geoenergy has risen from obscurity to one of the most popular heating techniques. Over these two decades I have met many geoenergy experts who have believed in the technology and its economic and environmental potential. From the mid-1980s until late-1990s few others did, and these visionary individuals received little appreciation for their ground-breaking, hard work that some of them had been doing since the 1970s. Discussions with these experts and working with skilled installers, drillers and other specialists in the field have taught me a lot about the technology itself and about responsible attitudes to practising this trade.

This PhD project began when I contacted docent Timo Vuorisalo and asked him how I could combine my geoenergy experience with my previous studies in environmental science. “You could always write a PhD thesis,” Timo pondered and offered to supervise it. So I did although it certainly was not what I had had in mind. As a supervisor Timo has done a great job (and lots of it): he has been helpful, patient, encouraging and excellently available for consultations. Timo has reviewed, edited and co-authored diligently, and his faith in this project has astonished me many times. So, Thank You Timo!

Professor Anne Kumpula (Faculty of Law, University of Turku) and Dr. Teppo Arola (Geological Survey of Finland) have also co-authored articles for this thesis. Anne and Teppo have contributed valuable new ideas and insights as well as significant legal and geological expertise that have crucially improved the outcome of this multidisciplinary project. The preparation of article manuscripts has been assisted by Tero Klemola, Matti Ketola, Totti Tuhkanen, Tommi Heikkinen, Timo Saarinen and Timo Kilpeläinen through statistical advice, IT consultations and manuscript comments. Jussi Hirvonen (Finnish Heat Pump Association) has provided information and statistics for my research.

I extend my warm thanks to the esteemed pre-examiners of this thesis, Professor Peter Bayer and Professor Peter Lund, for their contribution, and reassuring and helpful comments.

The staff at the Department of Biology and the BGG Doctoral Programme have been most helpful. Thank you, Hanna, Jon, Sari and Tiia, for your continued support and all the interesting seminars and events that have brought me out of my lonesome research den. Furthermore, I thank my research directors Kai Norrdahl and Pekka Niemelä for their contributions.

The team spirit among BGG students has been a source of joy and much support. Thank you, Camilla, Fabio, Glenda, Hanna, Henna, Jussi, Markku, Robin, Saija, Tam, Tapani and all others, for good collaboration, friendship and sharing this bumpy voyage.

Much of the data for this thesis has come directly from geoenergy professionals and municipal authorities. They have devoted time into giving questionnaire responses and interviews and compiling permit applications from archives. I very much appreciate their efforts which have been vital for this work. Also, Finnish geoenergy-related organisations helped by delivering the questionnaire to their members.

I gratefully acknowledge the research and travel grants that I have received for this project from Kone Foundation, Maa- ja vesitekniikan tuki ry, Fortum Foundation, Department of Biology at the University of Turku and the BGG Doctoral Programme at the University of Turku.

I am forever thankful to my father and late mother for the profound and diverse support in my life and studies. Your positive thoughts have followed me throughout this work. Likewise, I appreciate the frequent encouragements and happy times shared with other members of my extended family and friends: Thank you to my sister Katri and to Annikki, Barbara, Eeva-Riitta, Irma, Jaana, Kirsi, Leila, Salla, Terhi, Terttu and Mikko, all your families and many others!

Finally, a thousand thanks to my dear family! Thank you Jouni for sharing your extensive technical expertise in geoenergy systems, reviewing manuscripts and encouraging me along. Thank you Anni for being such a helpful courier at the university. Thank you, Olli, Suvi, Emma and Anni for your love and patience, for keeping my feet on the ground, and for making my life meaningful.

List of References

Aittomäki A., 1983. *Maaperä ja vesistöt lämmönlähteinä*. (In Finnish, Ground and surface water as heat sources). Tampere University of Technology, Department of Mechanical Engineering, Thermal Engineering, Report 37. Tampere.

Aittomäki A. & Wikstén R., 1978. *Maaseudun asuinrakennusten lämmitys lämpöpumpulla*. (In Finnish, Heat pump heating of residential buildings in the countryside). State Technical Research Centre, Laboratory of HVAC Technology, Report 38.

Anderson S. P., 1988. The upfreezing process: Experiments with a single clast. *Geological Society of America Bulletin*, 100: 609–621.

Anon., 1948. Fireless furnace: It pumps heat from earth to house. *Life*, 25(17): 83–84.

