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Task 38

Ground Source De-Icing and Snow Melting Systems for Infrastructure

Final Report

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Introduction

The final report of Task 38: ‘Ground Source De-Icing and Snow Melting Systems for Infrastructure’ contains of a description of the TASK 38 and compilation of deliverable of Subtask 1-4 and final summary of each task.

Appendixes related to Task1: subtask 1.1: ‘State of the art in countries’ was presented in a separate document. The authors and contributors for each deliverable are presented below.

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CONTENTS

1 SHORT DESCRIPTION OF TASK 38

Thermal de-icing and snow melting methods to control winter conditions on surfaces of transport infrastructure offer several advantages compared to conventional techniques. These include the automated control of safe surface conditions, avoidance of chemicals and their environmental impact and prolongation of the life of the infrastructure. Hydronic systems can take advantage of the collection of solar energy mainly during summertime and seasonal storage of thermal energy by geothermal heat exchange. Making use of these renewable resources and energy storage enables savings in primary energy.

Due to its versatile applications, the market potential for snow-melting and/or de-icing systems is enormous. According to a recent global market survey [1], snow-melting and de-icing systems are expected to grow at an annual rate of 5.4% (Fig. 1). The global market volume of this technology is currently about $ 5 billion/year, according to this study. Assuming an average heating power of the systems of 300 W/m2 [2], this means an annual installed heating capacity of approx. 10-15 GW at prices of approx. US $ 100-150/ m2 of installed heating surface.

Normally snow melting and de-icing systems are conventionally heated. According to a study by the Ministry of Transport, Energy and Regional Planning of the State of North Rhine-Westphalia [3] in Germany, electricity in combination with electrical resistance heaters is the most common form of energy source. The remaining systems are operated by a hydraulic circuit that is heated with either gas, oil, or district heating. Using resistance heaters is a challenge for the electric grid since these systems have a huge power demand (ICE point ≈ 50 kW, helicopter landing pad ≈ 50 kW, football field ≈ 2000 kW) with relatively low operating time of about 100-300 h/year [2]. Since the systems are consistently used in critical sections of the infrastructure, the connection power in the electrical network must always be available. The result is peak load generators with very little operation time, but also additional requirements for the electrical grid, if the market for these systems grows. These negative effects can effectively be counteracted if hydraulic circuits connected to geothermal heat sources are used, as the connected electric load drops considerably.

There are already systems that are connected to geothermal energy storage and operated with a heat pump. In the US and Japan, some demonstration plants were built with heat pumps, including for bridges, walkways and parking lots [3].

Direct geothermal systems without temperature increase by a heat pump have also already been realized. Such systems rely on pavement surfaces such as solar energy collectors and seasonal energy storage using borehole thermal energy storage (BTES) or Energy Piles. An example is the project SERSO from Switzerland [4]. In this project, since 1994, a motorway bridge is directly heated in wintertime by a BTES and cooled in summertime. With the heat collected from the bridge the BTES is recharged. Several research projects were conducted that examined this technique [5-8]. Other examples are the systems that use the principle of a two-phase thermosyphon instead of conventional geothermal probes. This technique has been applied for railway points, subway access, a tramway station and a ramp at a fire-brigade [9-15].

Shallow geothermal energy, as a classic storage technology, offers great potential for the substitution of conventional energy and can also contribute to relieving the power grids in winter, as snow melting and de-icing systems can't simply be switched off, since they are always used in critical sections of infrastructure. In some cases, the cooling of pavements during summer will decrease the wear on the surface as well as on tires.

In principle, all existing hydraulically operated systems can be relatively easily converted to ground-coupled heat pumps. In the case of new plants, direct-electrical systems can and must also be replaced, since these are no longer compatible with the upcoming challenges of the energy transition in the medium term (grid load).

Furthermore, there are other initiatives e.g. the World Road Association – PIARC- have launched a global call for proposals for the "Positive Energy Roads". The core idea is that a road infrastructure should produce more energy than it consumes during operation phases or during construction and operational phases.

Objectives and Scope

- Main Goal

The overall goal of this ANNEX was to contribute to the replacement of electrical resistance heater systems and expanding utilization of direct geothermal heating systems or ground source heat pumps in de-icing and snow melting of infrastructure.

- Objectives

To achieve the goal of this annex the existing knowledge of the experts working in this area has been summarized and further developed by the planned research activities in the subtasks. According to that, a potential study is to be carried out in each of the participating countries, in which the market volume of as many relevant applications as possible is to be determined. In addition, an overview of the state of the art of these systems for different applications in various climates has been worked out.

Some geothermal systems for de-icing and snow melting have already been built in Japan, USA, Canada, Switzerland, Sweden, the Netherlands and Germany, either as pilots or, in some cases, as full-scale systems. These systems have been documented as uniformly as possible and, wherever possible, have been accompanied by monitoring. Within the framework of the accompanying research projects, further demonstration plants have been built, which also have been monitored. In addition to demonstrating the full functionality of the technology, valuable experience has been gained from existing facilities (function, performance, energy consumption, investment and operating costs, ...).

From the experience gained from the construction and operation of the demonstration plants in various climatic conditions, as well as from the experience of existing plants, recommendations have been made which summarize the essential aspects regarding the planning, construction, operation and maintenance of geothermal snow melting and de-icing systems. These recommendations were the input to national guideline committees, e.g. VDI 4640 in Germany.

With the summarized knowledge gained from the experts of surface heating systems, snow melting and de-icing systems will be developed for specific applications which are adapted for efficient geothermal heating. The development will include design programs and simulation tools for calculations of thermal loads.

An important aspect to bringing these systems more into the market is to work out the benefits for the environment, social as well as the economic benefits. This has been handled in a separate work package for the different applications of technology.

Finally, the results of the annex have been used to develop recommendations for further market and technology development.

Scope

All applications for snow and/or ice maintenance have been considered, which can be supplied either directly with geothermal energy, BTES or in combination with a heat pump. Storage of heat in the ground to cool traffic areas in summer and thus protect the surfaces, prolong their technical lifetime and reuse the stored heat in winter has been a main part of the work.

The following applications have been considered:

- Railway switches
- Ramps, Stairs and entrances
- Platforms
- Bridge decks
- Road parts (between tunnels, sensitive slopes etc)
- Walking/biking paths
- Parking lots
- Aircraft parking areas
- Runways/Helicopter platforms
- Tunnel entrances
- Sport fields

In addition to specific applications, the following aspects that are important for this technique have also been considered:

- Microclimate (temperature range, humidity, number of days etc) and Climate forecasting
- Control of heating system
- Ground source (ground temperature, conductivity, limitations etc)
- Ground heat exchanger types and design
- Technology use in different countries (switches, etc)
- Existing examples and previous studies (survey, annotated bibliography)
- State-of-the-art report and market potential

Organizational Structured

The task has been divided into 4 subtasks and each subtask divided into several activities as is shown in Figure 1.

Subtask 1 leads by Sweden (Signhild Gehlin), subtask 2 leads by Italy (Diana Salciarini), Subtask 3 leads by Belgium (Wim Van den bergh/Taher Ghalndar) and finally subtask 4 Leads by Sweden (Bijan Adl-Zarrabi/Ali Naman Karim)

Subtask 1: *Market potential and State-of-the-Art*

- Market potential for all marketable applications
- State-of-the art of conventional de-icing and snow melting systems
- State-of-the art of geothermal de-icing and snow melting systems
- Economic evaluation
- Overview and discussion of environmental and social aspects

Subtask 2: Modelling of Geothermal Energy Storage and De-icing Systems

- Models for de-icing and snow melting load and energy assessment
- Design for effective de-icing, snow melting and solar collection
- Energy storage and heat source modelling
- Integrated system simulation and control

Subtask 3: Development of system components for selected applications

- Thermal design of the heating surfaces
- Mechanical requirements of the surface heating system when required
- Materials for geothermal heating systems
- Adapted drilling methods

Subtask 4: Planning, construction and monitoring

- Mapping of demonstration plants
- Recommendation on design, construction, operation and maintenance
- Recommendation on market and Technology development

Policy and R&D recommendations

Figure 1 Organizational Structure

Duration of Task

The Annex started on 1st July 2021 and remained in force until December 2024.

Experts Meetings

A total of six expert meetings were held between July 2021 and December 2024:

Kick-off meeting	Oct/2021
First expert meeting	April/2022 (online)
Second expert meeting	Nov/2022 Istanbul (Türkiye)
Third expert meeting	May/2023 -Antwerp (Belgium)
Fourth expert meeting	Oct/2023 (Online)
Fifth expert meeting	March/2024-Perugia (Italy)
Sixth and final expert meeting	Nov/2024- Gothenburg (Sweden)

Participation

Following countries actively participated in the Task with the support of their delegates: Sweden, Türkiye, Belgium, France, Germany, Italy. Furthermore, Japan, and the United States of America contributed to the state-of-the-art.

2 STATE-OF-THE-ART AND MARKET OVERVIEW SUBTASK 1, DELIVERABLE 1.1: STATE OF THE ART REPORT

This report of the work within Subtask 1 of IEA ES Task 38 is a work document compiled within the framework of the 2021-2024 IEA ES Task 38 “Ground Source De-Icing and Snow Melting Systems for Infrastructure”. It summarizes the national State-of-the-art reports from the participating countries Belgium, France, Germany, Italy, Sweden and Türkiye with additional information from non-participating countries, all collected within Task 38 and covering technology, applications and market for de-icing and snow melting systems, with focus on shallow geothermal energy as heat source.

The IEA ES Task 38 “Ground Source De-Icing and Snow Melting Systems for Infrastructure” is an international collaboration project run between 2021 and 2024. The overall goal of IEA ES Task 38 is to contribute to the replacement of electrical resistance heater systems and expanding utilization of shallow geothermal energy, e.g. direct geothermal heating systems or ground source heat pumps, as heat source in de-icing and snow melting of infrastructure.

To achieve the goal of Task 38 the existing knowledge of the experts working in this area is summarized and further developed within four subtasks.

In Subtask 1 – State-of-the-art and market overview - national overviews from each of the participating countries is compiled, and the market volume of relevant applications is investigated. These national overviews include investigations of systems for different applications in different climate conditions. The summarized knowledge from the experts will help the further development of surface heating systems, snow-melting and de-icing systems in general and for specific applications adapted for efficient geothermal heating. The development will include design programs and simulation tools for calculations of thermal loads. In addition, overviews of the state-of-the-art for non-participating countries is included.

Subtask 2 – Modelling of geothermal energy storage and de-icing systems – includes the development of models and design recommendations as well as integrated system simulation and control.

Subtask 3 – Development of system components for selected applications – comprises thermal designs materials and mechanical requirements for heating surfaces, as well as adapted drilling methods.

Subtask 4 - Planning, construction and monitoring – includes mapping of demonstration plants and test sites and the compilation of recommendations on design, construction, operation, management, and market/technology development.

An important aspect in bringing these systems more into the market is to work out the environmental, social and economic benefits and provide recommendations for further market and technology development. This is handled in Subtasks 2-4.

The authors gratefully acknowledge the financial support for their work from the Swedish Energy Agency, Grant 51491-1, and from their employers.

LIST OF ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger (includes the boreholes if grouted)
BTES	Borehole Thermal Energy Storage
CTES	Cavern Thermal Energy Storage
DH	District Heating
DHW	Domestic Hot Water
EED	Earth Energy Designer (a simulation tool for boreholes)
EHS	Electric Heating System
GHG	Green House Gas
GSHP	Ground Source Heat Pump
GWHP	Groundwater Heat Pump
HEX	Heat Exchanger
HHP	Hydronic Heated Pavement
HHS	Hydronic Heated System
HP	Heat Pump
HT-BTES	Hight Temperature Borehole Thermal Energy Storage
HVAC	Heating, Ventilation and Air-Conditioning, internal system for heating and cooling in buildings
LCC	Life cycle cost
OCM	Overall Control and Monitoring
ORC	Outdoor Recreation Canters
PE	Polyethene (as in plastic pipes)
PTES	Pit Thermal Energy Storage
PEX	Cross-linked polyethylene (for hot water)
SGE	Shallow Geothermal Energy
SPF	Seasonal Performance Factor
TRL	Technology Readiness Level
UTES	Underground Thermal Energy Storage

2.1 Introduction

Since the mid 1990’s the use of geothermal energy worldwide has been increasing with an accelerating pace. According to data presented by the International Geothermal Association (IGA) at the World Geothermal Congress 2020, the amount of geothermal energy direct utilization in 2019 amounted to 284 TWh, of which ground source heat pump (GSHP) applications account for 165 TWh (58%) with an installed total capacity of 108 GW (Lund and Toth, 2020). A small fraction (415 MW, 660 GWh) of the geothermal energy utilization is used for snow-melting, where typically a hydronic heated pavement (HHP) is used to melt snow and ice. Lund and Toth (2020) list Iceland, Japan, Argentina, the United States, Slovenia, Poland and Norway as reporting countries with such applications installed for e.g. streets and sidewalks. They estimate an area of 2.5 million square meters of heated pavement worldwide at the end of 2019, of which 74% located in Iceland. However, most of the systems listed in the World Geothermal Congress 2020 summary do not use heat pumps but high-temperature geothermal water at temperatures sufficient for snow melting without the aid of heat pumps. Such high-temperature geothermal resources are not available in most countries. In countries lacking high-temperature geothermal resources, ground source de-icing typically requires heat pumps and/or underground thermal energy storage (UTES), such as borehole thermal energy storage (BTES) or aquifer thermal energy storage (ATES), to provide sufficient temperatures and energy for de-icing. De-icing and snow-melting with ground source heat date back to the mid-1900s, with the oldest known documented bridge deck de-icing with high-temperature geothermal resources in Klamath Falls in Oregon (Lund 1999). Beginning in the 1960’s several examples of ground source de-icing and snow melting systems were built in Japan (Iwamoto et al., 1998, Katsuragi et al. 2020). The use of ground heat sources for de-icing and snow-melting is now applied in several countries worldwide in a variety of applications. Ghalandari et al. (2021) list around 60 large-scale hydronic heated pavement systems in 12 countries worldwide using solar heat, mostly for de-icing and snow melting. Several of these systems also use some sort of ground source heat.

This state-of-the-art report gives an overview of thermal de-icing and snow-melting using hydronic heated pavement (HHP) and ground sources as heat source, with focus on paved surfaces for transport infrastructure. The report is based on national state-of-the-art from the participating countries in IEA ES Task 38 (see appendix, D 1.1) and a general overview of the technology in non-participating countries worldwide.

2.2 GROUND SOURCE DE-ICING AND SNOW REMOVAL

The bulk of all ice and snow removal is done with mechanical (plowing, snowblowers, shoveling) and chemical (salts, brines) methods to improve accessibility and minimize risks for accidents among vehicles and pedestrians in winter conditions. In some locations or applications, where more continuous snow and ice removal is necessary and where mechanical or chemical snow removal methods are unsuitable or even prohibited, thermal snow and ice removal is an efficient alternative. Examples of such locations and applications are:

- Airport gates and helicopter platforms where mechanical snow removal leads to risk of interfering with the aircrafts, and the use of salt and brines are prohibited.
- Busy city centers with many pedestrians moving between shops and buildings.
- Platforms and stops for public transport.
- Road parts with increased risk for accidents due to snow- or ice accumulation, e.g. ramps, bridge decks, tunnel entrances etc.
- Railway switches where snow and ice accumulation cause problems with the operation.

Thermal snow and ice removal of some surfaces with limited size may be done using electric cables and infrared heaters, or with warm air, whereas hydronic systems are more suitable for larger applications. Hydronic snow and ice removal systems are typically closed loop systems where a heated fluid is circulated through a pipe circuit below or inside a paved surface. These hydronic heated pavement systems (HHPS) may use various heat sources, commonly district heating return heat or heat from an oil, gas or biomass boiler and also, as is the focus in this report and in the IEA ES Task 38 project – with shallow geothermal energy. Figure 1 gives a general overview of applied snow and ice removal methods, with the options for geothermal heat sources shaded.

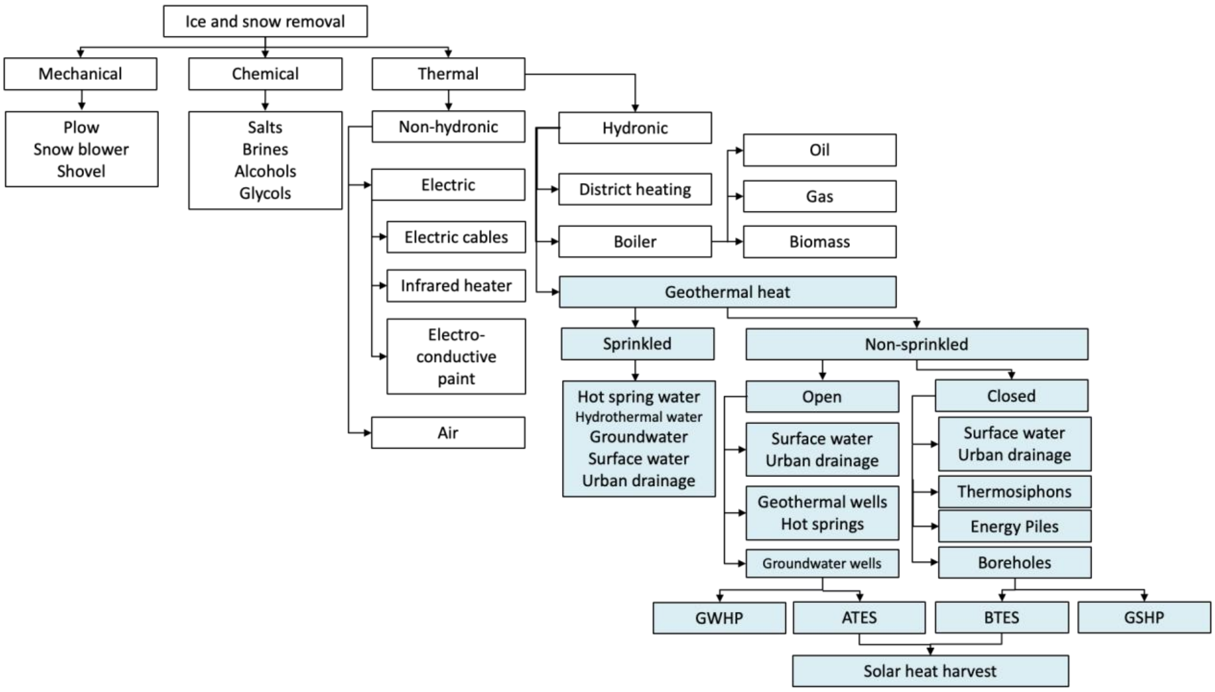

Figure 1. Ice and snow removal methods with geothermal ice and snow removal alternatives shaded.

Using the district heating return as heat source to a HHPS may often be a feasible solution which may also improve the district heating efficiency by allowing for a lower return temperature to the district heating plant. However, district heating is not always present where thermal snow and ice removal is needed. Fossil fuel heated boilers as heat sources for a HHPS cause unwanted CO2-emissions. Hence an attractive, yet not fully exploited, alternative is some sort of shallow geothermal energy as heat source for HHPSs, due to its economic and environmental benefits.

In its most general form, a ground source heated HHP de-icing and snow melting system consists of the heated surface, the ground heat source and a control system. The control system regulates the temperature of the surface using input from sensors that measure the current ambient temperature, precipitation, radiation, humidity and wind conditions etc., which in turn is used to forecast weather conditions and meet required thermal loads.

The heated surface is typically a paved surface, where asphalt and concrete are most common materials. Stone and tiled surfaces occur also. The heated surface could also be of metal, such as e.g. in the case of railway switches, or natural or artificial turf e.g. for sports field applications.

Even though high temperature geothermal energy resources are used in some places where such resources are present (e.g. Iceland) and there are examples with open hydronic snow-melting systems using sprinkled water, applications with shallow geothermal energy use are typically closed loop HHPSs that operate at ground source temperatures in the range 5-20°C. The HHPs may be used with or without heat pumps and may use the paved surface to harvest solar heat which may be stored in the ground in an aquifer thermal energy storage (ATES) or a borehole thermal energy storage (BTES). Figure 2 shows the main parts of a ground source HHP de-icing and snow melting system.