Arola T., 2015. *Groundwater as an energy resource in Finland*. Academic dissertation, University of Helsinki, Department of Geosciences and Geography, A36.

Arola T., Eskola L., Hellen J. & Korkka-Niemi K. 2014. Mapping the low enthalpy geothermal potential of shallow Quaternary aquifers in Finland. *Geothermal Energy* 2(1): 1–20.

Arola T. & Korkka-Niemi K. 2014. The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland. *Hydrogeology Journal* 22: 1953-1967.

AVI, 2018a. The environment. Regional State Administrative Agencies. Accessed 3 September 2019 http://www.avi.fi/en/web/avi-en/environment.

AVI, 2018b. Vesilupapäätökset (in Finnish, Water permit decisions). Regional State Administrative Agencies. Accessed 20 November 2018, https://www.avi.fi/web/avi/vesiluvat-paatokset?p_p_id=122_INSTANCE_aluevalinta&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_r_p_564233524_resetCur=true&p_r_p_564233524_categoryId=14398#.WsX7YX--mUm.

AVI, 2018c. Lupa-tietopalvelu (in Finnish, Permit information service). Regional State Administrative Agencies. Accessed 20 November 2018, https://tietopalvelu.ahtp.fi/Lupa/.

Banks D., 2012. *An introduction to thermogeology: Ground source heating and cooling*. 2nd edition. Wiley-Blackwell.

Bayer P., Saner D., Bolay S., Rybach L. & Blum P. 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. *Renewable and Sustainable Energy Reviews*, 16: 1256–1267.

Benou A., Sanner B., 2008. Proposals for improving GSHP standards. Deliverable 22, Project Ground-Reach. Accessed 29 July 2019 https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/ground-reach_proposals_for_improving_gshp_standards.pdf.

Bjørnstad E., 2012. Diffusion of renewable heating technologies in households. Experiences from the Norwegia Household Subsidy Programme. *Energy Policy*, 48:148–158.

Bleicher A., Gross M., 2016. Geothermal heat pumps and the vagaries of subterranean geology: Energy independence at a household level as a real world experiment. *Renewable and Sustainable Energy Reviews*, 64: 279–288.

Bonte M., 2013. Impacts of shallow geothermal energy on groundwater quality: A hydrochemical and geomicrobial study of the effects of ground source heat pumps and aquifer thermal energy storage. Doctoral thesis, Vrije Universiteit Amsterdam. Accessed 17 Mar 2015 http://dare.ubvu.vu.nl/handle/1871/49188.

BoreSysQM, 2019. Overview. Quality Management in Design, Construction and Operation of Borehole Systems. Annex 27 within the International Energy Agency (IEA) Implementing Agreement ECES – Energy Conservation and Energy Storage. Accessed 8 September 2019 http://www.eces-boresysqm.org/.

Bucci A., Prevot A. B, Buoso S., De Luca D. A., Lasagn M., Malandrino M., Maurino V., 2018. Impacts of borehole heat exchangers (BHEs) on groundwater quality: the role of heat‑carrier fluid and borehole grouting. *Environmental Earth Sciences*, 77:175.

Buday T., 2014. Reduction of environmental impacts of heat pump usage with special regard on systems with borehole heat exchangers. *Landscape & Environment*, 8(2): 66–77.

Council of Europe, 2019. 12 Principles of Good Governance and European Label of Governance Excellence (ELoGE). Accessed April 18, 2019 https://www.coe.int/en/web/good-governance/12-principles-and-eloge.

Czaja R., Blair J., 2005. Selecting the method of data collection. Chapter 3 in: Czaja & Blair (Eds.), *Designing surveys*, Pine Forge Press, p. 33-59.

Dehkordi S. E., Schincariol R. A., 2014. Guidelines and the design approach for vertical geothermal heat pump systems: current status and perspective. *Canadian Geotechnical Journal*, 51: 647–662.

EHPA, 2019. EUCERT. European Heat Pump Association. Accessed 3 September 2019 https://www.ehpa.org/quality/eucert/.

Elo S., Kyngäs H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62(1): 107 – 115.

Energy Committee 1989. *Energiakomitean mietintö* (In Finnish, Energy Committee report). Valtioneuvoston kanslia. KM 1989:11.

Energy Policy Council 1979. *Suomen energiapoliittinen ohjelma* (In Finnish, The energy policy programme of Finland). Komiteamietintö 1979:16.

Energy Policy Programme 1983. *Energiapoliittinen ohjelma*. (In Finnish). Helsinki.

Finland's Environmental Administration, 2017. Vesiluvan hakeminen (in Finnish, The application for a water permit). Accessed 7 June 2019 https://www.ymparisto.fi/fi-FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Luvat_ilmoitukset_ja_rekisterointi/Vesilupa/Vesiluvan_hakeminen.

Finland's Environmental Administration, 2019. Pohjavesialueen suojelusuunnitelma (in Finnish, Protection plan for a designated ground water area). Accessed 18 March 2019 https://www.ymparisto.fi/fi-FI/Vesi/Vesiensuojelu/Pohjaveden_suojelu/Pohjavesialueen_suojelusuunnitelma.

Fleuchaus P., Blum P. 2017. Damage event analysis of vertical ground source heat pump systems in Germany. *Geothermal Energy*, 5:10.

FMI, 2019a. Vuositilastot. Suomen keskilämpötila 1981-2010. (In Finnish, Yearly statistics. Average temperature in Finland 1981-2010.) The Finnish Meteorological Institute. Accessed 2 September 2019 http://ilmatieteenlaitos.fi/vuositilastot.

FMI, 2019b. Kovat pakkaset ja talven kylmimmät lämpötilat. (In Finnish, The coldest winter temperatures.) The Finnish Meteorological Institute. Accessed 2 September 2019 http://ilmatieteenlaitos.fi/kovat-pakkaset-ja-kylmimmat-talvet.

Ge M., Lebling K., Levin K. & Friedrich J. 2019. Tracking progress of the 2020 climate turning point. Working paper. World Resources Institute. Washington DC. Accessed 21 May 2019 https://wriorg.s3.amazonaws.com/s3fs-public/2020-turning-point-progress_2.pdf.

Geotrainet, 2011. Geotrainet training manual for drillers of shallow geothermal systems: Geo-Education for a sustainable geothermal heating and cooling market. Accessed 29 July 2019 http://geotrainet.eu/wp-content/uploads/2015/11/Drillers-Manual-Final-V2-10.11.pdf.

GTK, 2019. Geoenergia (in Finnish, Geoenergy). Geological Survey of Finland. Accessed 2 September 2019 http://www.gtk.fi/geologia/luonnonvarat/geoenergia/.

Haehnlein S., Bayer P., Blum P., 2010. International legal status of the use of shallow geothermal energy. *Renewable and Sustainable Energy Review*, 14: 2611–2625.

Hammersley M., Gomm R., 2008. Assessing the radical critique of interviews. In: Hammersley M (ed.), *Questioning Qualitative Inquiry*. SAGE Publications, London, p. 89–100.

Hansen S., 2017. Deep heat through hard rock. GeoDrilling International. Accessed 11 August 2019 http://www.geodrillinginternational.com/geothermal-ground-source/issue/1309931/deep-heat-hard-rock.

Heinonen E. W., Wildin M. W., Beall A. N. and Tapscott R. E., 1997. Assessment of Antifreeze Solutions for Ground-Source Heat Pump Systems. *ASHRAE Transactions*, 103: 747–756.

Heinonen E. W., Wildin M. W., Beall A. N. and Tapscott R. E., 1998. Anti-freeze fluid environmental and health evaluation – an update. In *Proceedings of the Second Stockton International Geothermal Conference*, 16–17 March 1998.

Heiskanen E., Hyysalo S., Jalas M., Juntunen J. K., Lovio R., 2014. User involvement in heating systems transition: The case of heat pumps in Finland. In Juniger S. & Christensen P. (Eds): *Highways and Byways of Radical Innovation: The perspective of design*. Kolding Design School. Kolding, DK, p. 171-196.

Hähnlein S., Bayer P., Ferguson G., Blum P., 2013. Sustainability and policy for the thermal use of shallow geothermal energy. *Energy Policy*, 59: 914–925.

Hänninen, P., Lintinen, P., Lojander, S., Sutinen, R., 2000. Suomen maaperän vedenjohtavuus [Hydraulic conductivity of the Finnish ground]. *Vesitalous* 41: 16–19.