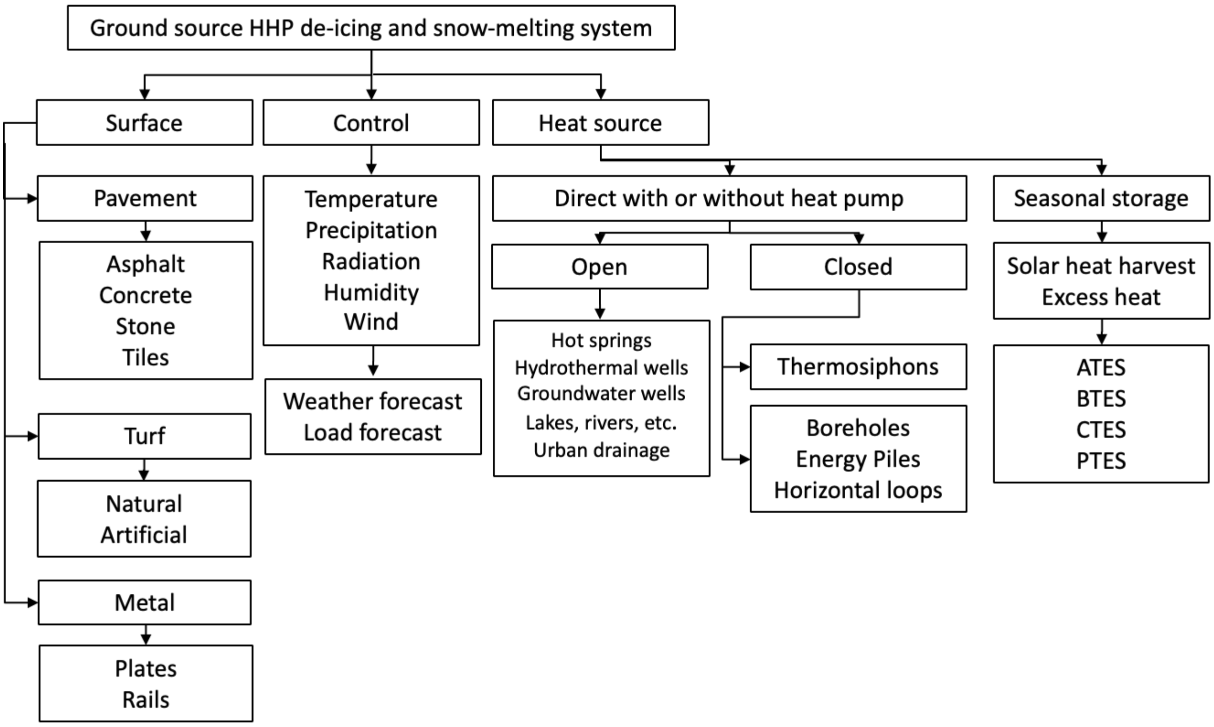

Figure 2. Schematic of hydronic heated pavement systems using ground source heating for de-icing and snow-melting.

Open loop ground sources used for ice and snow removal

Open loop ground sources for ice and snow removal may be divided into sprinkled systems and non-sprinkled systems. Sprinkled systems use groundwater, surface water or water from hot springs or urban drainage directly on an outdoor surface to melt snow and ice and are applied in some warmer but snowy areas in the southern parts of Honshu in Japan where the temperature in January does not fall below 0°C. In colder locations where sprinkled water would freeze, groundwater, surface water or water from hot springs or urban drainage are circulated in pipes below the paved surface to melt snow and ice. The heat from these sources may be used directly or with a heat pump to increase the temperature of the fluid, depending on the temperature of the ground source.

In areas where high temperature geothermal resources are not available, the most promising open loop ground sources for ice and snow removal are ground water heat pump (GWHP) systems where groundwater is pump from a natural ground water reservoir to a heat pump, and aquifer thermal energy storage (ATES) systems where the well systems is divided into a set of warm wells and a set of cold wells, and used to store heat in the aquifer between seasons. An artificial pit in the ground or a larger cavity below the ground surface could also be used to store heated water between seasons, but so far, these two applications have not been used for snow and ice melting purposes. A more detailed description of the most promising open loop ground sources for de-icing and snow melting is found in IEA ES Task 38 report D 1.2 *Market Potential for Ground Source Applications*.

Closed loop ground sources used for ice and snow removal

In closed loop ground sources for ice and snow removal, is an indirect system where a heat carrier fluid is circulated in a closed circuit between the heat source and the heat sink. The heat exchanger pipes with the heat carrier fluid inside, could be placed in a surface water reservoir, an urban drainage reservoir or as a horizontal or vertical loop in the ground. The most common and promising closed loop application is the vertical borehole heat exchanger (BHE), which could be connected to a ground source heat pump (GSHP) to raise the temperature of the heat carrier fluid or be used in a borehole thermal energy storage (BTES) system to store heat between seasons. For a more detailed description of the most promising closed loop ground sources for de-icing and snow melting, see IEA ES Task 38 report D 1.2 *Market Potential for Ground Source Applications*.

A thermosiphon (also thermosyphon) is a special closed loop application with a hermetic two-phase CO2 tube system in which heat from the ground or groundwater is transferred by evaporation of the CO2 inside the tube. The evaporated CO2 is then transported to the upper parts of the tube by buoyancy forces where it will condense and leave off heat. The condensed CO2 will then flow back to the bottom of the tube. The advantage of such a thermosiphon system is that it is purely temperature driven and needs no additional energy source for the operation. Zorn et al. (2015) describe in detail such a system, built and tested in Bad Waldsee, Germany.

2.3 HHP COMPONENTS, DESIGN, AND CONSTRUCTION

System components

The three main parts of a HHPS - the heat source, the hydronic pavement, and the control system are shown in figure 3.

The hydronic pavement is commonly constructed with a top layer of asphalt or concrete and an embedded circuit of plastic pipes at a depth of 50–100 mm and a spacing of 150-250 mm between the pipes. Other surface materials, such as stone, tiles or natural and artificial turfs may also be used.

The heat source is commonly a boiler with various fuels or district heating. So far ground source energy is rarely used. The objective of Task 38 is to increase the usage of ground source heat to reduce energy cost and CO2-emissions.

The control panel regulates the pumps, valves, etc. The panel is connected to several electronic sensors that detect temperatures in the loops, the ground surface, and the air. The weather station may also include moisture and wind speed sensors.

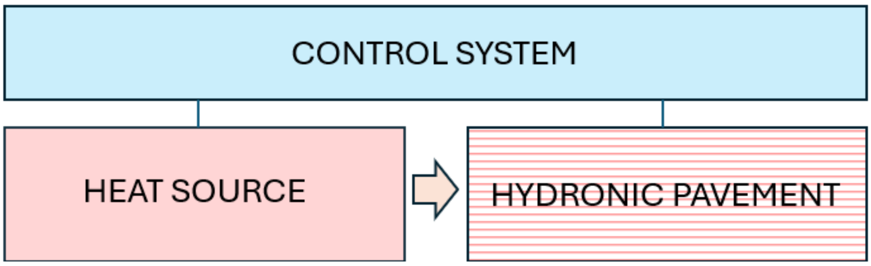

Figure 3. The main components in a hydronic heated pavement system (HHPS)

Design criteria

Load requirements

Studies on actual load requirements for HHPS considering different weather conditions are rare. However, to work properly the HHPS should have a heat load capacity in the range of 200-350 W/m^2. This criterion comes from handbooks used by installers but may vary depending on local conditions, amount of snowfall and melting, and operational strategies.

The HHP systems are commonly operated in three modes: (1) preheating, (2) snow melting, and (3) evaporation. The snow melting mode requires the highest heating demand. The intensity of snowfall that should be melted by the system will define the peak load capacity.

A certain snowfall intensity should require the same heating capacity to melt regardless of the geographical location of the HHPS.

Supply temperature

The required maximum supply temperature would be relatively high, often in the range +30 to +35^{o}C in most applications, even though there are examples of considerably lower temperatures (Andersson et al. 2024). In practice the high temperature demand is related to the speed of melting and how the system is controlled and operated. In a situation with continuous usage over the winter (turned on at an outdoor temperature of +2 or +3°C) the surface is always warm when there is snowfall or freezing. In such a case typical supply temperatures are shown in Table 1.

Table 1. Estimated interval of supply temperatures at different modes of operation of the HHP systems at Arlanda Airport in Stockholm, Sweden (Persson 2007)

Mode of operation	**Surface temp. (°C)**	**Required power (W/m^2)**	**Supply temp. (°C)**
Keep surface warm before snow fall	+1,0	20-150	3-13
Snow melting (0,02-2,0 H2O/h)	+ 3,0	150-270	17-27
Evaporation of H2O after snow melting	+5,0	100-230	12-22

As seen in table 1 the highest supply temperature demand will occur at the snow melting mode. However, there are other factors that will affect the temperature, such as the length of pipe loops and flow rate of the heat carrier fluid.

Heat carrier fluid

The HHP circuit is linked to an energy source that is distributed by pumping a heat carrier fluid through the HHP pipe system. The heat source is conventionally a gas boiler or district heating, but for ground source systems it is often a heat pump, at least for peak loads.

The heat carrier fluid in the HHP grid is water mixed with an antifreeze, typically glycol or ethanol, to prevent the system from freezing at shut down in extreme cold weather conditions. For this reason there is a heat exchanger between the heat source and HHP loops (Uponor 2015).

The fluid is circulated in the HHP loops with a frequency-controlled circulation pump. This allows the flow rate to adapt to the actual heating demand at any time of operation.

Annual heat requirement

The annual required use of heat for de-icing and snow melting varies greatly depending on the local winter climate, the type of application and the way in which the systems are operated.

In Sweden, occasional data indicate an annual energy consumption of 300-350 kWh/m^2 for busy city applications while in Iceland with some 1,2 million m^2 of HHP heated surfaces, approximately 430 kWh/m^2 is used annually (Ragnarsson et al 2020).

It is of importance to recognize that the annual heat requirement will not affect the design of the HHP grid, only the design of the ground source system if such a system is used as a heat source.

Solar energy harvest

When using the ground source systems ATES or BTES, the potential solar energy harvest is used to balance heat extraction from the ground during winter and reinjection during summer. It seems likely that this criterion could be achieved, even if there is a lack of proven measurements in realized projects.

Several studies performed on asphalt or concrete pavements suggest a solar heat harvesting factor on the order of 0.20-0.40 (D1.2 *Market Potential for Ground Source Applications).* This means that 20-40% of the solar radiation is captured. However, the higher values are without any larger influence of shading and other factors that may reduce the capture factor, for instance a too high supply temperature to the HHPS.

Construction

The construction stage of a typical HHP system is shown in Figure 4.

Figure 4. The construction stage of HHPS with grid support (Ghalandari et al 2021).

The pipes are commonly placed as close to the pavement surface as technically possible in order to be thermally optimized. Typically a distance of 5-10 cm is used. The pipe material is in most cases polyethylene (PE) with a diameter of 20-25 mm and 100-200 mm spacing. The challenge to achieve the optimum pipe embedment depth is to make a balance between thermal efficiency and preventing pipe damage. Due to practical limitations the pipes should be placed deep enough to resist potential structural failures, and to make maintenance of the surface layer performed without damaging the pipes (Ghalandari et al 2021).

Circulating fluid temperature, flow regime, flow rate, thermophysical properties of asphalt or concrete, and geometrical specifications are the key points of an optimum HHPS (Liu et al 2007).

In practice most HHPS are designed and constructed by specialized companies working in the field of de-icing and snow melting. They commonly also deliver the material and components that are used. One example of such an international company is Uponor.

2.4 FINANCIAL AND ENERGY RELATED ASPECTS

Ground source de-icing and snow melting systems have low operational and maintenance costs, but the initial costs may be high. Hence a new construction of a ground source HHPS for de-icing and snow melting, or at conversion from electric or fuel heated HHP systems to a ground source HHPS, the investment must be motivated by savings in operational and maintenance cost, compared to status quo.

Seven examples of calculated scenarios with ground source heated HHPS for de-icing and snow melting are presented in the IEA ES Task 38 report D1.2 - *Market Potential for Ground Source Applications*. The examples present energy calculations and cost calculations compared to conventional methods for snow and ice removal and prevention. The calculations are based on estimated seasonal performance "SPF" of the ground source HHP systems compared to HHPS with conventional heating, which are assumed to have an SPF value of 1. The calculations in the report also include aspects of the system lifetime, expressed as "cost-effectiveness". The calculations indicate that an economically attractive solution is adding a HHPS to an already existing ground source heated space heating system for a building. Likewise, combining ground source heating with HHP heating in a new system, is an advantageous solution. The calculations also indicate that BTES systems combined with HHPS are cost-effective. Although the calculated groundwater heat pump (GWHP) systems and ATES combined with HHPS are more cost effective than the BTES solutions, these concepts have limitation in availability of the right hydrogeological condition on site, and by more complicated permit procedures.

The cost for investment and operation should be put in relation to the long-term financial and environmental benefits as well as the improvement in pedestrian and vehicle safety. Amin et al. (2024) point out that reduction in winter-related accidents on sidewalks and roadways by HHPS decrease government expenditures on medical care, insurance claims, and compensation for injury-related social benefits, especially in urban areas. Suburban and highway applications of HHPS reduce traffic delays and improve roadway efficiency. As a bonus HHPS extend the pavement lifespan by preventing ice accumulation and mitigating freeze-thaw damage.

Standardization of system components and prefabrication of system modules is recommended in order to reduce investment cost for ground source heated HHPS for transport infrastructure and facilitate a wider implementation.

2.5 SOCIAL AND HEALTH ASPECTS

Thermal de-icing and snow-melting has the potential to reduce the number of traffic accidents due to snowy and slippery winter road conditions, as well as reducing fall-related accidents among pedestrians.

In Sweden icy and snowy conditions on paved surfaces account for 60% of all pedestrian fall injuries, most of them occurring in urban areas (Amin et al 2024). A study by Amin et al. (2024) comparing pedestrian fall accidents in four cities in Sweden indicate that thermal ice and snow removal could reduce the number of fall accidents in the winter by between 60-100 %, preventing approximately 160 injuries per year and thus saving some 11 644 000 SEK in costs for these fall accident injuries per year. Another study by the Swedish Transport Administration (Trafikverket 2012) show that approximately 25% of the fall accidents among pedestrians lead to permanent harm in the form of at least 30% disability.

Accident prevention may be the strongest promotion factor for HHP systems in busy inner cities and pedestrian areas. Carlsson et al. (2016) also point out increased comfort and safety, increased mobility and reduced insulation for vulnerable groups, simplified snow removal in "furnished" places, reduced wear and tear on sensitive materials in the substrate (marble), reduced use of sand and salt with following reduced wear in stores and escalators and reduced costs for cleaning, service and maintenance, as other important promotion factors for thermal de-icing and snow removal in pedestrian areas.

The cost for installation and operation of a ground source heated HHPS cost should be put in relation to the cost for injuries and deaths due to fall accidents among pedestrians and bicyclists and also the cost of traffic accidents and the following disruptions in accessibility due to slippery conditions for vehicles.

Ground source heated sports fields, e.g. soccer fields, have positive overall social and health benefits by preventing injuries caused by a frozen ground and also by prolonging the active season for most of the winter season.

2.6 ENVIRONMENTAL ASPECTS

The environmental impact of ground source heat for HHPS as compared to conventional heat sources mainly relate to the reduction of greenhouse gas emission from energy production and snow removal machinery, and reducing the amount of salt and brine. The construction of the hydronic pavement itself does not vary much regardless of which heat source is chosen, but the environmental impact of the heat production does make a difference. Conventionally heated systems using electric cables, fuel boilers or district heating cause greenhouse gas emissions depending on the primary energy source for the electricity, fuel and district heating production. The heat from shallow geothermal systems is renewable energy from the ground or from harvested solar heat, and a small amount of additional electricity is used for circulations pumps and heat pumps, if the system includes heat pumps.

Further details on environmental and social aspects of ground source heated HHPS for de-icing and snow melting from a market point of view are presented in the IEA ES T38 report D1.2 - *Market Potential for Ground Source Applications*.

Greenhouse gas (GHG) emissions

When comparing greenhouse gas (GHG) emissions from different de-icing and snow removal methods, the emissions from fuels for snow removal vehicles, boilers and district heating are put against GHG emissions from electricity use for electric cables, circulation pumps and heat pumps in electric and ground source de-icing and snow removal systems. The GHG emissions from electricity depends, in turn, on the use of fuels and renewable energy sources used in the national electricity mixes. The mean GHG emission from electricity production in the EU was about 200 gr/kWh in 2023, while the EU target for 2030 is 100 g/kWh and near zero by 2050.

The EU Directive on renewable energy (2007), stipulates that heat extracted from the ground (or air or water) is renewable and can be assessed to have no GHG emissions. However, from a life cycle cost (LCC) perspective shallow geothermal energy systems cause some GHG emissions (CO2) due to the drilling of boreholes, manufacturing and operation of drilling equipment and system components. Because the ground source systems have long lifetimes, over half a century, their LCC emissions are considered very low. Table 2 shows calculated GHG emissions from electricity and fossil fuels according to IPCC (2014). As a comparison, ground source heat using EU mean electricity for circulation pumps and heat pumps is calculated to cause GHG emissions in the range 8-65 kg/MWh, depending on type of ground source system (see further details in IEA ES report D 1.2

Market Potential for Ground Source Applications). Hence the GHG emissions from ground source de-icing and snow melting are just a small fraction of the GHG emissions from conventional thermal de-icing and snow-melting systems, using electric cables or fossil fuels.

Table 2. GHG emissions from mean EU electricity and fossil fuels according to IPCC (2014)

Source	**GHG emission (kg/MWh)**
Electricity	200 (EU mean value)
Coal	740 - 1690
Oil	510 - 1170
Gas	290 - 930

Local environmental impact

The local area around a closed loop ground source heating systems is temporarily impacted by the installation of the borehole heat exchangers during the construction period due to the drilling process. With a correct construction, there is no disturbance of the local environment once the construction is completed. The main environmental concern is groundwater protection for which most countries have introduced mandatory sealing of the boreholes by grouting (IEA- ECES 2020).

For open loop systems with groundwater as heat source, the static groundwater level will decrease near the abstraction wells and increase near the injection wells, which may have some impact on the environment close to the wells. Most countries require some sort of assessment studies based on hydraulic modeling and a survey of potential disturbances as a part of the application procedures for drilling permits. In these assessments the potential environmental impacts in the vicinity of a groundwater well or borehole field are described. Would the system be considered to cause unacceptable environmental impact on the ground, groundwater, buildings or infrastructure within a defined area of hydraulic influence, a permit for the construction would generally not be granted.

De-icing chemicals and salts

The most common de-icing chemical used in Europe to prevent and melt ice and snow on paved surfaces sodium chloride (NaCl), which in colder conditions may be mixed with calcium chloride ($CaCl_2$). At airports alternative chemicals such as urea, alcohols and glycols are often, as they do not cause corrosion like salts and brines. The chemicals and salts used for ice and snow prevention and removal mix with meltwater and stormwater and infiltrates into the groundwater and may reach creeks, rivers, and lakes. According to the Swedish Geological Survey (SGU 2004) salt leakage from roads lead to locally elevated salinity levels that may affect both flora and fauna. Salts can be toxic to plants, trees and aquatic life near the roadside and other de-icing chemicals can reduce oxygen levels in the groundwater and local surface water.

Road salt increase the risk of traffic accidents with wild animals that lick salt on the roads. In northern Sweden it is estimated that some 2000 reindeer die in traffic accidents every year.

Apart from biological impact, road salts are corrosive to metal in e.g. vehicles, rails, railway switches and reinforcement, and to concrete in infrastructure constructions and pipes in stormwater systems. Re-freezing meltwater and slush can also cause frost heaving with resulting damage to pavement.

Thermal de-icing with HHPS using ground source heat has no biological impact on groundwater and surface water and does not cause corrosion of metals or concrete. Hence it is a way to decrease the use of road salt and other de-icing chemicals.

2.7 OVERVIEW BY COUNTRY - PART 1: T38 PARTICIPANTS

This chapter gives an overview of the use and potential of ground source de-icing and snow-melting in the six countries involved in IEA ES Task 38. In addition, an overview of countries with documented experience from ground source de-icing and snow-melting is given. The information in this section is partly based on a conference paper for IGSHPA Research Conference 2024 by Gehlin et al. (2024).

Belgium

The temperate maritime climate in Belgium, characterized by mild winters with limited snowfall but frequent occurrence of frost and ice. The interest in thermal snow melting systems as an alternative to conventional snow removal has so far been limited.

Belgium has a developed use of shallow geothermal energy, especially in Flanders in the north of the country, where the geology is characterized by a thick overburden of clays and sand over a paleozoic bedrock (Dupont et al. 2022).

Thermal de-icing and snow-melting

Thermal de-icing and snow melting of paved surfaces is used both with electricity (EHPS) and with HHPS using district heating return or ventilation air from buildings as heat sources. The systems are used on pedestrian streets, building entrances, ramps, and sports fields. There are also examples of HHPS combining ground-source heat pumps solar heat or district heating.

Ground source de-icing and snow melting sites

There are no full-scale ground source de-icing and snow melting systems in operation in Belgium, as of today, but there are two pilot projects using HHPS for snow melting in Belgium, both located in Antwerp.

A research prototype site named Heat Exchange Asphalt Layer (HEAL) system is installed at the University of Antwerp. The HEAL test site is a 65 m^2 section of a bicycle path constructed in 2017. It has four heat exchanger sections, each 8.5 m x 1 m, and two non-heated reference sections of 30 m^2. The test surface is connected to a heat pump and a buffer tank. The heat pump is supplied with heat from two boreholes of 100 meters depth. The boreholes are fitted with single U-tubes which are filled with a heat carrier fluid mixture of water and monopropylene glycol. The asphalt HHP system collects solar heat in the summer and is used for de-icing and snow melting in the winter. The HEAL system can be run in several operational modes such as parallel or series pipe configurations and can be optimized for various weather conditions. It is described in more detail by Ghalandari et al. (2023) and Ghalandari and Van den Bergh (2023).

The Zonnige Kempen Social Housing Complex in Westerlo was constructed in 2006 and consists of an asphalt solar collector connected to a heat pump and a ground storage system in soil to provide heat for underfloor heating and domestic hot water (DHW) production for 13 houses. This system uses a smart control mechanism that prioritizes the production of DHW over underfloor heating. If the solar collectors provide sufficient heat, it can be transferred directly to the heating system; otherwise, stored heat from the ground storage system is used. The project reduced primary energy consumption with 32% during its first measurement period.