Ilieva D., Haderlein S.B. & Morasch B., 2014. Grundwassergefährdungspotenzial von Additiven in Wärmeträgerflüssigkeiten aus Erdwärmesonden. (In German, Groundwater pollution potential of additives used in borehole heat exchanger fluids). *Grundwasser*, 19: 263–274.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland. Accessed 3 September 2019 https://www.ipcc.ch/sr15/.

IPCC, 2019. Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Accessed 3 September https://www.ipcc.ch/report/srccl/.

Jacobson M. Z., Delucchi M. A., Ingraffea A. R., Howarth R. W., Bazouin G., Bridgeland B., Burkart K., Chang M., Chowdhury N., Cook R., Escher G., Galka M., Han L., Heavey C., Hernandez A., Jacobson D. F., Jacobson D. S., Miranda B., Novotny G., Pellat M., Quach P., Romano A., Stewart D., Vogel L., Wang S., Wang H., Willman L., Yeskoo T., 2014. A roadmap for repowering California for all purposes with wind, water, and sunlight. *Energy*, 73: 875–889.

Jardeby Å., Benson J., Räftegård O., 2013. National report Sweden. Regeocities project.

Joensuun korkeakoulu, 1983. *Ylipitkän aikavälin energiavaihtoehdot Suomessa: kaksi skenaariota* (In Finnish, Overlong-term energy options for Finland: two scenarios). Ministry of Trade and Industry, Energy Department, Series D:18. Helsinki.

Juvonen J., Lapinlampi T., 2013. *Energiakaivo. Maalämmön hyödyntäminen pientaloissa* (in Finnish, Energywell. Ground-source heat in one-family houses). Ministry of the Environment, Environment Guide 2013, Helsinki, Finland. Accessed 8 Sep 2016 https://helda.helsinki.fi/bitstream/handle/10138/40953/YO_2013.pdf?sequence=4.

Karjalainen U., 1959. Talo ilman savupiippua (In Finnish, A house without a chimney). *Uusi kuvalehti,* 10/1959: 26–27.

Karro E., Lahermo P., 1999. Occurrence and chemical characteristics of groundwater in Precambrian bedrock in Finland. Geological Survey of Finland, Special Paper, 27: 85–96.

Karytsas S.C., Chaldezos I.P., 2017. Review of the Greek legislative framework for ground source heat pumps (GSHPs) and suggestions for its improvement. *Procedia Environmental Sciences*, 38: 704–712.

Kivimaa P., Mickwitz P., 2011. Public policy as a part of transforming energy systems: framing bioenergy in Finnish energy policy. *Journal of Cleaner Production*, 19: 1812-1821.

Klotzbücher T., Kappler A., Straub K. L., Haderlein S. B., 2007. Biodegradability and groundwater pollutant potential of organic anti-freeze liquids used in borehole heat exchangers. *Geothermics*, 36: 348–361.

Korsman K., Koistinen T., 1998. Suomen kallioperän yleispiirteet (in Finnish, General features of Finland's bedrock). Chapter 3 in Lehtinen M., Nurmi P. & Rämö T. (ed.): *Suomen kallioperä – 3000 vuosimiljoonaa*. The Geological Society of Finland. Jyväskylä, p. 93-103. Accessed 2 September 2019 http://www.geologinenseura.fi/suomenkalliopera/CH3.pdf.

Kukkonen I. T., 2000. Geothermal energy in Finland. *Proceedings World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May 28 – June 10, 2000.

Kukkonen I. T., Peltoniemi S., 1998. Relationships between thermal and other petrophysical properties of rocks in Finland. *Physics and Chemistry of the Earth*, 23(3): 341–349.

Lacombe S., Sudicky E. A., Frape S. K., Unger A. J. A., 1995. Influence of leaky boreholes on cross-formational groundwater flow and contaminant transport. *Water Resources Research*, 31(8): 1871–1882.

Laitinen A., Tuominen P., Holopainen R., Tuomaala P. Jokisalo J., Eskola L. & Sirén K., 2014. *Renewable energy production of Finnish heat pumps: Final report of the SPF-project*. VTT Technical Research Centre of Finland. VTT Technology 164. http://www.vtt.fi/inf/pdf/technology/2014/T164.pdf.

Lankia O., Kleiman H., 2009. Maalämpökaivo voi olla riski pohjaveden ja talousvesikaivojen veden laadulle (in Finnish, A ground source energy well may be a risk for water quality of groundwater and domestic water wells). *Ympäristö ja Terveys*, 40(7): 66–67.