See also the IEA ES Task 38 national state-of-the-art report for Belgium in the appendix, D1.1.

France

The climate in France varies from mild winters in the southern and western parts to more severe winters in the central and eastern regions, and includes also oceanic, continental, Mediterranean, and mountainous climate types.

Shallow geothermal energy is used in more than 200 000 houses in France, with vertical boreholes and horizontal loops spread throughout the country and groundwater systems concentrated to the northern and western parts where the geology consists of sedimentary basins favorable for aquifers (Schmidlé-Bloch et al. 2022).

Thermal de-icing and snow-melting

Winter road maintenance is generally done with mechanical and chemical (salt) methods in France and thermal de-icing and snow melting of paved surfaces is not extensively in use. EHPS and gas heated HHPS are used for de-icing rail infrastructures, sidewalks and sports fields.

Pavement solar collectors with embedded piping and heat storage in the ground have been developed over the last decade and commercial systems and products are available on the French market. Research on porous layer systems is ongoing. The pavement solar collector systems with and without boreholes and heat pumps have so far been implemented for space and water heating but can be used for solar heat collection combined with de-icing and snow-melting. Cooling of the pavement in summertime increases the service life of the surface.

Ground source de-icing and snow melting sites

On the Autoroute A10 in Saint-Arnoult-en-Yvelines a ground source de-icing and solar heat harvesting system named Power Road® has been installed. The installation covers an area of 500 m² and combines a heat pump connected to boreholes and energy-positive asphalt to provide both roadway de-icing and building heating.

The Power Road projects in Egletons and the Dromotherm project in Chambéry harness solar energy in the summer and store it for de-icing purposes in the winter.

These projects are described in more detailed in the IEA ES Task 38 national state-of-the-art report for France in the appendix, D1.1.

Germany

Germany has a varying climate with temperate lowlands and snow-prone mountain regions. The west has temperate and marine climate, there is humid continental climate in the east, temperate in the center and south, and oceanic in the northwest and north. Winters are cold and summers are warm.

Germany is the second largest user of geothermal energy in Europe, utilizing both deep and shallow geothermal resources. At the end of 2021 there were some 435 000 GSHPs installed in German buildings (Weber et al 2022).

Thermal de-icing and snow-melting

Thermal de-icing and snow-melting systems are widely used in Germany for a range of applications such as driveways, parking areas and sports facilities. Most of the thermal de-icing systems are EHPS or HHPS heated by a gas or oil furnace. EHPS systems are mostly used for residential and commercial purposes such as de-icing of driveways, sidewalks, stairs, and roofs. HHPS are used for loading areas, parking ramps

There are several full-scale implementations of ground source de-icing in operation in Germany for various paved surfaces as well as for rail switches.

Ground source de-icing and snow melting sites

Germany is one of the leading countries in the use of shallow geothermal energy for de-icing and snow melting systems for a range of applications such as roads, bridges, tunnels, metro stations, platforms, bus lanes and railway switches. The ground sources vary from groundwater to boreholes, with and without heat pumps, as well as two-phase thermosyphons. Commercial systems and products for ground-source heated HHP are available on the German market.

Germany is one of few countries that have tried out CO2-thermosyphons for de-icing and snow melting. A CO2-thermosyphon is a closed tube where heat from the ground is transferred to a heat sink, in this case the pavement, by a temperature driven evaporation-condensation process. No additional energy or control system is needed to operate the CO2-thermosyphon. They have been used for de-icing of railway switches, metro stations and ramps.

In Germany mastic asphalt systems have been used in combination with GSHPs or other heat sources to de-ice large surfaces such as bus lanes and parking ramps. Mastic asphalt is known for its durability and energy efficiency, making it suitable for industrial applications.

A test site for a passive open-space ground source heating system at a service yard for a tunnel in Füssen (Germany) was constructed in 2019-2020 and operated in the winter of 2021-2022 to keep the surfaces free from snow and ice throughout the test winter (Moorman and Buhmann, 2017). Groundwater from the mountain was pumped directly through piping in the pavement without heat pumps and heat exchangers and is used both for de-icing in the winter and cooling the surface in the summer.

See also the IEA ES Task 38 national state-of-the-art report for Germany in the appendix.

Table 3. Ground Source De-icing Systems in Germany (from Gehlin et al, 2024)

Location	**Application**	**Ground Source**	**Reference**
Therese-Giehse-Allee, Munich	Metro station	Groundwater/ thermosyphon	[Schenk, 2011]
Berkenthin	Canal Bridge	Groundwater heat pump	[Eilers et al., 2020]
Bergson strasse, Munich	Buslane	Groundwater heat pump	-
Audi, Ingolstadt	Garage Ramps	Unspec. Ground source	-
Fire department, Bad Waldsee	Exit Ramp	Boreholes/thermosyphon	[Zorn, 2015]
Grünberg	Railway switch	Boreholes/thermosyphon	-
Hamburg	Railway switch	Boreholes/thermosyphon	-
Sponholz	Railway switch	Boreholes/thermosyphon	-
Bad Lauterberg/Barbis	Platform heating	Boreholes + heat pump	-
Riegelplatz, Dresden	Tram platform and switch heating	Boreholes/thermosyphon	[Hamann et al., 2005]

Italy

The Italian climate is largely characterized by Mediterranean climate conditions but ranges between Alpine climate in the northern and central mountainous regions to mild climate along the coastline and on islands.

Italy has vast geothermal resources, both shallow and deep, and the use of geothermal energy for electricity, district heating and GSHPs has expanded significantly over the last decades. Italy is among the world top 15 geothermal energy using countries in the world (Lund and Toth 2020).

Thermal de-icing and snow-melting

Snow-removal and de-icing systems in Italy mainly rely on mechanical and chemical (salt) removal. EHPS are limited to indoor heating and small-scale uses such as residential ramps, stairways, and helicopter landing areas, and are challenged by the high electricity cost and strain on the electrical grid. Italy has an extensive district heating (DH) network and a promising development of geothermal energy, but there are so far no reported HHP installations for de-icing and snow-melting using either DH, or ground source heating in the country.

Ground source de-icing and snow melting sites

There are no examples of installed ground source de-icing systems in Italy so far, but there is a significant potential for such systems, both from a climatic and geothermal resource availability point of view.

See also the IEA ES Task 38 national state-of-the-art report for Italy in the appendix, D1.1.

Sweden

Sweden has a cold climate with very cold and snowy winters in the mid and northern parts of the country and milder but icy winters in the southern parts.

Sweden is also the third biggest geothermal energy using country in the world after China and the USA (Lund and Toth 2020). 20-25% of all single-family houses use a GSHP. Despite this, geothermal energy is not yet used for de-icing and snow-melting to any significant extent.

Thermal de-icing and snow-melting

Thermal de-icing with HHPSs using district heating (DH) return as heat source is widely used in Sweden for de-icing of pedestrian areas, roads, bridges, sports fields, and airports. As of today, a total area of some 600 000 m^2, mainly for pedestrian streets and sidewalks in city centers, is heated with district heating heated HHPS, commonly at a temperature of some 35°C. Apart from heating pavements, hydronic heating systems are also used to heat artificial turf sports fields. Approximately 8% of the fields have HHP systems, representing a heated surface area of some 500 000 m^2 (Andersson et al., 2023).

EHPS have also been widely used in Sweden to keep smaller paved areas such as building entrances and roofs free from snow and ice, and for de-frosting railway switches. Increasing electricity prices have, however, led to a decrease in numbers of such systems.

Ground source de-icing and snow melting sites

While district heating return is the most frequent heat source for HHPS systems in Sweden, there are also examples of ground source heated HHPS used for sports fields. Backadalen IP in Katrineholm, Täby football arena, Torvalla arena and Kungsängen sports center all use BTES systems as heat source and a soccer field in Hallsberg uses heat from groundwater (Andersson et al., 2024).

Sweden is the third biggest geothermal energy user in the world after China and the USA (Lund and Toth, 2020). 20% of single-family houses use a GSHP. Despite this, geothermal energy is not yet used for de-icing and snow-melting to any significant extent.

An exception is Arlanda International airport in Stockholm that uses its large-scale ATES system partly for snow melting at aircraft parking areas. To keep the aircraft free of ice the ATES connected HHPS provides free heating down to approximately -10°C at an inlet temperature of 10-15°C. The return temperature is then cold enough to be stored in the ATES system cold wells. At medium and heavy snowfall the supply temperature has to be increased by using district heating (Lind 2013 and von Shotting 2018).

Several commercial and institutional buildings that use GSHP systems for space heating and cooling, also include smaller HHP systems such as entrances and ramps (Andersson et al 2023).

There is one experimental road section in Östersund called The Nordic HERO project (Johnsson, 2019) where an HHPS connected to four boreholes. This test site was set up in 2017-18 and has a 20 m long and 3.5 m wide heated concrete pavement surface with embedded PEX pipes. The paved surface is used as a solar collector in the summer and the heat is stored in the four boreholes for de-icing in the winter.

See also the IEA ES Task 38 national state-of-the-art report for Sweden in the appendix.

Türkiye

Türkiye has a diverse and generally temperate climate, with coastal climate around the Mediterranean and Black Sea, and more continental climate at the center. The coastal regions have mild and rainy winters, while the lower plateaus at the center have cold snowy winters and the higher plateaus have severe and snowy winters.

The geothermal potential in Türkiye is considerable, with both low-temperature ground heat sources, and high-temperature geothermal heat and deep geothermal resources have been increasingly utilized over the last decade. Cetin (2020) estimates the geothermal heat potential in Türkiye as 35 500 MW_t and the geothermal power generation potential as 4500 MW_e.

Thermal de-icing and snow-melting

Thermal de-icing using EHPS or HHPS with gas boilers as heat source is widely used especially for for heating sports fields in Türkiye. 22 soccer fields with an area of about 157 000 m^2 are heated with hydronic heating systems using fossil fuel as heat source and another ten arenas with a total area of about 71 400 m^2 are heated with electric cables. Electric heating is also used for keeping pedestrian streets, ramps, roofs, greenhouses, and hospital entrances free from ice.

Ground source de-icing and snow melting sites

Türkiye has no examples of installed ground source de-icing systems so far. There have been academic studies and laboratory testing of ground-source HHPS in Türkiye, but so far there are no actual installations.

The vast deep geothermal resources in Türkiye offer good potential for ground source de-icing and snow-melting systems, both with shallow geothermal energy and high temperature geothermal fluids. Using BTES or ATES for de-icing and snow melting with HHPS would also allow for surface cooling in the summer, which would be a valuable service to prolong the lifetime of asphalt and concrete surfaces in the Turkish climate.

See also the IEA ES Task 38 national state-of-the-art report for Türkiye in the appendix, D1.1.

2.8 OVERVIEW BY COUNTRY - PART 2: WORLDWIDE

Argentina

Chiodi et al. (2020) estimated the installed capacity for geothermal snow melting systems in Argentina to 1.36 MW installed capacity and 8 GWh. Since 1998 the Copahue-Caviahue thermal field has been used for heating streets and roads in the Copahue Village, southwest of Buenos Aires (Pesce, 2000). Geothermal steam at 8 bar pressure and 178°C is used to heat radiant panels that keep the streets free from snow.

Iceland

The use of geothermal water for heating sidewalks and pavements to melt snow during the winter in Iceland has increased over the years and the total area in 2019 covered 1 200 000 square meters, mostly in the Reykjavik area. The total installed capacity was 260 MW, and the geothermal energy use was 525 GWh for snow melting in 2019, which is 3.2% of the total geothermal direct use in Iceland (Ragnarsson et al., 2020).

Japan

Around 60% of the total area of Japan is subject to severe and snowy winter weather. When cold air from Siberia passes over the Japanese Sea and reaches the land it can cause extreme snowfall. Already in 1957 the Japanese government implemented a special act concerning road maintenance in cold and snowy districts to prevent traffic accidents and isolation of cities due to snowfall (Katsuragi et al 2020). In 1961 snow melting systems that sprinkled groundwater directly on the road surface was implemented in the middle part of Japan and along the coast. In the 1980’s and 1990’s snow melting systems with closed fluid loops, first horizontal pipes and later with borehole heat exchangers, were introduced to Thermal de-icing and snow melting methods have since developed and spread in Japan and is commonly used in multiple applications, using both shallow geothermal energy and high temperature geothermal resources where available, as well as EHPS and HHPS with other heat sources than geothermal heat.

EHPSs and electric heated hot air snow-melting methods are used for removing snow and ice from railway tracks.

HHPS is used in a number of applications and a variety of heat sources, such as heat from groundwater, geothermal water, the ground, solar heat or biomass. It is used for de-icing and snow melting of various paved surfaces as well as residential roofs.

According to Yasukawa et al. (2020), geothermal snow melting systems with an installed capacity of 150 MW in total and a heat delivery of 12 GWh were installed in Japan by the end of 2019. They counted 103 geothermal snow melting systems for roads and one for a parking lot in 2019 and this had increased to a total of 106 systems for roads and parking lots in 2022 (Yasukawa et al. 2023). Groundwater, surface water, geothermal water and boreholes are used as ground source heating for de-icing and snow-melting, with and without heat pumps in Japan. Most of these applications use HHPS but there are also examples of warm water sprinkling systems (Ochifuji, 2000). Sprinkled snow-melting methods use pipes that spray water (groundwater, hot spring water, surface water or urban drainage) onto snow-covered surfaces to melt the snow. This method is used in warmer snowy regions, where temperatures do not go below 0°C in the winter.

In Sapporo, one of Japan’s snowiest cities, an extensive road heating system using both EHPSs and HHPSs, of which part is heated with geothermal resources is installed. The system covers 52 km of roads (221,000 m²) and used 84% electric heating, 11% gas heated water and 5% geothermal spring water.

Table 4. Ground Source De-icing Systems in Japan

Location	Application	Ground Source	Reference
Ato, Yamaguchi, 1997	Parking lot	BTES	[Sanner, 2007]
Hiwa, Hiroshima, 1997	Road and bridge	BTES	[Sanner, 2007]
Muraoka, Hyogo, 1997	Parking lot	BTES	[Sanner, 2007]
Funo, Hiroshima, 1996	Road and tunnel	BTES	[Sanner, 2007]
Aomori, Aomori, 1992	Parking lot	Boreholes	[Sanner, 2007]
Kyowa, Akita, 1991	Road	Horizontal heat pipe	[Sanner, 2007]
Yonezawa, Yamagata, 1993	Road	ATES	[Sanner, 2007]
“Gaia”, Ninohe, 1995	Road	Boreholes	[Sanner, 2007]
Sekiyama tunnel, Tohoku, 2002	Tunnel	Boreholes with heat pump	[Sanner, 2007]
Sakai, Fukui, 1999+2006	Bridge deck	Steel piles	[Sanner, 2007]
Fukui, 2006	Parking lot	Steel piles	[Sanner, 2007]
Happiness bridge, Fukui, 2007	Bridge deck	Steel piles	[Sanner, 2007]
Nagaoka city, Niigata, 1961	Roads	Sprinkled groundwater	[Katsuragi et al 2020]
Akita city, Akita, 1980	Roads	Groundwater	[Katsuragi et al 2020]
Yamagata city, Yamagata, 1981	Roads	Groundwater	[Katsuragi et al 2020]
Kuriko tunnel, Tohoku, 2017	Tunnel	Groundwater	[Katsuragi et al 2020]

The Netherlands

The Netherlands has some documented examples of ground source de-icing systems. Sanner (2007) report a railway section with 32 switches in Sidings in Lelyland in the Netherlands, installed in 2004 and proceeded by a test installation in Arnheim in 2003, using classical borehole heat exchangers with a ground source heat pump. A sports facility in Gelredome in Arnheim uses an ATES system with four groundwater wells of 80 m depth to heat a grass field and provide heating and cooling for the sports buildings (Sanner 2007). Sullivan et al (2007) describe and list several Dutch examples of ground source HHPS connected to ATES used to harvest solar heat with the main purpose of using the heat for space heating of buildings, with the additional use of cooling the asphalt in the summer and de-icing in the winter. Some of the examples of the Dutch concept were installed in the UK.

Norway

In Norway, two examples of geothermal snow melting systems for helicopter landing areas are installed at Gardermoen International airport in Olso and at Taraldrud ski municipality. The boreholes are 1500 m deep and fitted with coaxial borehole heat exchangers (BHE). At Gardermoen International airport in Olso, Norway, an ATES system is also used for snow melting at airplane parking areas.

Poland

Kepinska (2020) mentions geothermal snow melting systems in two locations in Poland - a heated football pitch and walking paths in Uniejów and a snow melting system for a parking area in the Podhale region. The total installed capacity is 0.5 MW and the heat provided is 550 MWh.

Slovenia

In Slovenia, there was 1 MW installed capacity providing 4.43 GWh geothermal heat for snow melting by the end of 2019. These systems are installed in three localities in Slovenia: In Lendava a sidewalk heating system uses excess geothermal heat from a thermal water doublet system, at Hotel Vivat in Moravske Toplice there are two geothermally heated football pitches and in Čatež there are another three geothermally football pitches (Rajver et al., 2020).

Switzerland

Another example of ground source heated de-icing systems for transport infrastructure, installed in 1994, is the SERSO project near Därlingen in Switzerland (Eugster, 2002, Eugster, 2007, Lund, 2000 and Pahud, 2007). Solar heat is collected from the road surface, and the heat is stored in a borehole storage in rock, to be used with heat pumps to keep the road free from ice in the winter.

USA

In the USA there are several large-scale snow melting systems using the ground as a heat source. Lund et al. (2020) estimate the total installed capacity as 2.1 MW at the end of 2019. Already in 1948 ground source snow melting systems were installed in Oregon in Klamath Falls for a bridge deck (Lund, 1999) and have since been expanded for sidewalks and on a bridge deck leading up to the high school, altogether accounting for some 1.17 MW installed capacity and 1 GWh heating. Additional systems are installed for stairs at the Oregon Institute of Technology camps (0.06 MW) and a steeply inclined state highway section at a traffic signal on a state highway steep hill (0.26 MW) which prevents vehicles from sliding when they stop at the signal. In 1969 a ground source bridge heating system with horizontal pipes filled with glycol/water heat carrier was installed in Trenton, New Jersey, for snow melting. The ground heat exchanger pipes were buried at 1-4 m depth and were twice the length of the snow melting pipes in the pavement. Lund et al. (2020) also list bridge deck snow melting in Sybille Canyon and Spring Creek near Laramie (0.06 MW, 300 MWh), installed in 1976 and 1980, and in Cheyenne (0.26 MW, 1.5 GWh), installed in the 1970’s, where ammonia heated from a ground temperature of 8°C is circulated in the pipes. Minsk (1999) describes ten bridge deck de-icing systems in the USA, of which two in Oregon and one in Texas use the ground as heat source. Later research efforts on thermal de-icing with ground sources include an experimental heated bridge deck in Oklahoma (Spitler and Ramamoorthy, 2000, Liu et al., 2007a, Liu et al., 2007b)

Several airports in the USA have installed ground source de-icing systems, e.g. Greater Binghamton Airport in New York, which has a ground source de-icing system for the airport pavement using BTES (Ziegler and Nixon, 2023).

Table 5. Ground Source De-icing Systems in the USA

Location	Application	Ground Source	Reference
Klamath Falls, Oregon, 1948	Bridge deck, sidewalk, stairs, highway section	Geothermal water at 102°C	[Lund, 1999]
Trenton, New Jersey, 1969	Bridge deck	Horizontal ground loops	[Sanner, 2007]
Oak Hill, West Virginia, 1970's	Ramp	Heat pipes	[Lund, 1999]
Cheyenne, Wyoming, 1970's	Ramp	Heat pipes	[Lund, 1999]
Sybille Canyon, Laramie, Wyoming, 1976	Bridge deck	Heat pipes	[Lund, 1999]
Spring Creek, Laramie, Wyoming, 1980	Bridge deck	Heat pipes	[Lund, 1999]
Silver Creek, Oregon, 1995	Bridge deck	Groundwater heat pump	[Sanner, 2007]
Amarillo, Texas	Bridge deck	Boreholes with heat pump	[Sanner, 2007]
Smart Bridge project, Oklahoma, 2000	Bridge deck	Boreholes with heat pump	[Spitler and Ramamoorthy, 2000] [Liu et al., 2007a] [Liu et al., 2007b]
Prairie Village, Kansas, 1993	Car wash area	Boreholes with heat pump	[Sanner, 2007]
Greater Binghampton Airport, New York, 2009	Airport	Boreholes	[Ziegler and Nixon, 2023]
Zion Hot Springs, Utah	Walking path	Geothermal water	

Summary

De-icing and snow-melting of outdoor surfaces to prevent accidents at slippery surface conditions or to improve accessibility is used worldwide. It can be done with chemicals (brines) or thermally, e.g. using electric cables, warm air or various types of hydronic heat distribution. Heat sources for thermal de-icing and snow-melting include electricity, district heating, fossil fuel boilers, and ground source heat.

Using heat from the ground to melt snow and ice has been done at least since the mid-1900s. The oldest known documented bridge deck de-icing with high-temperature geothermal resources in Klamath Falls in Oregon was installed in the 1950s. In the 1960s a new snow-melting system using sprinkled groundwater on roads was introduced in Japan as a means of decreasing the number of traffic accidents and isolation of cities due to heavy snow fall. Since then, methods for using the ground as a heat source for de-icing and snow-melting have slowly spread to more countries, developing in an increasing variety of ground sources, heat distribution methods and applications for ice- and snow melting. Iceland and Japan are today the two countries with the most extensive use of ground-source heating for de-icing and snow-melting, accounting for around three quarters of the global market. Both these countries have geologies rich of high-temperature geothermal resources which enables using geothermal water at temperatures sufficient for snow melting without the aid of heat pumps. Such high-temperature geothermal resources are, however, not available in most countries. In countries lacking high-temperature geothermal resources, ground source de-icing typically requires ground source heat pumps (GSHP) and/or underground thermal energy storage (UTES), such as borehole thermal energy storage (BTES) or aquifer thermal energy storage (ATES), to provide sufficient temperatures and energy for de-icing.

This report gives an overview of thermal de-icing and snow-melting using hydronic heated pavement (HHP) and ground sources as heat source, with focus on paved surfaces for transport infrastructure such as road parts, bridge decks, parking areas and paths and surfaces for pedestrians and bicyclists. Additional non-paved applications include de-icing of railway switches, and solutions for keeping snow and ice off non-infrastructure surfaces such as soccer fields and golf greens with natural or artificial turf.

Ground source de-icing and snow-melting with HHP combines developed techniques for retrieving and storing heat in the subsurface (GSHP and UTES), hydronic subsurface heat distribution and control systems using weather forecasting. Applications and system design depend largely on local geohydrological and climatic conditions and may include actively stored solar heat.

National overviews of the state-of-the-art for ground source de-icing in the participating countries in IEA ES Task 38 are appended to this summarizing report, which also includes a general overview of the technology in non-participating countries worldwide.

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3 STATE-OF-THE-ART AND MARKET OVERVIEW SUBTASK 1, DELIVERABLE 1.2: REPORTMARKET POTENTIAL FOR GROUND SOURCE APPLICATIONS

This report is compiled within the framework of the 2021-2024 IEA ES Task 38 “Ground Source De-Icing and Snow Melting Systems for Infrastructure”. The report is an extension of the State-of-the-Art Report (D1.1) and covers market potential issues using shallow geothermal as a heat source for de-icing and snow melting systems (HHP systems).

Based on experience from existing ground source applications for space heating added by scenario calculations, the most promising systems for ground source coupled HHP applications are identified and ranked. The ranking is preferably based on the expected seasonal performance factor (SPF), cost effectiveness, and geological availability.

3.1 INTRODUCTION

Geothermal sources that potentially can be used for melting snow and ice are commonly grouped into two main categories, Deep and Shallow geothermal. Even if there is no strict boundary between “shallow” and “deep” the recent suggestion by the European Geothermal Energy Council (EGEC) is to use the ambient temperature of the ground as a definition. According to EGEC, a ground source temperature at, or above +30°C is regarded as “deep”. The same temperature is used by GeoERA (2020) to define the upper limit for “shallow geothermal”.

A common way of classifying shallow geothermal systems is to use the terms OPEN and CLOSED systems. OPEN systems mean using groundwater as a heat carrier. In CLOSED systems a heat carrier (fluid) is circulated in a closed and pressurized loop into and out of the underground. The main difference is that open loop systems can provide a considerably higher supply temperature than closed loop systems and therefore are less dependent on supporting heat pumps.

Basically all Deep Geothermal systems are open systems. The heat source would typically be hot water from thermal aquifers at a depth of a kilometer or more, or water heated by flowing through fracture systems in hot rock at great depths. Hot water is commonly directly used in e.g. district heating grids or industries. In some plate tectonic active areas, such hot water can be produced from more shallow depths or even from hot springs. Such conditions can only be found in active volcanic areas around the world. In these areas geothermal systems are sometimes also used for electricity production.

In most areas of the world, geothermal aquifers with temperatures high enough for direct de-icing and snow melting are found at depths of at least 1,000 m. These aquifers may be of interest as a source for HHP systems, but then in many cases in conjunction with space heating in order to be cost effective.

This is also the case for an emerging technology with moderately deep boreholes into hard crystalline rock. These are half-closed loop systems often named Standing Column wells in which groundwater is circulated and heated by direct contact with the borehole wall and with a central pipe for return. The Standing Column well systems, although used over several decades, are still under development.

The shallow geothermal sources commonly known as Ground Source Heat Pump (GSHP) systems can harvest low enthalpy heat through shallow boreholes or wells and also from the upper soil and surface water. These systems need heat pumps to increase the supply temperature to a useful level and are commonly used for space heating all over the world.

Using common GSHP systems for de-icing and snow melting exclusively would require too large investment to serve the small amount of heat needed for an HHP system. However, in general minor HHP systems combined with space heating for buildings are of great market interest. This applies also to energy piles (FEP) used for heating and cooling of larger buildings.

A special application is HHP systems for railway switches. According to Staudacher (2024) several such GSHP systems are reported from Germany, also including ground source thermosyphon systems without heat pumps (GST).

Underground Thermal Energy Storage (UTES) systems are favored by the fact that HHP systems can be used as solar collectors. In other words, solar heat can be harvested and stored in the UTES system during the summer to be used for de-icing and snow melting in the following winter season.

The UTES systems include Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES) as the most commercial ones. Cavern Thermal Energy Storage (CTES) and Pit Thermal Energy Storage (PTES) may also be of interest in the future.

An emerging UTES technology is Foundation Energy Piles (FEP) for the storage of thermal heat. These systems are commonly applied for large buildings and are used for combining space heating and air conditioning for the building itself. Just like GSHP systems an additional HHP function for minor HHP applications may be of great market interest.

Most UTES systems allow for storage of surplus heat obtained from other heat sources, e.g. industrial waste heat or surplus heat in district heating grids, in this sense named High Temperature UTES (HT-UTES). Based on their ability to seasonally store heat in the summer at a very low cost, the UTES systems have high market potential to be used for larger-sized HHP systems exclusively. They may even be used to replace the more expensive heat sources used in existing HHP systems. For this reason, they are of great market interest.

In Table 1 the geothermal system is classified and summarized with respect to market potential for usage in HHP applications.

To understand the fundamentals of HHP applications using shallow ground source heating systems the construction of HHP systems and their ability to harvest solar energy for storage are described in the first two chapters in this report. In the following chapters, the most promising concepts are described and ranked from a technical perspective and their market potential is analyzed. Finally, the environmental benefits of using ground source coupled HHP systems are overviewed.

As support for the market ranking several scenarios of applications have been performed. These are separately reported in Appendix D1.2

Table 1. Classification of geothermal systems with respect to source temperature and HHP market potential

GEOTHERMAL HEAT SOURCE	SOURCE TEMPERATURE	HHP MARKET POTENTIAL
Deep Geothermal	High enthalpy (>30°C)	Combined with space heating
Ground Source Heat Pumps	Low enthalpy	
GSHP	5-10	Combined with space heating

GWHP	5-15	HHP exclusively
Thermosyphons (GST)	Low enthalpy	Mainly for railway switches
UTES Systems	Low enthalpy	
ATES	5-20	HHP exclusively
BTES	5-15	HHP exclusively
FEP	0-15	Combined with space heating
HT-UTES Systems	High enthalpy (>30°C)	
BTES	30-80	HHP exclusively
CTES	40-90	Combined with space heating
PTES	40-90	Combined with space heating

3.2 HHP SYSTEMS IN OVERVIEW

This chapter describes how a HHP system is designed, constructed, and controlled to understand the basis for design using ground source heating systems.

In principle, HHP systems consist of three main components: the heat source, the hydronic pavement, and the control system (Figure 1)

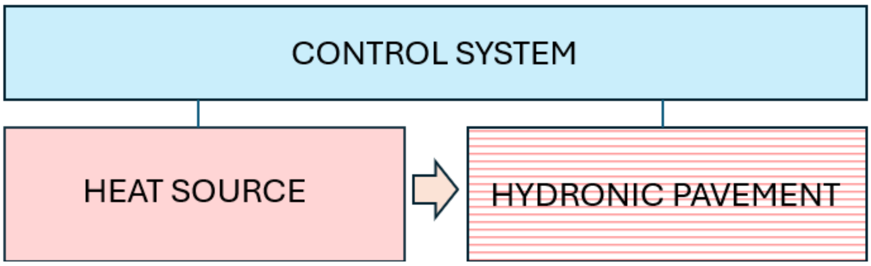


Figure 1. The main components in a hydronic heated pavement (HHP)

Commonly hydronic heated pavements are constructed with a top layer of asphalt or concrete with a network of plastic pipes embedded underneath at a depth of 50–100 mm and with a common spacing of 150-250 mm (Figure 2).

Figure 2. HHP pipes fixed to a mesh of rebar and ready to be cast into concrete (Uponor)

The most common applications are for pedestrian pathways and sidewalks, bus and train stations, bridges, sections of roads with slippery conditions, and outdoor sports arenas. The objective of the installation is to avoid accidents among vehicles and pedestrians. They will also decrease the cost of mechanical snow removal and the use of salt.

Load characteristics

In order to work properly the HHP systems should have a heat load capacity in the range of 200-350 W/m^2. This criterion comes from handbooks used by installers but may vary depending on local conditions, amount of snowfall and melting, and operational strategies.

In a global perspective where deep geothermal is directly used for snow melting the required mean power rate is 130-180 W/m^2 (Lund et al 2020), while in Iceland the mean power is estimated to 216 W/m^2 (Ragnarsson et al 2020). In these estimates, the peak power has not been addressed.

Studies on actual load requirements considering different weather conditions are rare to find. However, a comprehensive study was performed at the Stockholm Arlanda Airport. In this case, the HHP system is installed in concrete (Person 2007). The study is based on measurements over a full winter season (2006-2007). The HHP systems are operated in three modes; preheating, snow melting, and evaporation of which the snow melting capacity of 2 mm H_2O per hour has been used for the design (Figure 3).

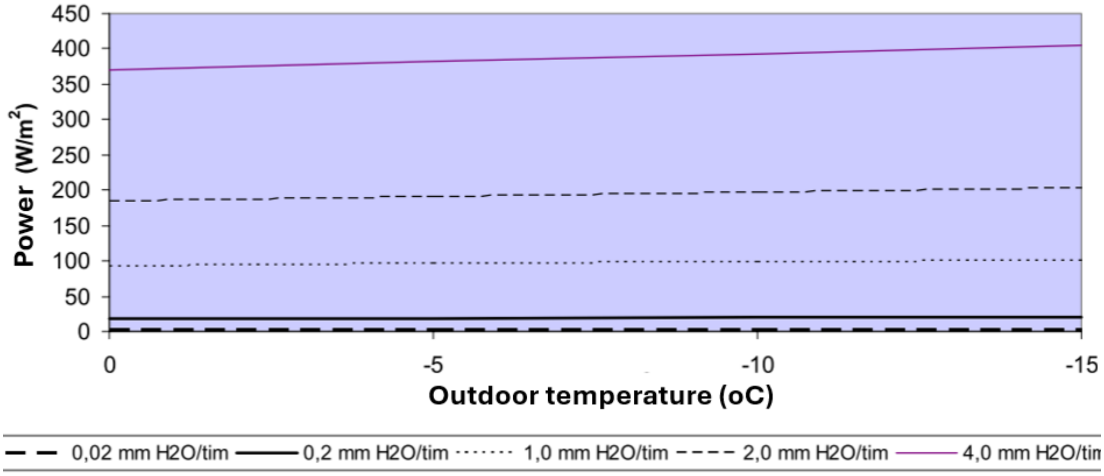


Figure 3. Required power rate for continuous melting of different snow fall rates (as melted to water) and outdoor temperatures (Persson 2007)

Since it takes the same heat capacity to melt a certain volume of snow, this criterium would be more or less the same regardless of the geographical location of the HHP system.

Heated artificial football fields in Scandinavia are most often designed to keep the turf free of frost down to a temperature of -20°C. Typical power demand at this temperature is in the range of 50-75 W/m^2 for modern HHP systems. This will only melt a light snowfall, while heavy snowfall is mechanically removed.

Supply temperatures

The maximum supply temperature would be relatively high, often in the range of +30-35°C in most applications, even though there are examples of lower temperatures (Andersson 2024).

The supply temperature is often held at a steady level when the HHP system is running. However, the operator may adapt the temperature to the actual needed level. For instance, it takes less power and a lower temperature to just keep the surface warm in a preheating situation, at least with a low wind speed. At the Arlanda Airport the required supply temperatures for the different modes of operation are shown in Table 2.

Table 2. Estimated interval of supply temperatures at different modes of operation of the HHP systems at Arlanda Airport (Persson 2007)

Mode of operation	**Surface temp. (°C)**	**Required power (W/m^2)**	**Supply temp. (°C)**
Keep surface warm before snow fall	+1.0	20-150	3-13

Snow melting (0,02-2,0 H_2O/h)	+ 3.0	150-270	17-27
Evaporation of H_2O after snow melting	+5.0	100-230	12-22

Annual heat consumption

The annual required use of heat for de-icing and snow melting varies greatly depending on the winter climate, the type of application and the way in which the systems are operated. In Sweden, occasional data indicate an annual energy consumption of 300-350 kWh/m^2 for busy city applications.

There is a lack of published information from other parts of the world, but in Iceland with some 1,2 million m^2 of HHP heated surfaces, approximately 430 kWh/m^2 is used annually (Ragnarsson et al 2020).

At Arlanda Airport with highly controlled modes of operation the mean annual heat consumption in 2003-2007 was 168 kWh/m^2 (Persson 2007).

The mean heat consumption of football fields in Scandinavia is on the order of 100 kWh/m^2 (Andersson et al 2024).

Control system

Typically, modern hydronic de-icing and snow melting systems use a control panel to regulate the pumps, valves, etc. The panel is connected to several electronic sensors that detect temperatures in the loops, the ground surface, and the air. The weather conditions may also include moisture and wind speed sensors. Some have sensors that can detect snow or ice directly on a driveway or walkway.

By interfacing with an overall control and monitoring system (OCM) using BACnet or Modbus the system can be automatically operated to cover any de-icing and snow melting situation.

By using weather forecasts the system can also be alerted for upcoming weather conditions. However, not all types of local weather conditions can be forecasted at any time. For this reason, manual operation may be an alternative as an addition. This can be done in a simple way by changing the operational set points, e.g. the supply temperature at heavy snowfall.

De-icing and snow-melting market

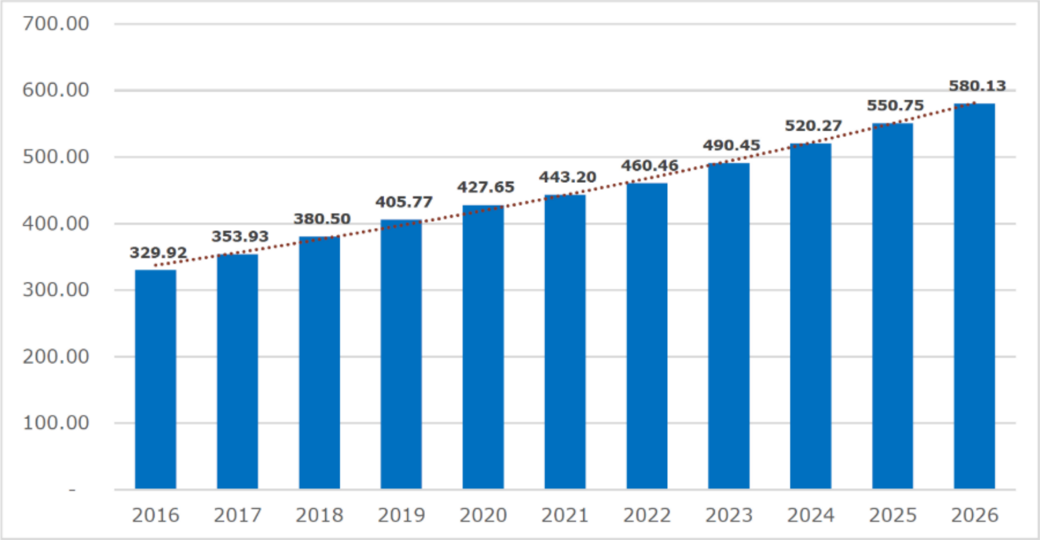
Unfortunately, statistical data on the de-icing and snow melting market is hard to find. However, Germany reports a volume of around EUR 490 million in 2023 and is expected to reach a volume of around EUR 580 million by 2026 (Staudacher 2024) and represent a steady growth rate of 5-6% annually (Figure 3).

The reported volumes refer only to the components and not to the fully installed system. Furthermore, they do not categorize if the components are for hydronic or electric systems. However, it is estimated that about 60% are hydronic systems and the rest is electric.

In terms of application, the overall industry is categorized into Driveway, Roof, Wood Deck, Pavers, Parking, Runway, Sport Facilities and others. As shown in Table 3, the Driveway, presumably with asphalt or concrete pavements, has the largest market share, followed by Parking and Pavers. The other sectors are all more or less of the same order of magnitude.

Even though Germany is the only country that has reported this kind of statistics it is likely that the other participating countries also have a growing market, but with other volumes. In theory, this also means the market for ground source heated HHP systems also can be regarded having a growing market potential.

Market analysis worldwide and country by country can be bought from Zion Market Research (2025), however to a considerable cost.



Source: Primary Interviews, Surveys, Secondary Sources, In-house & Paid External Databases, Zion Market Research, 2023

Figure 3. Growth of the German Snow Melting System Market, 2016 – 2026 (EURO Million)

Table 3. German Snow Melting System Market, by application and annual growth rate, 2022 – 2026

Application	2022	2023	2024	2025	2026	CAGR
Driveway	108.92	115.83	122.67	129.64	136.33	**5.77%**
Roof	32.93	35.01	37.07	39.17	41.19	**5.75%**
Wood Deck	31.60	33.82	36.06	38.36	40.61	**6.47%**
Pavers	71.21	76.33	81.48	86.80	92.01	**6.62%**
Parking	76.59	82.11	87.67	93.41	99.03	**6.63%**
Runway	40.17	42.06	43.87	45.66	47.28	**4.16%**
Sports Facilities	47.64	50.93	54.23	57.62	60.91	**6.34%**
Others	51.40	54.36	57.23	60.10	62.77	**5.12%**
Total	**460.46**	**490.45**	**520.27**	**550.75**	**580.13**	**5.95%**

Source: Primary Interviews, Surveys, Secondary Sources, In-house & Paid External Databases, Zion Market Research, 2023

3.3 SOLAR ENERGY HARVEST

HHP systems may be used for harvesting solar energy to be seasonally stored using UTES system. The primary parameters for the estimation of the heat potential that can be harvested is the solar radiation, number of sun hours, and the albedo effect of the surface. Secondly there are many other factors that may impact the heat harvest performance, such as depth and distance between pipes, thermal conductivity of the covering material, etc.

Solar radiation and sun hours

The solar radiation over a year would be around 1 000 kWh/m^2 for countries that may use de-icing and snow melting systems. The solar heat is obtained during 1200-1800 sun hours. In southern Europe and the Mediterranean area it is commonly 1800-2500 sun hours or more (Figure 4).

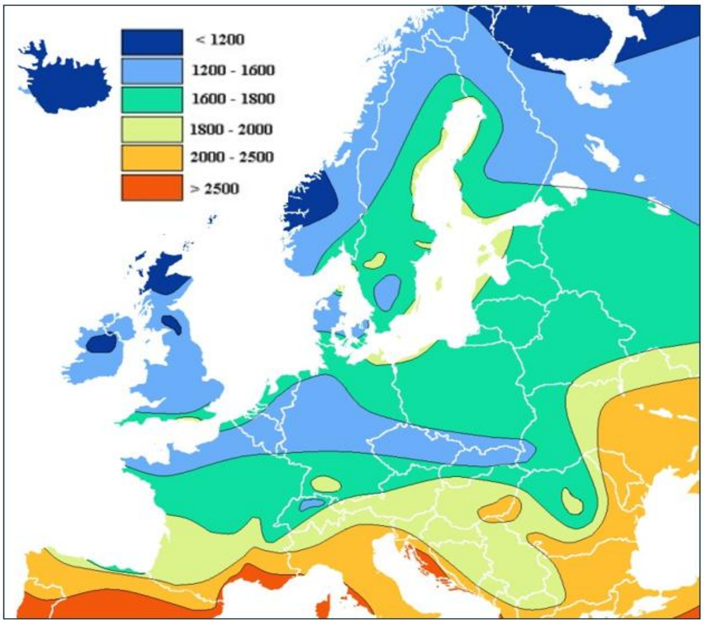


Figure 4. Sunshine duration (hours/year) for parts of Europe. (Wikimedia 2012)

Most solar radiation hits the ground during the summer months. In Stockholm, 75% of the solar radiation was received between April and August, according to SMHI statistics 1961-1990 (Persson 2007).

It can be estimated that the potential to harvest solar heat during the summer months would potentially be large enough to cover the heat that is required for de-icing and snow melting in the winter for most places. At the Arlanda Airport, in Stockholm, Sweden, the relation between solar radiation and the use of energy for the HHP system is shown in Figure 5.