Lauttamäki V., 2018. *Geoenergia kiinteistöjen lämmitysratkaisujen markkinoilla Suomessa energiakriisien ajoista 2030-luvulle* (in Finnish, Ground-source heat on facilities' heating market in Finland from the times of energy crises in the 1970s until 2030). Doctoral thesis. Annales Universitatis Turkuensis, E 29. https://www.utupub.fi/handle/10024/144984.

Liu X., Lu S., Hughes P., Cai Z., 2015. A comparative study of the status of GSHP applications in the United States and China. *Renewable and Sustainable Energy Reviews*, 48: 558–570.

Lounaistieto, 2018. Väestötilastot (in Finnish, Population statistics). Regional information service for Southwest Finland. Accessed 18 January 2018 http://www.lounaistieto.fi/tietopalvelut/tilastot/vaestotilastot/.

Majuri P., 2016b. Practitioners' observations on the policies and regulation of ground source energy use in Finland. European Geothermal Congress, Strasbourg, France, 19–24 September 2016.

Mattinen M. K., Nissinen A., Hyysalo S., Juntunen J. K., 2015. Energy Use and Greenhouse Gas Emissions of Air-Source Heat Pump and Innovative Ground-Source Air Heat Pump in a Cold Climate. *Journal of Industrial Ecology*, 19(1): 61–70.

ME, 2015. Ympäristöministeriön ohje rakennustyön suorituksesta ja valvonnasta (in Finnish, The Ministry of the Environment instructions for performing and supervising construction work). Ministry of the Environment, YM5/601/2015. Accessed 18 February 2019 https://www.edilex.fi/data/rakentamismaaraykset/YM_ohje_rakennustyon_suorituksesta_ja_valvonnasta.pdf.

MEE, 2008. Pitkän aikavälin ilmasto- ja energiastrategia (In Finnish, Long-term Climate and Energy Strategy). Ministry of Employment and the Economy, Energy and the climate 36/2008. https://www.tem.fi/files/21079/TEMjul_36_2008_energia_ja_ilmasto.pdf.

MEE, 2013. Kansallinen energia- ja ilmastostrategia. Valtioneuvoston selonteko eduskunnalle 20. päivänä maaliskuuta 2013 (In Finnish, The National Energy and Climate Strategy. Council of State Report to Parliament on 20 March 2013). Ministry of Employment and the Economy, Energy and the climate 8/2013. https://www.tem.fi/files/36221/TEMjul_8_2013_web_20032013.pdf.

MEE, 2014. Final report of the Working Group to Advance Small-Scale Energy Production (in Finnish). Ministry of Employment and the Economy Publications, Energy and the climate 55/2014.

MEE, 2017. Government report on the National Energy and Climate Strategy. Publications of the Ministry of Economic Affairs and Employment. Energy. 12/2017. Accessed 9 August 2019 http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/79247/TEMjul_12_2017_verkkojulkaisu.pdf?sequence=1&isAllowed=y.

Morofsky E., Cruickshanks F., 1997. Underground thermal energy storage: Procedures for environmental impact assessment. Working report, IEA ECES program, Annex 8.

Motiva, 2019. Lämmitysjärjestelmän valinta (in Finnish, Selecting a heating system). Accessed 24 June 2019 https://www.motiva.fi/koti_ja_asuminen/rakentaminen/lammitysjarjestelman_valinta.

MTI, 1992. The Finnish Energy Strategy: Council of State Report to Parliament on Energy Policy. – Ministry of Trade and Industry, Energy Department. C:31.

MTI, 1997. Suomen energiastrategia. Valtioneuvoston selonteko eduskunnalle (In Finnish, The Finnish Energy Strategy. Council of State Report to Parliament on Energy Policy). Ministry of Trade and Industry 5/1997.

MTI, 2001. Kansallinen ilmastostrategia. Valtionevoston selonteko eduskunnalle (In Finnish, The national climate strategy – Council of State Report to Parliament). Ministry of Trade and Industry 2/2001. http://ktm.elinar.fi/ktm_jur/ktmjur.nsf/All/58DF3F554AE83273C2256A1C00240943/$file/selonteko_1503_lopullinen.pdf.

MTI, 2005. Lähiajan energia- ja ilmastopolitiikan linjauksia. Kansallinen strategia Kioton pöytäkirjan toimeenpanemiseksi (In Finnish, Definitions of energy and climate policy for the near future – A national strategy for implementing the Kyoto protocol). Ministry of Trade and Industry, Energy Department 25/2005.

Myllyntaus T. (ed.) 1999. *Energian hinta 1800–1998* (In Finnish, The price of energy 1800–1998). Ministry of Trade and Industry, Helsinki.

Nilsson L. J., Åhman M., Nordqvist J., 2005. Cygnet or ugly duckling: What makes the difference? A tale of heat-pump market developments in Sweden. In: Energy Savings: What Works & Who Delivers? ECEEE 2005 Summer Study, Mandelieu La Napoule, France, p. 1033–1044

Nyborg S., Røpke I., 2015. Heat pumps in Denmark: From ugly duckling to white swan. *Energy Research & Social Science*, 9: 166–177.

Paloniitty T., Kangasmaa S., 2018. Securing scientific understanding: Expert judges in Finnish environmental administrative judicial review. *European Energy and Environmental Law Review*, 27(4): 125-139.

Park K. J., Turner A., Minderman J., 2013. Integrating applied ecology and planning policy: the case of micro-turbines and wildlife conservation. *Journal of Applied Ecology*, 50: 199–204.

PCECI, 2014. Energy and Climate Roadmap 2050. Report of the Parliamentary Committee on Energy and Climate Issues. Ministry of Employment and the Economy, Energy and the climate 50/2014. https://www.tem.fi/files/41451/TEMjul_50_2014_web_14112014.pdf.

Pilpola S., Lund P. D., 2018. Effect of major policy disruptions in energy system transition: Case Finland. *Energy Policy*, 116: 323-336.

Plant J. A., Whittaker A., Demetriades A., De Vivo B. & Lexa J., 2005. The geological and tectonic framework of Europe. In: Salminen R. (ed.) 2005: *Geochemical Atlas of Europe. Part 1: Background Information, Methodology and Maps*. Geological Survey of Finland, Espoo.

Poratek, 2015. Tutkintotodistus vahvistaa ammattiosaamisen (In Finnish, Adiploma verifies the professional competence). *Poratek Uutiset*, December 2015, p. 28-29. Accessed 3 September 2019. http://poratek.fi/wp-content/uploads/2016/01/Poratek-Uutiset-2015_kevyempi.pdf.

Programme of Prime Minister Antti Rinne’s Government, 2019. Inclusive and competent Finland – a socially, economically and ecologically sustainable society. Publications of the Finnish Government 2019:25. Accessed 7 August 2019 https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161664/Inclusive%20and%20competent%20Finland_2019.pdf?sequence=9&isAllowed=y.

Ranta E., Rita H., Kouki J., 2012. *Biometria*. Gaudeamus Helsinki University Press.

Rantamäki M., Jääskeläinen R., Tammirinne M., 2009 *Geotekniikka* (in Finnish, Geotechnics). 22. Edition. Otatieto Oy, Helsinki.

RCSF, 2018. Kunnat (in Finnish, The municipalities). Regional Council of Southwest Finland. Accessed 27 June 2018 https://www.varsinais-suomi.fi/fi/maakunta/kunnat.

Rebouças A. 2004: Well drilling and design methods. In Kovalevsky V.S., Kruseman G.P. & Rushton K.R. (ed.): *Groundwater studies. An international guide for hydrogeological investigations*. IHP-VI, Series on Groundwater No. 3, UNESCO, Paris. Pp. 185-215.

REGEOCITIES, 2013. Overview of shallow geothermal legislation in Europe. D2.2: General Report of the current situation of the regulative framework for the SGE systems. Accessed 2 September 2019 http://ubeg.de/Regeocities/D2.2-EN%20overview%20shallow%20geothermal%20regulation%20Europe.pdf.

Riegger M., Heidinger P., Lorinser B., Stober I., 2012. Auswerteverfahren zur Kontrolle der Verfüllqualitätin Erdwärmesonden mit faseroptischen Temperaturmessungen (in German, Evaluation of fibre optic temperature measurements in borehole heat exchangers for grouting quality control). *Grundwasser*, 17(2): 91 – 103.