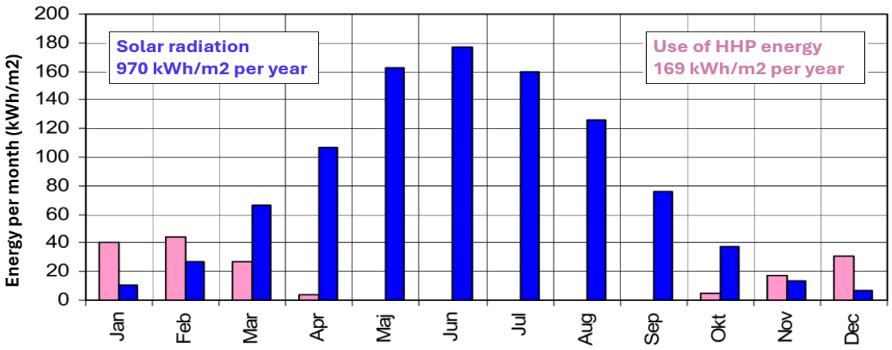


Figure 5. The relation of solar radiation and energy used in HHP system at Stockholm Arlanda Airport (Persson 2007)

Albedo effect

Albedo is the fraction of the incident solar radiation that is reflected from a surface. A material with high albedo reflects more solar energy, whereas a material with low albedo absorbs more solar energy. Typically, a lighter color is more reflective than darker. Thus, newly constructed concrete pavements have a higher albedo than newly constructed asphalt pavements. However, as pavements age, the albedo changes. The concrete pavements usually darken over time, decreasing their albedo, while asphalt pavements typically become lighter, increasing their albedo.

Applied as a heat source for storage, the albedo effect for both asphalt and concrete pavements seems to become 0.15-0.25 after 10-15 years of age (Figure 6).

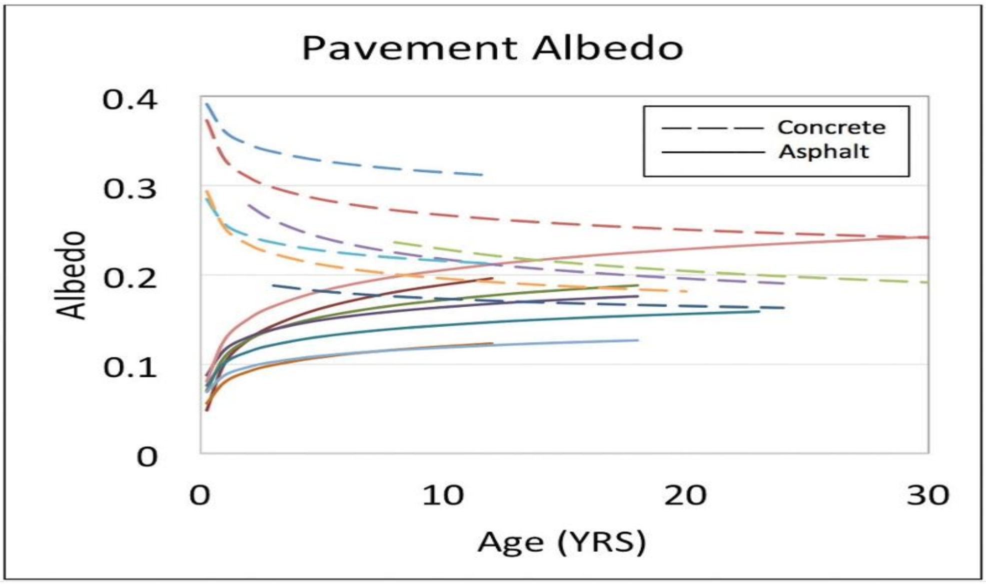


Figure 6. Field-measured asphalt and concrete surface albedo change with time (NCAT 2016)

This means that asphalt and concrete pavements will absorb some 75-85% of the solar radiation. Stone pavements will have an albedo typically close to that of concrete if the stones are light colored and close to asphalt if they are dark.

The albedo for natural grasslands would be on the order of 0.25 while artificial turfs, commonly used for sport arenas, absorb about twice as much as natural grassland: 0.11 as a mean value (Aoki et al 2015).

To sum it up, the albedo will reduce the solar heat that is absorbed by the surface with a factor that could be as high as 40% for a light-colored concrete surface, but only 10% for a dark asphalt surface, which are the two most common pavement types for HHP installations. For artificial grass turfs a conservative albedo value around 20% is recommended.

Underground temperatures

The solar radiation causes seasonal temperature variations of the subsurface down to a depth of 10-20 m. The amplitude of the temperature swing decreases with increasing depth. Just below the surface the temperature is highest in the summer and lowest in the winter (FIG 7).

Figure 7, lower graph, indicates a delay of temperature response with depth caused by the relatively low thermal conductivity of the soil. Furthermore, the upper graph in Figure 7 indicates a general increase of the soil temperature over the past decades, caused by the ongoing global warming.

On a daily basis heat will be stored in the soil as long as the surface temperature is higher than the subsurface temperature. On the other hand, if the ambient air temperature is lower than the surface temperature, the ground will lose stored heat to the ambient air.

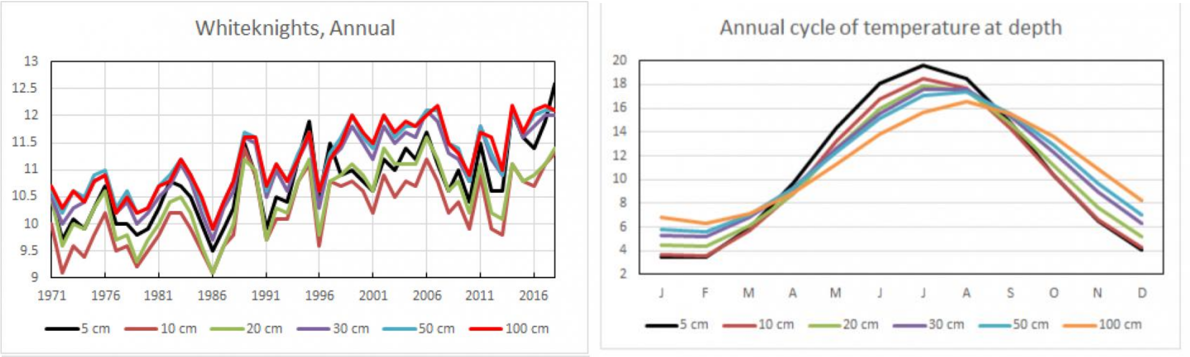


Figure 7. Example of temperature distribution over a year in the upper meter of the subsurface in England (Halesowen Weather 2024)

Heat losses may also be caused by evaporation from the surface or upper soil layer. Another surface chilling factor would be the wind speed. Hence, the amount of the absorbed solar heat that is left for storage will depend on local weather conditions.

Keeping the entering temperature to a HHP system as low as possible during storage mode will cause less heat losses to the surroundings. As a result, the chances to extract and store enough heat to match the required energy for the full winter season increases with a lower entering temperature to the HHP.

Experience of solar heat harvesting

There is yet a lack of knowledge of how much solar irradiation can be harvested. A literature study presented by Johnsson (2019) indicates that approximately 30% of the incoming solar irradiation can be harvested from HHP pipes that are close to the asphalt or concrete surfaces.

In the HERO project (Johnsson 2019) (concrete HHP) a solar heat harvesting efficiency of 42% was measured representing some 380 kWh/m^2. The harvesting period was from the 14th of May to the 31st of August 2018. The heat used in the HHP system was almost three times less than the harvested heat indicating that there should be enough solar heat for balancing the HHP system, in this case a small-scale BTES. Experimental results from Chalmers University (Andersson et al., 2018) indicate similar values (376-395 kWh) for asphalt and a full summer solar radiation. However, in that case the road had an insulating layer beneath the heat collection pipes.

An experimental plant (HALE) placed on a bicycle path at the University of Antwerp covers 35 m^2 with asphalt pavement. The thickness of the pavement is 12 cm, with 3 cm top layer and 4 cm collector layer with dense asphalt, while the base layer (5 cm) consists of another type of asphalt. The investigation revealed that the total annual heat harvesting of the HHP system was 165 kWh/m^2 with pipes, DN20, in four sections, each section 50 m long. By modelling the results in a hybrid FE-ANN model it was predicted that the total yearly heat harvest is 325 kWh/m^2 for a pipe section length of 300 m (Ghalandari et al 2023). This should correspond to a solar collection fraction of some 30%.

In a French regional theoretical study (Le Tous et al 2018) it was found that the solar radiation varies in the range of 786-1035 hours. Applied for a HHP system 8 cm beneath an asphalt pavement a solar collection amount of 320 and 500 kWh is expected. This corresponds to a solar radiation fraction of some 40%. However, these results have not yet been verified in real applications.

Worldwide there are indications from several reports that the solar collection fraction varies in the range of 20-50%, but the information is mostly limited, and several reports present theoretical models without validation. However, scientifically proven values indicate fractions around 25-40%. E.g. for a bridge deck in China it was reported a variation in the interval of 26-46% (Wue et al 2020). In another example, with an asphalt a road pavement, a solar fraction of 36% was reported (Zhoe et al 2013).

Based on the available information it is assumed that a HHP system placed 8-10 cm below an asphalt or concrete pavement with a pipe c/c-distance of 150-200 cm and with an individual parallel pipe length of 200-300 m has the capacity to harvest at least 30% of the solar radiation.

3.4 PROMISING OPEN LOOP SYSTEMS

The most promising open loop systems are characterized by a low operational cost caused by higher efficiency and hence low emission of greenhouse gases compared to traditional heat sources such as electric heating cables, gas boilers or district heating. They would also be looked upon as local resources that need a minimum of heat transport.

In this chapter the two most promising systems are described and rated in terms of efficiency, cost effectiveness, and geological availability.

Groundwater Heat Pump systems (GWHP)

There are two types of aquifers, unconfined having a free groundwater level, and confined having a piezometric groundwater level. These are shown in Figure 8 with abstraction wells and reinjection wells entering the two types of aquifers.

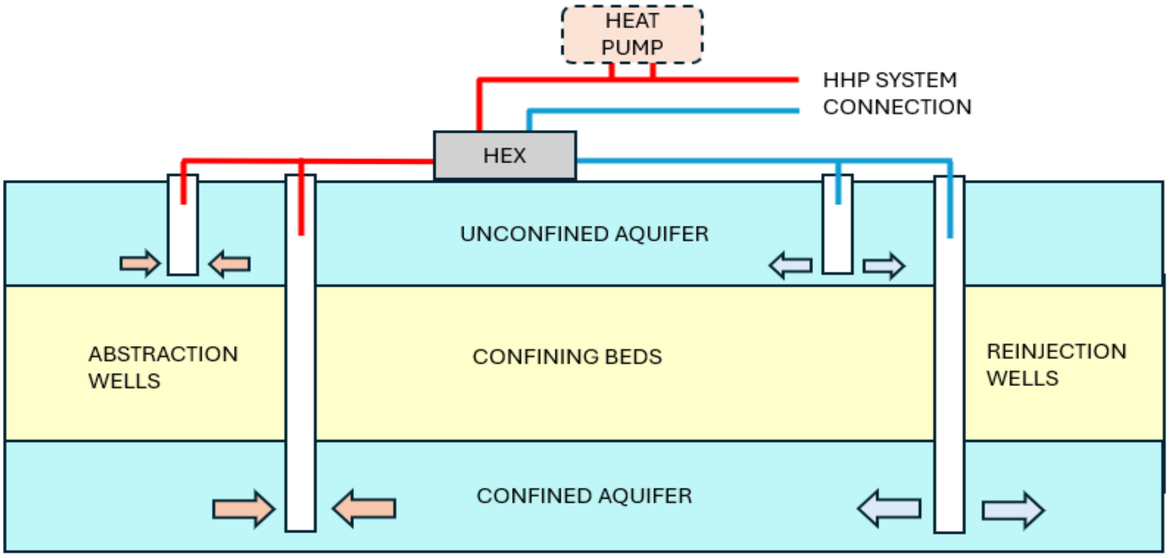


Figure 8. The principal for the GWHP system using shallow aquifers for the heat supply of HHP systems

Aquifers at depths of 10 m or more have a temperature that corresponds to the mean outdoor temperature. However, in areas with a permanent snow layer in winter, the temperature is somewhat higher due to the snow insulation effect. At greater depths, the geothermal gradient increases the temperature, commonly in the range of 1.5 -3.0 degrees per 100 m in areas with older sedimentary rocks.

One or several production wells are used, from which the groundwater is pumped to a heat exchanger (HEX) through which heat is transferred to the HHP system. The chilled water is then directly reinjected to the same aquifer through reinjection wells. The groundwater loop should be perfectly airtight and pressurized to minimize the risk of clogging and corrosion.

In the long run, this kind of system will cool down and eventually decrease the production temperature (thermal breakthrough). For this reason, the distance between the production and reinjection wells must be far enough to maintain a stable supply of the groundwater temperature.

The supply temperature to the HHP system is always somewhat lower than the temperature in the aquifer due to a temperature drop over the heat exchanger (HEX).

Depending on the temperature demands of the HHP system, the systems may or may not need a heat pump for a temporary increase of the supply temperature or peak loads. The deeper the aquifer, the less dependence on heat pump support is required.

In theory and with an aquifer temperature ranging from 5-15 °C, this type of system would have SPF in the range of 8-14. The example in Appendix D1.2, Scenario 2, indicates 12.5 at +12°C.

Proper aquifers may be hard to find at locations for HHP utilizations and permits may be difficult to get. This limits the potential of using GWHP systems for HHP applications.

Aquifer Thermal Energy Storage systems (ATES)

This type of system differs from the GWHP systems in the way that harvested heat from the HHP surface is stored in one part of the aquifer. This way a higher temperature than the ambient can be obtained during the winter season.

Conventional ATES is divided into a warm and cold side with warm and cold wells. All wells are equipped with submersible pumps. During summer, groundwater is extracted from the cold wells, heated by solar heat, and injected into the warm well set. When the winter and time for snow melting comes, the flow direction is reversed. Warm water is then pumped to the HHP system, and the cooled water is injected to the cold wells (Figure 9).

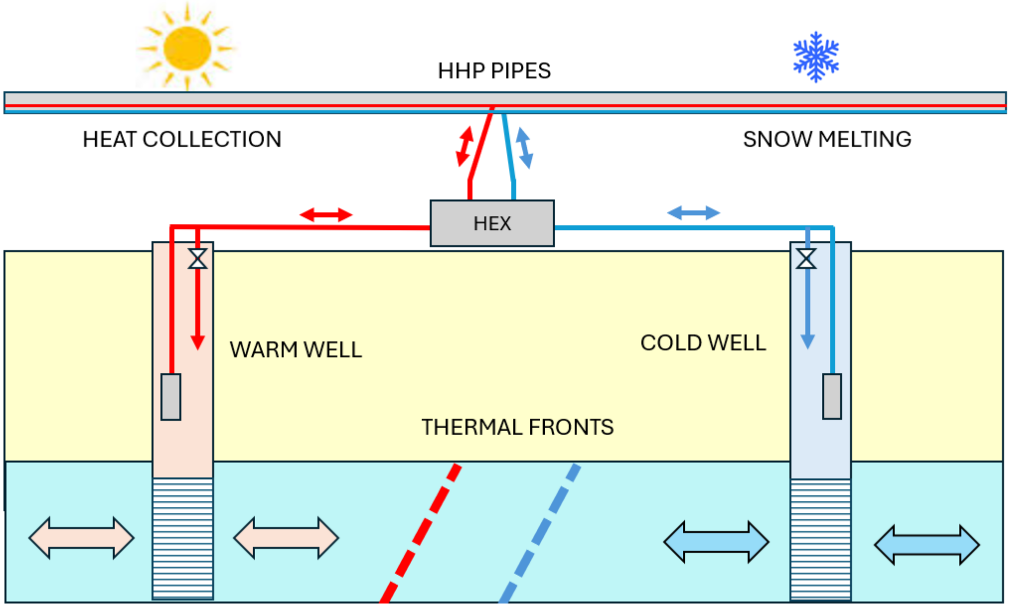


Figure 9. The principal for ATES as a heat source for HHP systems

Compared to the GWHP system the distance between the wells can be shorter but should be far enough to not allow for too much overlapping of the thermal fronts that separate the warm and cold sides.

In an aquifer storage, warm or cold water will gradually increase/decrease the temperature of the subsurface grains as it flows in the pores of the aquifer. The porosity in unconsolidated sands and gravel is commonly around 25%. This means that some 75% of the heat is stored in the solid subsurface material in the aquifer and 25% in the groundwater itself. Since the solids in general have a volumetric heat capacity of 0.6 kWh/m^3/K and the groundwater volumetric heat capacity is 1.164

kWh/m^3/K, the mean heat capacity would be on the order of 0.75 kWh/m^3/K. This value is somewhat less for consolidated sandstones and even less for fractured aquifers in consolidated rocks.

For ATES systems applied for heating and cooling of buildings, the temperature on the warm side would be 12-15°C and 4-8°C on the cold side. For HHP systems the temperature on the warm side of the ATES will be significantly higher. The storage temperature is mainly a function of the surface temperature, and the temperature coming from the cold side of the aquifer. Also, the burial depth of the HHP pipes and the thermal conductivity of the material above the pipes will affect the outlet temperature from the HHP system. A calculated example illustrating what to expect as a supply temperature using 15°C as the inlet temperature to the HHP system at the Stockholm Arlanda airport is shown in FIG 10 (Persson 2007).

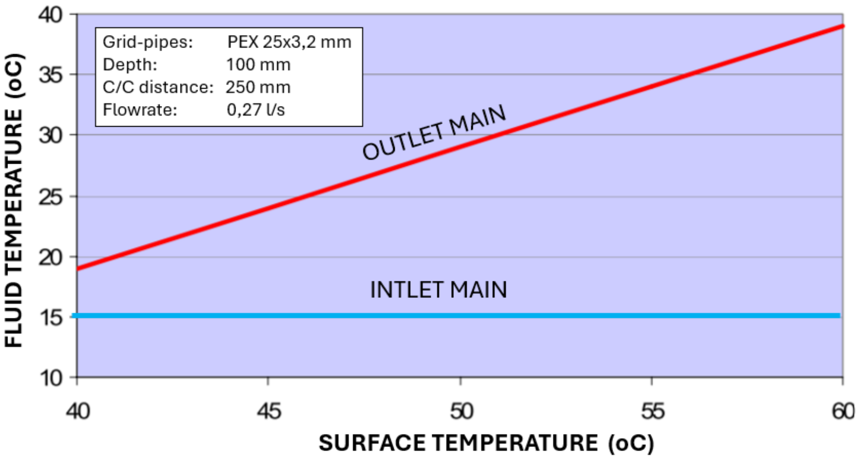


Figure 10. Calculated outlet temperature from solar heat harvest as a function of surface temperature for Stockholm Arlanda Airport Pir 30 HHP system using a constant inlet temperature of 15°C.

Due to heat losses especially from the warm side of the aquifer, the supply temperature to the HHP grid will gradually drop. If the purpose is to continuously melt heavy snowfall, a heat pump may be needed. If not, the SPF would be in the range of 30. With a heat pump included to cover 25% of the heat, the SPF would drop to about 10-12 as is indicated in Scenario 6, Appendix D1.2.

ATES obviously offers the advantage of directly utilizing stored summer heat. On the other hand, proper aquifers may be hard to find at locations for HHP utilizations. Furthermore, permits to use an aquifer may be denied and the permit procedure is often costly and time-consuming. All together this means that ATES has limited market potential,

High Temperature ATES

In a High Temperature ATES application (HT-ATES), the same type of system is used as for conventional ATES (FIG 9) but for storage of heat at temperatures up to 90°C.

There are several potential heat sources for HT-ATES, such as surplus heat from solar collectors, waste heat from industries, or surplus heat in district heating grids. These sources would typically represent storage temperatures above +60°C.

Heating up and cooling down natural groundwater will disturb the chemical balance of the water. Especially carbonates will be oversaturated and cause scaling typically at temperatures around 40-50°C. This has been studied in the IEA ECES - Annex IV (TNO 1990) and the subject of scaling and corrosion is described by Andersson (1992).

The water can be treated to prevent scaling in the system, but this is a sensitive balance and may result in corrosion problems instead.

There are very few HT-ATES systems in operation in the world, and in those cases groundwater chemistry is not sensitive to scaling, something that is rare.

For the time being HT-ATES has limited use because of the potential scaling and corrosion that probably will occur in most groundwater chemistry. In addition, the temperature level makes the well system costly to construct.

Wells for open loop systems

The construction of wells makes a substantial investment cost for open loop systems. The well designs depend on several geological conditions that are often country specific. However, the most common constructions can be divided into two sub-types screened and open hole wells as illustrated in Figure 11.