Rognon F., 2008. The Role of the State and the Economy in the promotion of heat pumps on the market. Federal Department of the Environment, Swiss Federal office of Energy. 9th International IEA Heat Pump Conference, 20 – 22 May 2008, Zürich, Switzerland.

Ruggiero S., Varho V., Rikkonen P., 2015. Transition to distributed energy generation in Finland: Prospects and barriers. *Energy Policy*, 86: 433–443.

Santi P. M., McCray J. E., Martens J. L., 2006. Investigating cross-contamination of aquifers. *Hydrogeology Journal*, 14(1–2): 51–68.

Sass I., Burbaum U., 2010. Damage to the historic town of Staufen (Germany) caused by geothermal drillings through anhydrite-bearing formations. *Acta Carsologica*, 39(2): 233–245.

Schmidt K. R., Körner B., Sacher F., Conrad R., Hollert H., Tiehm A., 2016. Biodegradability and ecotoxicity of commercially available geothermal heat transfer fluids. *Grundwasser*, 21: 59–67.

SGU, 2015. Produkt: Brunnar (in Swedish, Product: Wells). Geological Survey of Sweden. Accessed 10 August 2018 http://resource.sgu.se/dokument/produkter/oppnadata/brunnar-oppnadata-beskrivning.pdf.

SGU, 2016: Normbrunn -16. Vägledning för att borra brunn. (In Swedish, The norm well -16. A manual to drill wells). Sveriges geologiska undersökning. Accessed 3 September 2019 https://resource.sgu.se/produkter/broschyrer/vagledning-normbrunn-16.pdf.

Silvasti T., 2014. Sisällönanalyysi (in Finnish, Content analysis). In Massa: *Polkuja yhteiskuntatieteelliseen ympäristöntutkimukseen*, p. 33–48.

Somogyi V., Sebestyén V., Nagy G., 2017. Scientific achievements and regulation of shallow geothermal systems in six European countries: A review. *Renewable and Sustainable Energy Reviews*, 68(2): 934–952.

Statistics Finland, 2018. Kuntien avainluvut (in Finnish, Key statistics of municipalities). Accessed 19 January 2018 http://www.tilastokeskus.fi/tup/alue/kuntienavainluvut.html#?year=2017&active1=SSS.

Statistics Finland, 2019. Energy prices: Consumer prices of liquid fuels in Finland. PX-Web database. Accessed 15 August 2019 http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin__ene__ehi/statfin_ehi_pxt_003_fi.px/.

Stern P. C., 1992. What Psychology Knows About Energy Conservation. *American Psychologist*, 47(10): 1224–1232.

SULPU, 2019. Myydyt lämpöpumput 2018 (in Finnish, Heat pump sales 2018). The Finnish Heat Pump Association. Accessed 24 June 2019, https://www.sulpu.fi/documents/184029/208772/Myydyt%20l%C3%A4mp%C3%B6pumput%202018.pdf.

Tarasti L., Rönn R., Pantsar M., Kuusiniemi K., Kähö T., 2015. Ympäristömenettelyjen sujuvoittaminen ja tehostaminen. Arvio toteuttamisvaihtoehdoista (in Finnish, Streamlining and enhancing environmental procedures. An evaluation of implementation alternatives). An evaluation report for the Ministry of the Environment. Accessed 15 August 2016 http://www.ym.fi/download/noname/%7B3958E753-B749-440E-8777-D71DD405BE87%7D/107681.

Thomas D. R., 2006. A general inductive approach for analyzing qualitative evaluation data. *American Journal of Evaluation*, 27 (2): 237–246.

Tsagarakis K. P., Efthymiou L., Michopoulos A., Mavragani A., Anđelković A. S., Antolini F., Bacic M., Bajare D., Baralis M., Bogusz W., Burlon S., Figueira J., Genç M. S., Javed S., Jurelionis A., Koca K., Ryżyński G., Urchueguia J. F., Žlender B., 2020. A review of the legal framework in shallow geothermal energy in selected European countries: Need for guidelines. *Renewable Energy*, 147: 2556–2571.

Vienken T., Schelenz S., Rink K., Dietrich P., 2015. Sustainable Intensive Thermal Use of the Shallow Subsurface – A Critical View on the Status Quo. *Groundwater*, 53(3): 356–361.

Working Group on Renewable Energy, 2003. Uusiutuvan energian edistämisohjelma 2003–2006 – Työryhmän ehdotus (In Finnish, Advancement Programme for Renewable Energy 2003–2006). Ministry of Trade and Industry, working group and committee reports 5/2003. http://julkaisurekisteri.ktm.fi/ktm_jur/ktmjur.nsf/f3b25c29fd404851c2256604003ab9da/4B1BDE137F9B5121C2256CE5002B3AC1/$file/tyto5eos.pdf.

Zogg M. 2008: History of Heat Pumps: Swiss Contributions and International Milestones, final report. Swiss Federal Office of Energy. www.zogg-engineering.ch/publi/HistoryHP.pdf.

Legislation cited

Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, 'the RES Directive'. Accessed 3 September https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32009L0028&from=EN.

Finnish statute 1992/1535. Tuloverolaki (in Finnish, Income Tax Act). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/ajantasa/1992/19921535?search%5Btype%5D=pika&search%5Bpika%5D=tuloverolaki.

Finnish statute 1999/132. Maankäyttö- ja rakennuslaki (in Finnish, Landuse and Building Act). Accessed 3 September 2019 http://www.finlex.fi/fi/laki/ajantasa/1999/19990132?search%5Btype%5D=pika&search%5Bpika%5D=Maank%C3%A4ytt%C3%B6-%20ja%20rakennus#L1.

Finnish statute 1999/895. Maankäyttö- ja rakennusasetus (in Finnish, Landuse and Building Decree). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/ajantasa/1999/19990895.

Finnish statute 2000/995. Tuloverolain muutos (Amendment to Income Tax Act).

Finnish statutes 2002/1021. Laki asuntojen korjaus- ja energia-avustuksista (in Finnish, Act on residential renovation and energy saving grants). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2002/20021021.

Finnish statute 2003/57. Valtioneuvoston asetus asuntojen korjaus- ja energia-avustuksista (in Finnish, Decree on residential renovation and energy saving grants). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2003/20030057.

Finnish statute 2004/1299. The Act on Water Resources Management. Accessed 12 June 2019 http://finlex.fi/fi/laki/ajantasa/2004/20041299?search%5Btype%5D=pika&search%5Bpika%5D=2004%2F1299.

Finnish statute 2008/115. Valtioneuvoston asetus asuntojen korjaus-, energia- ja terveyshaitta-avustuksista annetun asetuksen muuttamisesta (in Finnish, Amendment to the Decree on grants for residential renovation, energy saving and health standard improvement). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2008/20080115.

Finnish statute 2009/452. Government decree on the servicing and maintenance of devices containing ozone depleting substances or certain fluorinated greenhouse gases. Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2009/20090452?search%5Btype%5D=pika&search%5Bpika%5D=Valtioneuvoston%20asetus%20otsonikerrosta%20heikent%C3%A4vi%C3%A4%20aineita

%20ja%20er%C3%A4it%C3%A4%20fluorattuja%20kasvihuonekaasuja%20sis%C3%A4lt%C3%A4vien%20laitteiden%20huollosta.

Finnish statute 2010/1255. Valtioneuvoston asetus asuntojen korjaus-, energia- ja terveyshaitta-avustuksista annetun asetuksen muuttamisesta (in Finnish, Amendment to the Decree on grants for residential renovation, energy saving and health standard improvement). Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2010/20101255.

Finnish statute 2011/587. Vesilaki (in Finnish, Water Act). Accessed 3 September 2019 http://www.finlex.fi/fi/laki/ajantasa/2011/20110587?search%5Btype%5D=pika&search%5Bpika%5D=vesilaki.

Finnish statute 2014/527. Ympäristönsuojelulaki (in Finnish, Environmental Protection Act). Accessed 3 September 2019 http://www.finlex.fi/fi/laki/ajantasa/2014/20140527?search%5Btype%5D=pika&search%5Bpika%5D=ymp%C3%A4rist%C3%B6nsuojelulaki.

Finnish statute 2016/766. Government decree on qualification requirements for persons who handle devices containing fluorinated greenhouse gases or ozone depleting substances. Accessed 3 September 2019 https://www.finlex.fi/fi/laki/alkup/2016/20160766.

UNIVERSITY OF TURKU

GEOENERGY AND SUSTAINABLE DEVELOPMENT

Perspectives on environmental challenges and governance of geoenergy installations

Pirjo Majuri

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 363 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2020