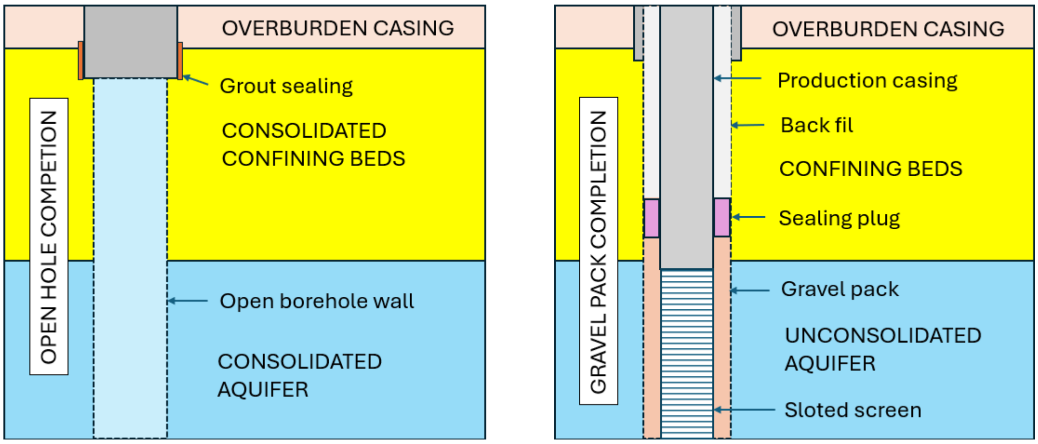


Figure 11. Common types of shallow wells applied for GWHP and ATES systems.

Open hole wells are commonly drilled with air driven Down-The-Hole-Hammer (DTH) with a high rate of penetration and with a minimum of casing. This method requires that the penetrated rock is stable and does not cave into the hole. Such conditions are often the case in consolidated sandstones or fractured limestone aquifers. This type of well is the most cost-effective type and can occasionally be applied for depths of several hundred meters.

The gravel pack completion is more complex and represents several stages. It is preferably used in unstable, or unconsolidated sandstones or delta formations. This type of well is most often drilled with the Conventional Rotary method (CR) as an open hole, stabilized with mud. In the next steps, a screen with production casing is installed followed by placement of a gravel pack ending with a sealing plug. Finally, the well is cleaned and developed, often by airlifting or on-off pumping. This type of well is considerably less cost-effective than the open hole completion.

Naturally developed “gravel pack” can be used in aquifers with glaciofluvial gravels or sand (Figure 12). This well-completion method was developed by accident and therefore is also called “Lost filter completion”. (The driller lost the screen at the bottom of a cased hole and simply withdrew the casing and developed the well by surging).

This well-completion method was further developed together with the DTH drilling of casing. It is now the most common type of well in glaciofluvial eskers and delta formations, riverbank deposits, and other sand/gravel settings, commonly to depths of 20-60 m.

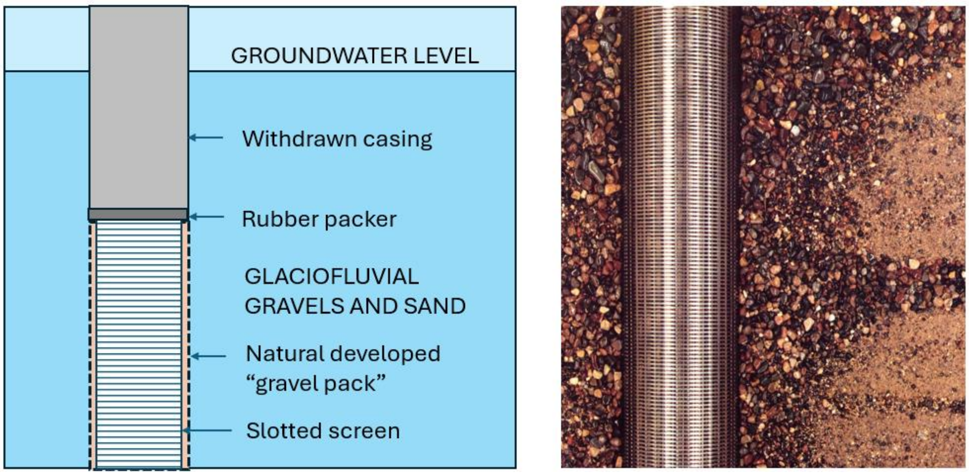


Figure 12. Natural developed gravel pack wells. Photo: From Driscol (1986)

The construction is fairly simple and quick. However, these types of wells require extensive cleaning, often performed by airlifting or jetting methods. Once cleaned, these wells are highly productive and efficient. They are also relatively easy to redevelop in case of clogging. Depending on the size of the screen and the slot size, the critical inflow of screens varies between 1-10 l/s per meter screen.

Due to their high efficiency and simple construction, formation filter wells are commonly very cost-effective.

The drawback of groundwater wells is their risk for clogging, either by fine particles or by precipitation of minerals, often iron hydroxides. For this reason, a maintenance program is essential. Depending on the groundwater chemistry, the wells may also be corroded. For these reasons groundwater chemistry is an essential parameter to consider in any ATES or GWHP application.

Storage in Pits (PTES)

Thermal Energy Storage in Pits (PTES) in soil is a technology that is under development within the district heating sector, especially in Denmark and Germany.

The purpose is to store high temperature solar heat or waste heat over seasons and to use the heat in district heating systems (IEA ES TCP 2024). For HHP systems, however, the working temperature would be lower than for district heating, and for that reason, PTES may be a storage alternative assuming that enough surface is available for the construction.

The PTES system consists of a pit with sloped sidewalls dug a few meters into the ground. The pit is covered with a watertight liner and a floating insulated lid.

The incoming and outgoing pipes enter the pit from the bottom, and for spreading the flow diffusers are used. The idea is to use the relatively high thermal resistance of the soil for insulation of the bottom and the sides of the pit (Figure 13).

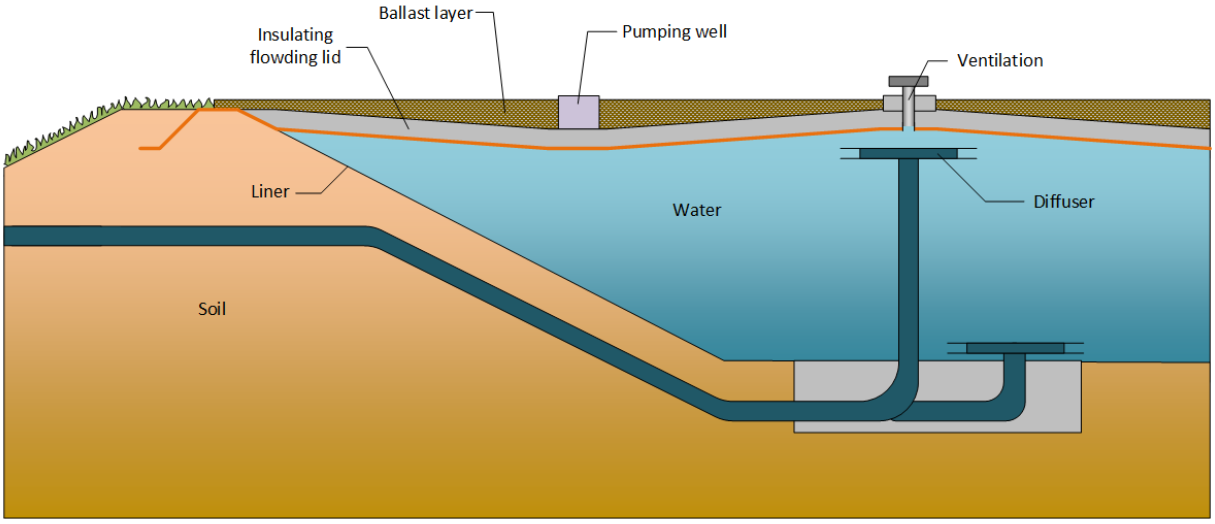


Figure 13. Principal for pit thermal energy storage (IEA ES TCP 2024)

The surface demand is primarily depending on the water volume and the working temperature (delta T). Secondary heat losses affect the size and design as well as the actual working temperatures if only solar energy from the HHP system is used.

For the time being the PTES system has limited use in urban environments because of its large surface area requirement. It is also relatively costly to construct, and the efficiency is not yet fully investigated.

Storage in underground cavities (CTES)

Thermal Energy Storage in Caverns (CTES) may consist of underground mining caves that are no longer in use, or blasted caverns for storage of oil that have been abandoned.

These shafts and caverns will be surrounded by rock acting as an insulation for stored heat. The principle is similar to PTES for blasted caverns, but in old mines, different shafts might be used to separate warm water from cold water.

In Europe there are at least 274 closed mines that could theoretically be used for thermal storage (Menéndes et al 2019). Some of these may be used for HHP systems, but it is not likely to find these mines in urban areas and for that reason, the market potential is regarded as low.

To construct completely new caverns to serve HHP systems exclusively is not likely to be economically feasible. The construction cost is too high for the small energy demand that an HHP system represents.

3.5 PROMISING CLOSED LOOP SYSTEMS

Ground Source Heat Pumps (GSHP)

Ground heat sources with closed loops for extraction of low enthalpy energy are commonly used as a heat source for heat pumps. In general, these systems go under the name of Ground Source Heat Pump (GSHP) systems and are mainly used for space heating. The most common applications are vertical loops in boreholes and horizontal loops in the soil. Foundation energy piles (FEP) have also been placed in this group. There are millions of these systems already installed worldwide in a growing market (Lund et al 2020).

GSHP systems, energy piles (FEP) included, are of less interest to use for HHP applications exclusively since they are less effective than systems that can harvest and store solar energy from the HHP system. However, as an add-on to a GSHP space heating system, a small size HHP system would be of great interest since the cost of heat would be about 65-75% lower compared to conventional heat for ice- and snow-melting (e.g. electric heating cables). Combining space heating and a HHP in a GSHP system may even promote the installation of new snow-melting grids.

Using the HVAC system also for HHP systems can easily be done by adding a secondary loop to the return loop of the heat distribution pipes in a building (Figure 14).

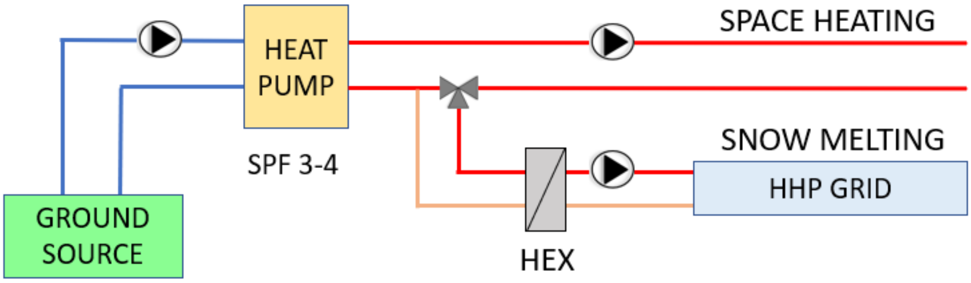


Figure 14. Principal for combining space heating and snow melting using a GSHP system

As shown in the figure the additional investment cost for heating the HHP grid would be limited to some extra pipes, a valve, a heat exchanger (HEX) and an additional circulation pump. The HEX is necessary to separate the HHP fluid with antifreeze from the space heating fluid, which is water.

The HHP system would in commercial and institutional buildings be automatically turned on and off as controlled by the weather forecast. For small buildings, the systems would probably be manually operated. Even in a building with low-temperature heating systems with a supply/return temperature of +40/30˚C the return would be high enough for a HHP grid to work properly under most weather conditions.

Since preheating, snow melting, and de-icing typically occur when the outdoor temperature is around or just below zero, the additional use of the HHP system will not affect the design of the heat pump. However, the use of the ground source will be extended. The low additional investment cost together with a SPF in the range of 3-4 will make GSHP systems the most promising shallow geothermal system of all for HHP applications as has been calculated in Appendix D1.2, Scenario 1.

Ground Source Thermosyphon systems (GST)

Ground source thermosyphons consist of a vertical borehole, typically 60 m to 200 m long. A double steel pipe system is installed in the borehole and the space between the outer pipe and the borehole wall is grouted. The pipes are sealed and pressurized at installation.

Cold liquid condensate (propane or CO_2) flows down the annulus between the outer and inner pipe due to gravity and is heated up by the ground. Vaporized liquid is transported upwards inside the inner pipe. At the heat sink it condensates again when the heat is released. This way the heat carrier is self-circulating, and no circulation pump is required (Grab et al 2011). However, compared to conventional boreholes with U-pipes the investment cost for this system is relatively high.

In Germany the system is used without support of heat pumps for heating railway switches. Three such systems were installed as pilot projects in 2012-2014. As far as known they are working reliably. However, the company that designed and constructed these systems is no longer active and no more system has been ordered (Staudacher 2024).

GST systems are considered non-commercial at the moment. However, since self-circulation will save electricity, further development may strengthen this type of technologies to become acceptable for the market in the future, especially for HHP systems serving railway switches, a huge market itself.

Borehole Thermal Energy Storage systems (BTES)

In an ordinary BTES system, solar heat harvested from a HHP system may be seasonally stored at a moderate temperature and later used as a heat source during the winter (Figure 15).

By moderate temperature means a temperature level that can be obtained from the HHP system during the summer, typically around 20°C in the Scandinavian climates as shown in the HERO project (Johnsson 2019) and up to +25°C or more in continental climate types. For instance, from a test plant on a bridge deck in Veil, Colorado, an average temperature of +26.5°C during a period of 72 days is reported (Omid et al 2020).

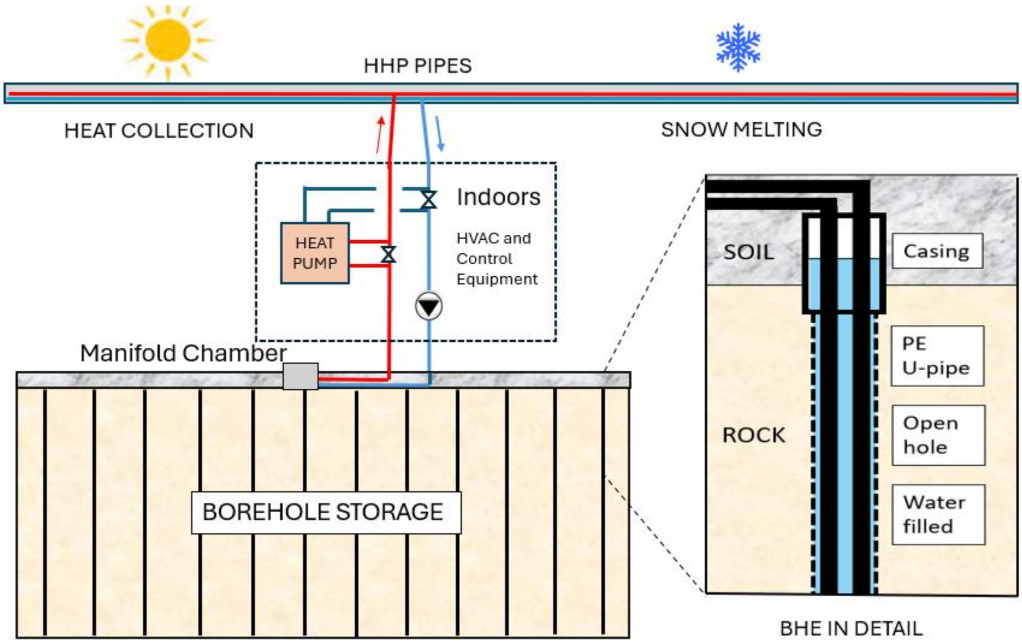


Figure 15. An example of a conventional BTES for HHP applications

BTES systems are characterized by using Boreholes Heat Exchangers (BHE) for transferring energy between a building heating system and the rock or soil. The temperature drop between the U-pipe and the rock limits the supply temperature level from the BTES system, unless using a heat pump to raise the outlet temperature from the ground to cover all required temperature levels. As an example, in the HERO test plant in Östersund (63°10’45”N 14°38’10”Ö) half of the energy used for de-icing and snow melting was obtained from the BTES boreholes, while the other half was provided by an electric boiler (Johnsson 2019).

The lower efficiency of the BHE is balanced by several advantages of using BTES. Most importantly, BTES can be applied in almost any geological setting. In addition, the borehole system has a low need for maintenance and the lifetime of the borehole system is very long (> 50 years).

With modern frequency-controlled heat pumps a BTES system would deliver the required temperatures for an efficient HHP function. Depending on how much of the heat that is produced as peak shaving by the heat pump a SPF of 9-13 is expected, see Appendix D1.2, Scenarios 3, 5 and 7.

High Temperature BTES

In High Temperature applications (HT-BTES), the same type of borehole system is used as for a conventional BTES, but at a heat storage temperature above +30°C.

There are several potential heat sources, e.g. surplus heat from solar collectors (already installed), industrial waste heat, waste heat in district heating grids (cogeneration plants), and condenser waste heat from chillers. These sources would typically represent temperatures in the range of +40 up to +80°C.

HT-BTES systems applied for HHP would primarily use the HHP system to collect solar heat and secondarily the HT heat source would increase the storage temperature (Figure 16).

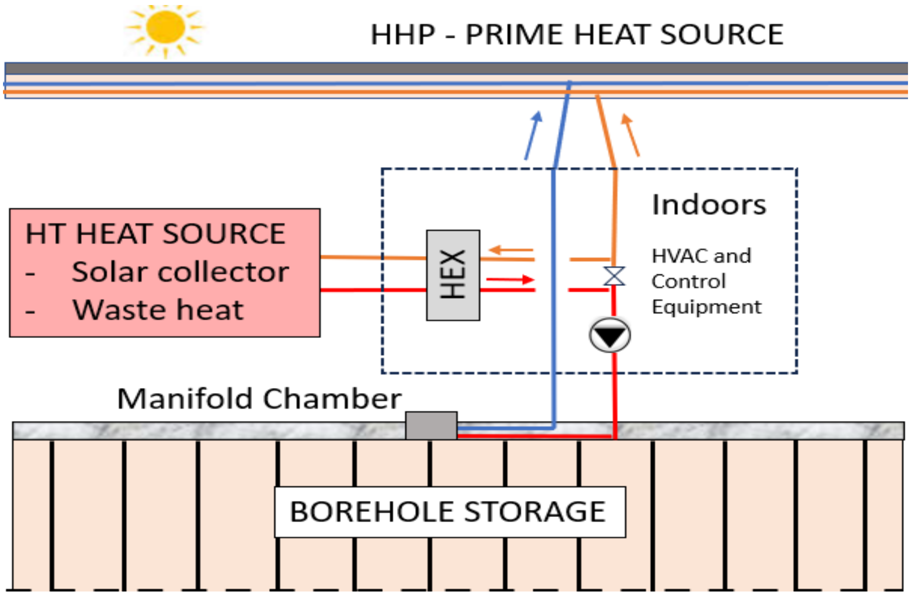


Figure 16. Example of heat storage with an HT-BTES system

Storage of heat at temperatures far above the normal rock temperature will cause considerable heat losses from the storage to the surrounding rock. The working temperature and the size and shape of the storage are the main parameters for storage efficiency. In borehole applications a cylindrical storage volume with the borehole length (L) equal to the cylinder diameter (D) will be the most efficient shape. The size of storage should, however, be large enough to minimize the relative losses (Fig. 17).

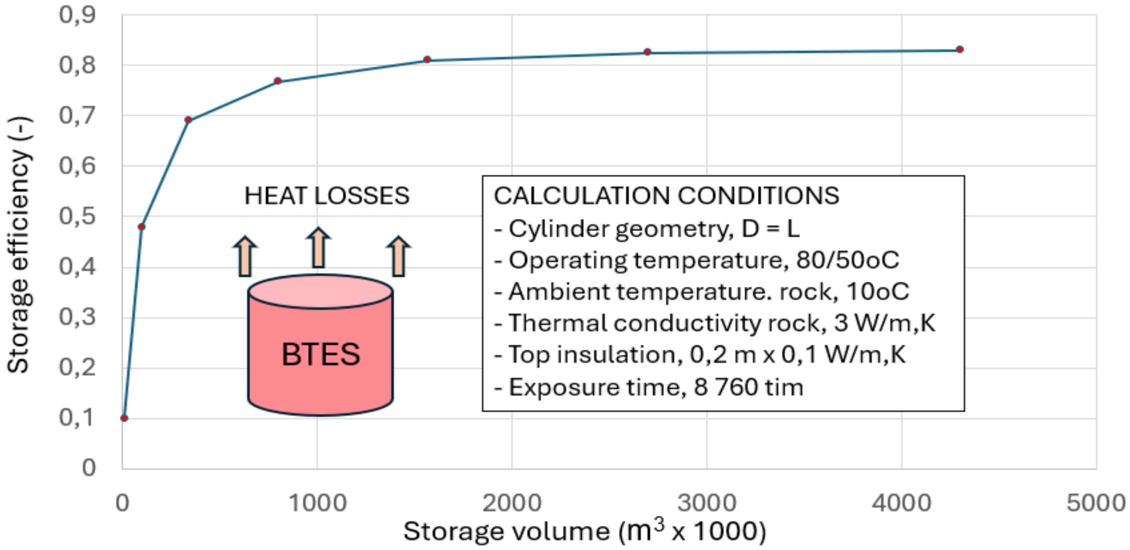


Figure 17. Example of heat loss calculation of a cylindrical HT-BTES application for storage of heat in rock.

The heat losses will decrease the recovery temperature well below the initial supply temperature. Still, by overcharging the heat storage with excess heat that otherwise has no economic value, the recovered temperature will be enough to meet any required temperature for an efficient function of the HHP system. Hence, there is no need for heat pumps in these applications. The used electricity will be limited to the circulation pumps for the heat carrier fluid. The estimated seasonal performance factor for the system boundary including borehole storage and the heat pump unit (SPFH1) will probably be in the range of 15-25.

What differentiates the HT BTES boreholes from conventional BTES is that thermally resistant U-pipe borehole heat exchangers must be used. There are several polymer options commercially available, e.g., various types of PEX, albeit at a considerably higher cost compared to the standard PE100 used in conventional BTES.

The high SPF for HT-BTES will keep the operational cost at a low level with a SPF of around 20, giving this system a high market potential even though the investment cost is high. An example of application is given in Appendix D1.2, Scenario 4.

Boreholes for closed loop systems

Boreholes for closed loop systems in soils and unconsolidated rock will preferably be drilled by using the Conventional Rotary Drilling (CRD) with bentonite-based mud as the flushing medium. The mud is circulated for cleaning the holes from cuttings and the bentonite will keep the borehole walls standing while inserting the U-pipes.

Occasionally the Hollow Stem Auger Drilling (HSA) may be used, especially for very shallow depths in fine grained sediments. After installation of the U-pipe the hollow stem is withdrawn.

In hard crystalline rock, such as granites and gneisses and consolidated sedimentary rock, the common drilling method is the Down-The hole Hammer (DTH). This is a percussion method driven by compressed air. The air drives the hammer and cleans the hole from cuttings. This is currently the most effective drilling method in areas with hard rock. In Scandinavia, a 200 m deep borehole can easily be drilled within one day, including the 10-20 m of casing that will be drilled prior to the open hole.

An emerging technology is the use of water powered hammers (Hydraulic DTH). The water must be free of particles and under high pressure. This drilling method, called Wassara in Scandinavia, is an option for drilling very deep boreholes or long sections of casing.

The hammer drilling methods are most common in hard rock in which they are very effective, while the rotary methods are best suited for sedimentary rock and thick layers of sand and silt, such as delta formations (Table 5)

Table 5. Summary of commonly used drilling methods for geothermal closed loop systems, their suitability for different geological settings, and their performance characteristics

Drilling method	Best suitable in	ROP[1)]	Use of energy[2)]
DTH - air driven	Crystalline and consolidated sedimentary rock	Very high	Low
DTH - water driven	Crystalline and semi consolidated rock	Very high	Very low
Conventional Rotary	Sedimentary rock in general and fine-grained soils	Moderate	Moderate
Hollow stem auger	Mainly soil sediments free of stones	Low	Moderate

[1)] Rate of penetration by experience; [2)] Diesel consumption per meter drilling

The drilling diameter is normally in the range 4.5-5.5 inches and adapted to the size of the U-pipe and depth of the borehole.

There are different types of borehole heat exchangers, of which the most common consists of a single U-pipe made of polyethylene (PE) with a standard outer diameter (OD) of 2x40 mm. In some cases, a double U-pipe is used with the OD 4x32 mm, especially for shallow boreholes.

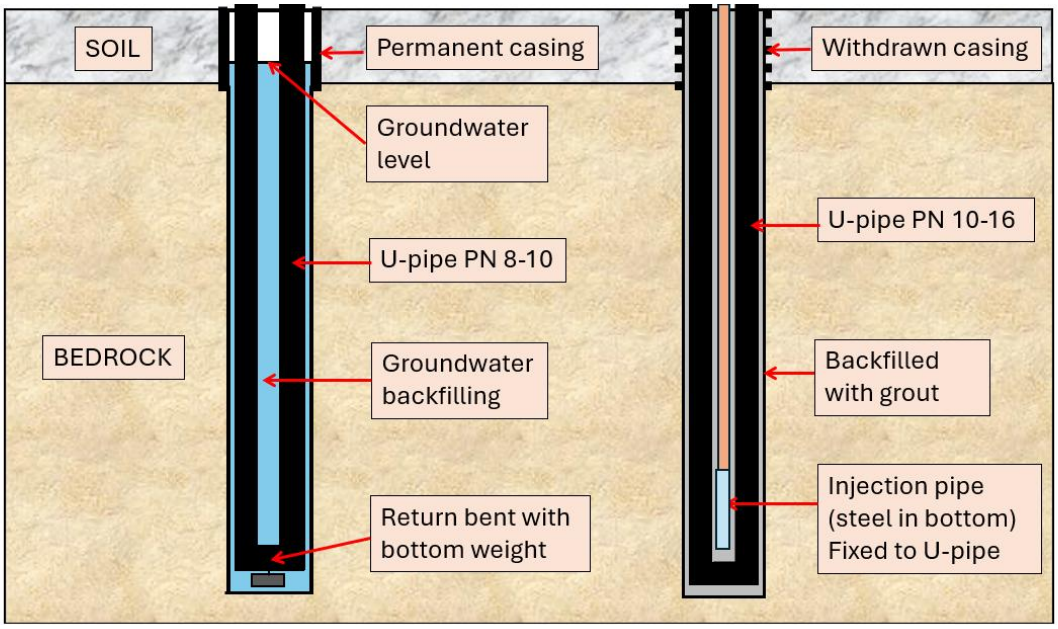


Figure 18. Main construction differences between groundwater-filled boreholes (left) and grouted boreholes (right).

After installation and tightness control the boreholes are either sealed by grout or kept open using the groundwater for heat transfer between the U-pipe and the boreholes walls. The main differences are shown in Figure 18.

In most central European countries grouted boreholes are mandatory, while natural filling with groundwater is used in Scandinavia. The grouted boreholes are more expensive to construct, but on the other hand, the entire borehole length is thermally active. In groundwater filled boreholes the groundwater level defines the upper limit of the thermally active borehole length.

The construction and function of closed loop boreholes have been thoroughly studied and reported in the IEA ECES project Annex 27 (IEA ECES 2020), “Quality Management in Design, Construction and Operation of Borehole Systems”. It is recommended to consult this report for detailed information on closed loop boreholes.

3.6 RANKING OF GROUND SOURCE SYSTEMS

The ranking considers the use of ground source heating of HHP systems within the infrastructure sector in terms of high and low potential. The ranked systems have already proven to be more or less commercial on the heating and cooling market and are described in detail in the former chapter 5.

As basis for the ranking, general experiences from the ground source heating and cooling of commercial and institutional buildings have been used supported by the Scenario analysis in Appendix D1.2. The result of the ranking is shown in Table 6 followed by a description of factors used for the ranking.

Table 6. Ranking of potential ground source systems as a heat source for HHP applications (+ = low; +++++ = high)

Ground source system	**Geologic availability**	**Surface requirement**	**SPF**	**Cost effectiveness**
Any GSHP combined with space heating	+++++	+	++	+++++
GSHP designed for HHP exclusively	+++++	+	++	++
GST designed for HHP exclusively	+++++	+	++	+
GWHP – HP for peak power demands	++	++	+++	++++
ATES – may even work without HP	++	++	++++	+++++
BTES - HP 50 % of energy demand	+++++	+	+++	+++
HT-BTES – No HP required	+++++	+	+++++	++++

Not all of the ranked ground source systems may be used in a certain location since the site-specific geology may prevent the application of a certain system type. In this ranking “geologic availability” describes the geological potential. Especially the use of open loop systems may also be restricted due to legislations that will limit the potential further.

In urban areas, there must be enough space to construct the ground source system. Most of the systems will have boreholes and sub-surface piping and the ground surface area will be of less importance, while others need larger ground surface area. To describe this parameter the term “surface requirement” has been used.

The Seasonal Performance Factor (SPF) is defined according to Gehlin and Spitler (2022) as the system boundary H1. This means the ratio between heat produced and electricity used, which also includes circulator pumps on the brine side, and solar energy harvest in UTES applications.

For heating an HHP system exclusively with a ground source system the investment must compete with the savings of the operational cost. This is based on the estimated seasonal performance factor “SPF” compared to conventional heating, which assumed to have an SPF value of 1.

Finally, the “cost effectiveness” is a combined factor of savings and estimated capital cost for the additional investment in the ground source system. In this factor the estimated lifetime of the ground source wells and boreholes is considered.

As shown in the table the most promising concept is adding an HHP system to an already existing ground source space heating system or to combine ground source heating with HHP heating in new GSHP systems. The latter is considered the most cost-effective alternative and may even initiate the installation of new HHP systems.

The BTES concepts are all cost-effective and require a minimum of surface area. The investment cost can be paid off over a long period of years and the savings are large enough to make these systems profitable.

Even though GWHP and ATES concepts are more cost effective than BTES, the restricted geological availability for these systems as well as the more complicated permit procedures give them less potential. Still, there might be several areas in which they can be used.

HT- ATES, PTES, and CTES are all excluded from this ranking due to limited experience using these systems. However, they may be further developed and potentially used in time. The systems with thermosyphon technologies are also excluded from the top-ranking list since they are not ready for the commercial market at the time being.

The most commercial systems have been analyzed further in Appendix D1.2 by calculated scenarios at different size and applications.

3.7 ENVIRONMENTAL ASPECTS

An important market potential factor is the environmental impact of using ground source heat compared to conventional sources, especially considering the reduction of emission of greenhouse gases.

Since the distribution systems are practically the same for any HHP application, the main difference is the way the heat is generated. Conventionally heated systems typically use electric heating cables, boilers with different types of fuels, or district heating. In shallow geothermal systems, the heat is generated from the ground and a minor amount of electricity is used to run the system.

Reduction of Green House Gas Emissions (GHG)

The GHG emissions of electricity production differ significantly between countries (FIG 19). This is mainly due to the different uses of fossil fuels, renewables, nuclear, and hydropower in national electricity mixes.

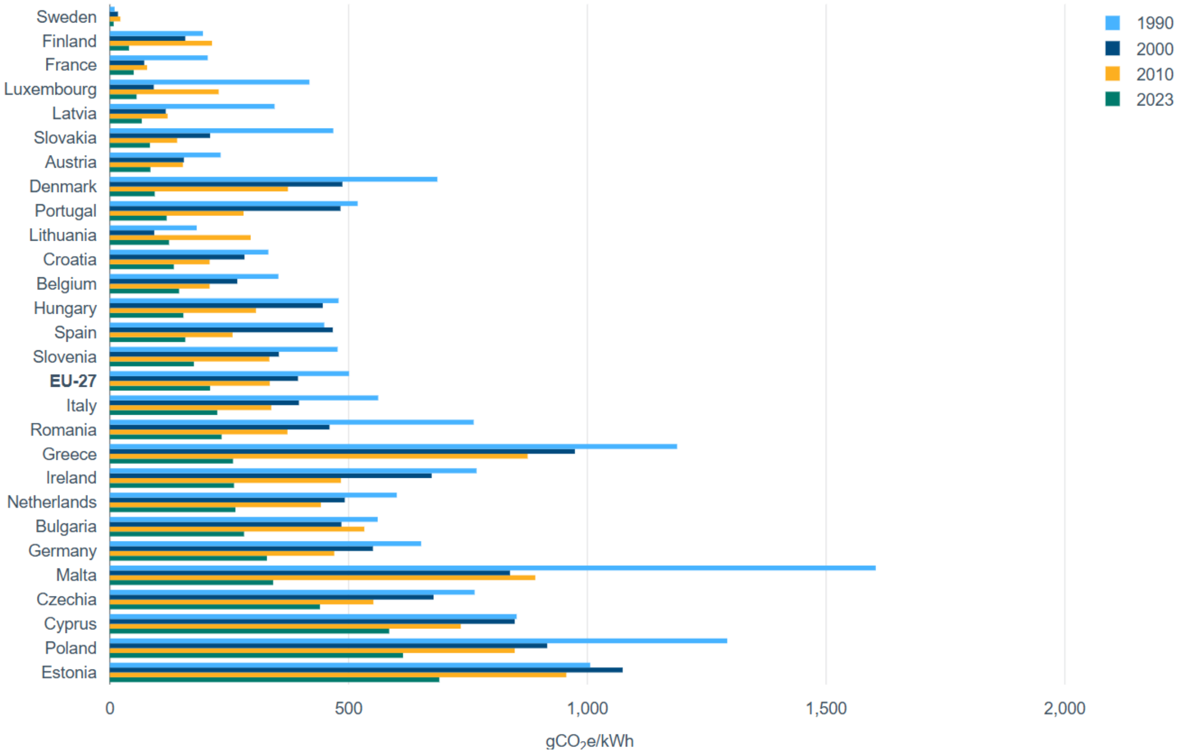


Figure 19. Greenhouse gas emission of electricity generation, EU country level (EEA 2024).

The mean value for EU 2023 is about 200 g/kWh and the EU target is 100 g/kWh in 2030 to be practically zero by 2050.

The large variation of GHG emissions makes it impossible to make a uniform evaluation of the emission savings using ground source HHP heating compared to conventional heating. However, using electrical heating cables or fossil fuels as conventional heat sources will always emit more GHG compared to ground heat sources.

The emissions from fossil fuels differ depending on the fuel used but also on the burning technology and efficiency. The emission is largest for coal fired boilers, followed by diesel/oil and natural gas.

Biomass is another source. The emissions from this form of heat source are traditionally assumed to be climate neutral. However, the release of CO2 when it is burned has considerable GHG emission. It has been proposed that burning biomass should be counted as not neutral CO2, since the GHG emission is affecting the climate at present time, instead of its natural decomposition during several decades.

According to the EU Directive on renewable energy (2007), heat extracted from the ground is renewable and can be assessed to have no emission of greenhouse gases.

From a Life Cycle Cost perspective (LCC), however, shallow geothermal borehole systems cause some CO2 emissions by drilling of boreholes, manufacturing of drilling equipment and components used in the systems. On the other hand, a ground source borehole system has a very long lifetime (>50 years). For this reason, the LCC emissions can be considered very low.

By using the GHG emission values stated above and the expected SPF for the shallow geothermal systems the emission can be calculated, Table 7.

Table 7. Annual CO2 emissions using ground source alternatives compared to conventional heat sources. Conventional heating according to IPCC (2014)

HHP heating system	**GHG emission (kg/MWh)**
CONVENTIONAL HEATING	
Electricity	200 (mean EU)
Coal	740-1690
Oil	510-1170
Gas	290-930
GROUND SOURCE HEATING (driven by electricity)	
GSHP (SPF 3.0-4.0)	50-65
GWHP (SPF 4-8)	25-50
ATES (10-15)	15-20
BTES (8-10)	20-25
HT-BTES (20-25)	8-10

It is obvious that the GHG emissions from ground source heating systems are considerably lower than from any of the conventional heat sources. This is a strong market indicator that should greatly favor the use of ground source heat.

Burning of biomass is partly related to waste used as fuel in district heating. This fuel contains plastics. In Sweden this makes the mean emission of GHG for district heating in order of 50 g/MWh, while the GHG from electricity generation in Sweden is 10 mg (Andersson et al 2023).

Local environmental impact of using ground source heat

For open loop systems using groundwater as a heat source a disturbance of the groundwater level will take place. The static level will be lowered around abstraction wells and uplifted around injection wells. This may impact on the environment close to the wells.

In most countries, the environmental impact in the vicinity of the well or borehole field is described in an assessment study based on hydraulic modeling and a survey of potential disturbances as a part of permit procedures. In general, the permit is not given if the system is judged to cause an unacceptable environmental impact on buildings and infrastructure within a defined area of hydraulic influence.

For closed loop systems groundwater protection is the dominating environmental issue. To protect the groundwater several countries have introduced mandatory sealing of boreholes by grout (IEA ECES 2020).

Usage of salt

A traditional way to prevent slippery road surface conditions is to use road salt, mainly in the form of sodium chloride (NaCl).

Large amounts of salt are annually spread on public roads as well as walkways and roads in urban areas.

The salt forms a saline meltwater that mixes with stormwater, infiltrates into the groundwater, or flows directly into creeks, rivers, and lakes. This leads to locally elevated salinity levels that may affect both flora and fauna (SGU 2004).

In addition to a negative biological impact, road salt also leads to increased corrosion of metals, especially on cars, that come into contact with the salt. The same also applies to concrete pipes in stormwater systems. For the same reason, there is a concern about the use of salt for snow and ice melting on railway platforms, railway crossings, or railway switches.

Road salt is also considered to increase the risk of traffic accidents as some animals are drawn to salted roadways to lick salt. This has e.g. been noted in northern Sweden, where about 2000 reindeer per year are lost in traffic accidents.

The alternative to salt is sand, but on busy roads, the sand does not last very long and requires large quantities. Using sand also requires extensive transport and thus is a source of larger emissions than using salt (Trafikverket 2018).

By using HHP systems in general the usage of salt is decreased. Since ground source heated HHP offers considerably less operational cost, they may initiate a larger usage of HHP systems in order to decrease the environmental impacts of using salt.

3.8 CONCLUSIONS

There is a large variety of ground source heating systems. In this document, these systems are classified in terms of usefulness for de-icing and snow melting systems (HHP). Some systems may be used without the support of heat pumps, while others need heat pumps to work at adequate temperature levels.

Regardless of what heat source is used, a HHP system is mainly designed depending on its snow melting capacity.

- A common goal is to continuously melt a snowfall intensity of 4 mm H_2O/hour, which requires a power of 300-350 W/m^2
- To keep the surface free of frost down to -10°C less power is needed, often in the range of 200-250 W/m^2. This will also melt snow at an intensity of 2 mm H_2O/hour

By using the experiences of already existing usage of shallow geothermal systems for space heating and cooling buildings, most systems have been ranked as potential heat sources for HHP systems. The ranking is mainly based on cost-effectiveness, geological availability, and energy efficiency expressed as SPF. In addition, the ranking is supported by several calculated scenarios (Appendix 1).

- GSHP systems combined with space heating/cooling with minor HHP applications have the highest market potential. This includes both existing and new applications of shallow geothermal systems. The grading is due to a low additional investment cost.
- A high market potential is also expected for using groundwater heat pump systems (GWHP) that show the second-best economic performance. However, with restricted geological availability.

Underground thermal energy storage (UTES) systems offer the advantage of directly utilizing stored summer heat in the winter. A relevant question is whether enough solar energy can be harvested to balance the requirements for de-icing and snow melting in the winter.

- The results in this study indicate that additional heat can be stored in the most common UTES commercial systems (ATES and BTES) and then later used for de-icing and snow melting.
- ATES systems show the best performance and are less dependent on heat pumps to work properly. On the other hand, ATES has a low level of geological availability. In addition, there may be obstacles when it comes to legislation and permits.
- BTES systems are highly ranked since they can be applied in almost any geological setting and environment. On the other hand, they are more costly and dependent on heat pumps. Even if the investment cost is substantial, the performance factor combined with a long lifetime and practically no maintenance cost makes BTES competitive.

BTES can also be used for the storage of surplus and waste heat at high temperatures (HT-BTES). In such cases, the heat losses will be an important additional factor to consider. In the best case, no supporting heat pump is needed.

- HT-BTES with storage temperatures of 60 -70°C, will have the highest performance factor of all shallow geothermal systems. Considering that the surplus and waste heat are free of charge, the storage losses are of less economic concern. However, the number of applications is a limiting factor when it comes to market potential.

Other forms of UTES such as pit storage (PTES) and storage in caverns and old mines (CTES) are not a part of this evaluation because of the lack of experience from their construction cost and performance.

From an environmental point, it is obvious that the GHG emissions from ground source systems are considerably lower, often at least 10-fold less, than from any of the conventional heat sources. This makes the ground source system market attractive with respect to the ongoing climate change.

Using HHP systems in general will also limit the usage of salt that may cause environmental problems and corrosion damage on cars, etc. Using ground source heating for HHP systems for the reason of using less salt may be of interest to the market.

Summary

Hydronic Heated Pavement (HHP) is used to prevent accidents caused by slippery conditions. These systems are widely spread in several countries and are typically heated by electricity (electric heating cables), fuel boilers, or district heating. The market for these systems is steadily growing with an annual rate of approximately 6%. So far only a limited number of applications use geothermal energy as a heat source.

Most of the existing HHP systems are designed for managing snow melting of an intensity of 1-4 mm H_2O, corresponding to a power requirement of 100-350 W/m^2. The annual use of heat depends on the winter climate conditions and varies within a typical range of 100-400 kWh/m^2.

In this study, the most promising shallow geothermal systems from a market perspective have been chosen and evaluated in terms of geological availability, space requirement, operational efficiency, and cost effectiveness. The ranking of systems is mainly based on long-term experience using these systems for space heating and cooling. For support, several scenarios have been calculated (Appendix D1.2).

The most promising shallow geothermal system is to add a minor HHP loop to an already existing ground source heat pump (GSHP) space heating application. The HHP loop, serving, e.g. entrances and ramps, can be installed at a moderate investment cost. With a seasonal performance factor (SPF) of 3-4 the additional investment would be paid off within a couple of years.

For shallow geothermal systems, exclusively designed for HHP systems, groundwater-based alternatives, groundwater heat pumps (GWHP) and aquifer thermal energy storage (ATES), show the best performance and cost effectiveness. On the other hand, proper aquifers are seldom available in the vicinity of HHP system applications. For this reason, they have a restricted market potential.

The closed loop systems in the form of Borehole Thermal Energy Storage (BTES) and High Temperature Borehole Thermal Energy Storage (HT-BTES) can be applied almost anywhere. Through their relatively high efficiency and reasonable cost-efficiency they can be regarded as promising concepts ready for the commercial market.

Other forms of Underground Thermal Energy Storage (UTES), such as Pit Thermal Energy Storage (PTES) and Cavern Thermal Energy Storage (CTES), are not easily evaluated due to a lack of knowledge of how they would work in HHP concepts and uncertainties when it comes to investment cost. For these reasons, they are regarded as having low market potential for the time being.

Of special interest is HT-BTES in which surplus or waste heat can be stored. Such systems are rated as having high market potential since the heat should be free of charge and they work without the support of heat pumps.

An important economic advantage of using closed loop ground source systems is that the investment in the borehole system can be slowly depreciated, in practice 40 years or more. This will decrease the annual capital cost. Furthermore, these systems are practically free of maintenance costs, which will improve the annual operational cost.

A low maintenance cost may also be true for open loop systems, but in most cases, the lifetime of water wells is shorter, and periodic maintenance is often needed. These systems may also require more permit effort prior to their realization.

From an environmental point of view, ground source coupled de-icing systems will contribute significantly to lower emissions of greenhouse gases and other environmentally harmful substances compared to other heat sources (electric heating cables, fuel boilers, and district heating). Since ground source coupled HHP systems offer considerably lower operational cost and are environmentally favorable they may even initiate a larger usage of de-icing and snow melting systems worldwide.

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SUMMARY OF ACTIVITIES FOR SUBTASK 1

The objective of **Subtask 1** has been to compile **a State-of-the-art overview and a Market Potential overview** of de-icing and snow-melting systems for infrastructure applications, using geothermal resources as heat sources.

The activities started with a kick-off meeting in **October 2021**. **Subtask 1** has met its objectives by **compiling national state-of-the-art reports** from the participating countries **(Belgium, France, Germany, Italy, Sweden, Türkiye),** additional material from Japan and the USA, and information from several other countries**.** Based on these national reports and extra material, along with information from work within Subtask 2, 3, and 4, **summarizing reports on 'State-of-the-art' and 'Market Potential'** have been compiled.

MEETINGS AND COLLABORATIVE EFFORTS

The work within **Subtask 1** has been carried out at multiple international experts' meetings, online and on-site:

October 2021 – **Online kickoff meeting** with 15 experts from seven countries, where the timeline and agenda of Task 38 and its subtasks were discussed, and the project participants and subtask leaders were introduced.

April 2022 – Online meeting with the international experts where the outline of the national state-of-the-art reports was discussed.

November 2022 – On-site experts' meeting in **Istanbul, Türkiye,** in which the first draft of the Swedish and Turkish national state-of-the-art reports were reported and discussed along with additional material from Canada and Japan. A study on the frequency and cost of fall accidents among pedestrians and fall accident prevention with heated footpaths was presented.

May 2023 – On-site experts' meeting in **Antwerp, Belgium**, where the completed Swedish national state-of-the-art report was presented, and early drafts of the German, Belgian and Italian national reports were discussed along with additional information from the USA.

October 2023 – Online webinar **to present and discuss the completed national state-of-the-art reports** from Germany, Italy, Turkey, and Belgium.

March 2024 – On-site experts' meeting in **Perugia**, **Italy**, where a first 'world overview' was presented and the outlines of D1.1 and D1.2 were discussed.

November 2024 – Final on-site experts' meeting in **Göteborg, Sweden,** where D1.2 was discussed and harmonization of abbreviations and terminology in the Subtask reports from all subtasks was agreed upon.

Summary of Activities from Deliverable 1.1: State-of-the-art of existing technologies and applications for de-icing and snow-melting of transport infrastructure with shallow geothermal energy

The D1.1 report includes an **overview and state-of-the-art of conventional de-icing and snow-removal methods, heated and hydronic heated pavement systems (HHPS) and heat sources for heated and hydronic pavement systems** with an emphasis on shallow geothermal energy solutions, including:

Compilation of national state-of-the-art reports for the six participating countries covering local conditions, installed applications and test sites for heated pavement systems.

A brief historical review and overview of de-icing and snow-melting of transport infrastructure using shallow geothermal energy, non-participating countries included.

This deliverable gives a wider picture and understanding of existing **de-icing and snow-melting of paved surfaces for transport infrastructure applications**, available statistics and design criteria included.

Summary of Activities from Deliverable 1.2: Market potential for shallow geothermal energy applications for de-icing and snow-melting of transport infrastructure

The D1.2 report gives a picture of the **market potential for shallow geothermal energy applications for de-icing and snow-melting of transport infrastructure** with focus on the six participating countries. The report includes:

Description of fundamentals of hydronic heated pavements (HHP) applications using shallow ground source heating systems, the design and construction of HHP systems and their ability to harvest solar energy for storage.

Description, ranking and analysis of the market potential for the most promising concepts from a technical and commercial perspective, supported by several scenarios of applications.

Compilation and ranking of seven scenario calculations based on experience from existing shallow geothermal applications for space heating. The ranking is mainly based on the expected seasonal performance factor (SPF), cost effectiveness, and geological availability.

Overview of environmental benefits for the use of ground source coupled HHP systems, compared to conventional heat sources.

This deliverable shows the market potential for extending the use of shallow geothermal resources for **de-icing and snow-melting of paved surfaces for transport infrastructure applications**, replacing more costly and less environmentally friendly heat sources such as fossil fuel based de-icing systems and electric de-icing systems, and provides support for decision makers in their economic and environmental considerations when choosing systems for de-icing and snow-melting.

4 MODELLING OF GEOTHERMAL ENERGY STORAGE AND DE-ICING SYSTEMS, SUBTASK2: DELIVERABLE 2.1 THE STATE OF THE ART IN SYSTEM MODELING AND DESIGN LOAD ASSESSMENT

Prioritizing winter traffic safety by preventing snow accumulation and ice formation in critical infrastructures is imperative. Over the last 20 years, hydronic sub-surface heating systems have been utilized to control snow and ice on diverse paved surfaces, including viaducts, roads, walkways, airport aprons, and helicopter pads, as an alternative solution to the application of salt or chemical treatments. Their operation relied on the use of traditional sources of energy, *i.e.* electricity (Electric Heating Systems, EHS). Recently, the exploitation of shallow geothermal energy to support hydronic heating systems showed significant promise as a substitute for more conventional heat sources (*e.g.*, electricity).

A crucial stage concerns modelling the processes of snow melting and de-icing on the heated surface for the correct operation of a hydronic system. This is intricate due to various factors, including the complex heat and mass transfer mechanisms involved, as well as the temporal and spatial variability of surface and weather conditions. This leads to a wide variety of approaches to modelling i) climatic conditions representative of the cold season, ii) energy demand for heated surface, and iii) utilized heat source.

As regards the design phase of geothermal source systems, it is crucial to evaluate the overall system performance by integrating various model types to account for climate interactions and energy storage considerations. To enhance the development of more efficient designs, diverse models for snow-melting and de-icing on hydronic heated pavements using geothermal energy have been proposed. These models differ in their ability to address transient conditions and the level of complexity in representing surface conditions.

This work aims to study the availability, development, and capabilities of the models required to effectively design and control geothermal de-icing, and snow-melting systems for rail/pavement/bridge deck applications. Based on this, an overview of these systems' modelling methods is provided by utilizing over twenty illustrative examples sourced from existing literature and inserted into a database. The database serves as a valuable resource for extracting information about both the components of the analysed systems and the most prevalent and effective modelling approaches. Additionally, it facilitates the compilation of detailed fact sheets for each case study, thus creating a practical tool that might support the efficient design of these systems, considering their extensive potential.

This report serves as the initial step in Subtask 2, focused on the *Modelling of Geothermal energy storage and De-Icing systems*, within the framework of the Technology Collaboration Programme on Energy Storage (ES TCP) Task 38 - Ground Source De-Icing and Snow Melting Systems for Infrastructure project, initiated by the International Energy Agency (IEA) in 2021.

4.1 INTRODUCTION

Thermal de-icing, snow melting, and prevention of ice formation strategies based on Hydronic Heated Pavement Systems (HHPS), employed to manage winter conditions on surfaces of transportation infrastructure, present numerous advantages, that encompass the automated control of safe surface conditions, the avoidance of chemicals and their associated environmental impacts, and the extension of the infrastructure's lifespan. HHPS can efficiently utilize solar energy collected during the summer, combined with seasonal thermal energy storage via geothermal heat exchange. By harnessing these renewable resources and implementing advanced energy storage solutions, significant savings in primary energy consumption can be achieved. In this context, Shallow Geothermal Energy (SGE) holds significant promise for replacing conventional energy sources.

SGE systems are gaining popularity for their dual environmental and economic benefits. By utilizing the ground as a source and repository of thermal energy, SGE systems efficiently regulate the temperature of buildings. Yet, their utility surpasses building heating and cooling, expanding into applications like slab and pavement heating, agricultural drying, and swimming pool temperature management. A recent development involves integrating SGE systems with deep foundations, creating a versatile element that offers both structural support and thermal energy exchange with the subsurface. These thermo-active foundations deliver the advantages of SGE systems without incurring extra expenses related to drilling (Brandl, 2006, Bowers, 2016, Bourne-Webb et al., 2009, Katzenbach et al., 2014).

The integration of SGE into the HHPS might reduce strain on power grids during winter when snow melting and de-icing systems, integral to critical infrastructure, cannot be easily switched off. Additionally, in certain instances, the cooling of pavements during the summer months can reduce rutting phenomena on road surfaces as well as tire wear.

De-icing, snow-melting, and prevention of ice formation systems typically operate as closed-loop systems, and their components include heat transfer fluid, piping, a fluid heater (energy source), pumps, and sensors for measuring the actual weather conditions, and system control (Figure 1).

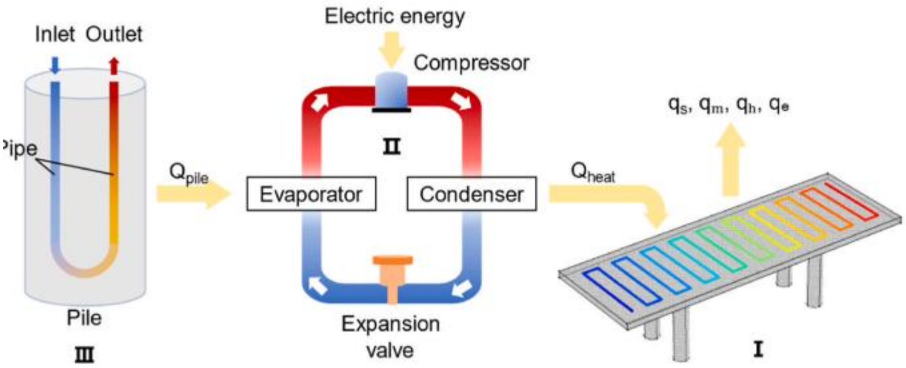


Figure 1. Energy exchange between geothermal energy pile, heat pump, and bridge deck heating system (from Cao et al., 2024)

Designing and modelling geothermal energy storage systems and HHPS for de-icing and snow melting presents a complex challenge. These systems require careful consideration of numerous variables, including solar radiation, wind, air temperature, supply temperature, fluid flow rate in pipes, and pipe dimensions and depth, among others. In addition, the design phase necessitates a thorough assessment of the overall system performance. This evaluation integrates various modelling approaches to account for climate interactions and energy storage (Adl-Zarrabi et al., 2023).

A key factor in designing a ground source HHPS is its intended outcome, with system efficiency being paramount. Efficiency directly impacts both the system capacity and its energy consumption, making it a critical design consideration. In essence, the following operational strategies are available for these systems:

- **Prolonged use with low power**. Common in applications like artificial turf football fields, these systems operate by keeping the ground warm enough to prevent frost formation down to a certain air temperature threshold, such as -10°C. While they operate for extended periods, their heating capacity remains low.
- **Intermittent use with higher power**. Typical in urban environments, these systems ensure that surfaces remain frost-free at sub-zero temperatures, while also providing sufficient heat for snow melting. They operate intermittently with varying heating capacities depending on conditions.
- **Continuous use with high power**. These systems are designed to preheat and maintain dry surfaces throughout the winter, essential in settings like airports that experience heavy snowfall or snowstorms. Continuous operation ensures readiness for intense snow events and rapid response to adverse weather conditions.

The choice of operational mode is not solely functional but also weighs energy costs. Hence, manual control with an intermittent operational strategy might be the optimized approach for most scenarios.

In literature, a range of modelling and design cases for such systems is available, employing diverse approaches that may involve laboratory-scale or full-scale prototypes, pure modelling, or a combination of both, incorporating a broad range of methods for conceptualization, study, and analysis of these systems and their components, which have contributed to their dissemination.

The different modelling approaches to the problem, that have been proposed in the literature so far, range from simplified models (e.g., Ismail, 2013, Umas, 2014, Dupray et al., 2014), to more accurate and integrated methods (Liu et al., 2007, Mirzanamadi, 2017). A more accurate and validated model was presented by Johnsson, et al. (2019). Nevertheless, there is significant divergence in their ability to effectively handle the problem, and in reliability and practicality in their application. The biggest challenges lie in integrating various components and implementing a control system to optimize storage during charging and discharging processes.

In the following chapters, a technical report will be introduced, elucidating the primary characteristics pertinent to the modelling of HHPS for snow-melting and de-icing of infrastructure utilizing shallow geothermal energy, starting from the definition of the particular climatic conditions involved, and followed by a systematic approach to modelling the required heat flux and the geothermal heat source, and the discernment and selection of pivotal operational parameters concerning geothermal design and the de-icing and snow-melting system.

4.2 PRESENTATION OF CASE STUDIES

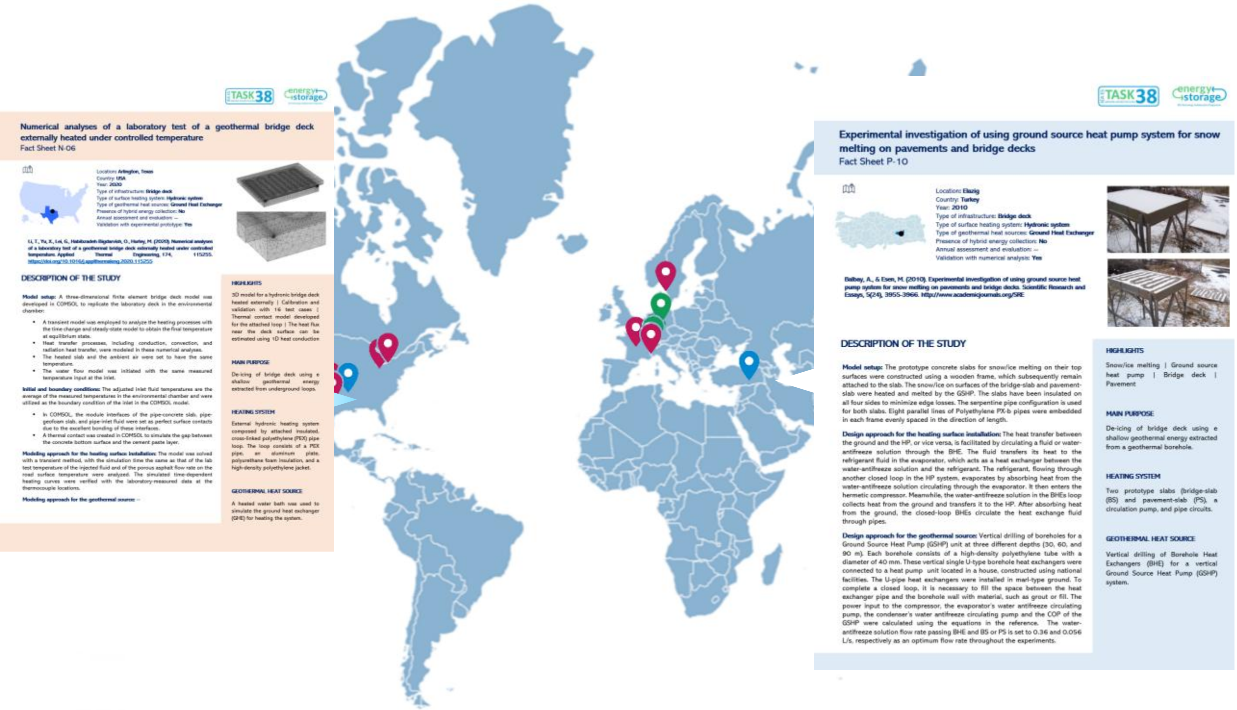
This work examines approximately 20 case studies of ground source HHPS, encompassing a range of approaches including numerical modelling, laboratory experiments, full-scale prototypes, or a combination of these methods. By categorizing the case studies and incorporating some operational examples, their distribution is mapped in Figure 2. The analysis reveals a notable trend: a significant number of prototypes are developed in Eastern countries such as China, while numerical studies are more commonly conducted in the United States.

Figure 2. Location of case studies analysed

This study highlights the variations in system components, configurations, heated surface types, and heat sources across geothermal HHPS applications. The aim is to provide a comprehensive state-of-the-art review of modelling approaches for these systems, covering both numerical studies and prototypes. Since these two types of configurations often complement one another, this work seeks to identify commonalities, effective solutions, and advancements in the field, distinguishing between older approaches and more innovative techniques.

The first step involved compiling a database of case studies from published literature. Each case was categorized by location, year of implementation or publication, type of study, and the infrastructure involved. Subsequently, the database was enriched with technical details, including the type and components of the heated surface systems, geothermal resources, and the corresponding modelling approaches or protocols. Additional information on hybrid energy collection systems and any annual performance evaluations was also incorporated.

To present this information in a concise and structured format, fact sheets were created for each case study and included in the Appendix D2.1 of this report. These fact sheets summarize the key features of systems modelled numerically, experimentally, or both, providing a clear overview of their characteristics and methodologies (Figure 3).



Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature
Fact Sheet N-06

Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: --
Validation with experimental prototype: **Yes**

Li, T., Yu, X., Lei, G., Habibzadeh-Bigdarvish, O., Hurley, M. (2020). Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature. Applied Thermal Engineering, 174, 115255. https://doi.org/10.1016/j.applthermaleng.2020.115255

DESCRIPTION OF THE STUDY

Model setup: A three-dimensional finite element bridge deck model was developed in COMSOL to replicate the laboratory deck in the environmental chamber:

- A transient model was employed to analyze the heating processes with the time change and steady-state model to obtain the final temperature at equilibrium state.
- Heat transfer processes, including conduction, convection, and radiation heat transfer, were modeled in these numerical analyses.
- The heated slab and the ambient air were set to have the same temperature.
- The water flow model was initiated with the same measured temperature input at the inlet.

Initial and boundary conditions: The adjusted Inlet fluid temperatures are the average of the measured temperatures in the environmental chamber and were utilized as the boundary condition of the inlet in the COMSOL model.

- In COMSOL, the module interfaces of the pipe-concrete slab, pipe-geofoam slab, and pipe-inlet fluid were set as perfect surface contacts due to the excellent bonding of these interfaces.
- A thermal contact was created in COMSOL to simulate the gap between the concrete bottom surface and the cement paste layer.

Modeling approach for the heating surface installation: The model was solved with a transient method, with the simulation time the same as that of the lab test temperature of the injected fluid and of the porous asphalt flow rate on the road surface temperature were analyzed. The simulated time-dependent heating curves were verified with the laboratory-measured data at the thermocouple locations.

Modeling approach for the geothermal source: --

HIGHLIGHTS

3D model for a hydronic bridge deck heated externally | Calibration and validation with 16 test cases | Thermal contact model developed for the attached loop | The heat flux near the deck surface can be estimated using 1D heat conduction

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from underground loops.

HEATING SYSTEM

External hydronic heating system composed by attached insulated, cross-linked polyethylene (PEX) pipe loop. The loop consists of a PEX pipe, an aluminum plate, polyurethane foam insulation, and a high-density polyethylene jacket.

GEOTHERMAL HEAT SOURCE

A heated water bath was used to simulate the ground heat exchanger (GHE) for heating the system.

Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks
Fact Sheet P-10

Location: **Elazig**
Country: **Turkey**
Year: **2010**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: --
Validation with numerical analysis: **Yes**

Balbay, A., & Esen, M. (2010). Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks. Scientific Research and Essays, 5(24), 3955-3966. http://www.academicjournals.org/SRE

DESCRIPTION OF THE STUDY

Model setup: The prototype concrete slabs for snow/ice melting on their top surfaces were constructed using a wooden frame, which subsequently remain attached to the slab. The snow/ice on surfaces of the bridge-slab and pavement-slab were heated and melted by the GSHP. The slabs have been insulated on all four sides to minimize edge losses. The serpentine pipe configuration is used for both slabs. Eight parallel lines of Polyethylene PX-b pipes were embedded in each frame evenly spaced in the direction of length.

Design approach for the heating surface installation: The heat transfer between the ground and the HP, or vice versa, is facilitated by circulating a fluid or water-antifreeze solution through the BHE. The fluid transfers its heat to the refrigerant fluid in the evaporator, which acts as a heat exchanger between the water-antifreeze solution and the refrigerant. The refrigerant, flowing through another closed loop in the HP system, evaporates by absorbing heat from the water-antifreeze solution circulating through the evaporator. It then enters the hermetic compressor. Meanwhile, the water-antifreeze solution in the BHEs loop collects heat from the ground and transfers it to the HP. After absorbing heat from the ground, the closed-loop BHEs circulate the heat exchange fluid through pipes.

Design approach for the geothermal source: Vertical drilling of boreholes for a Ground Source Heat Pump (GSHP) unit at three different depths (30, 60, and 90 m). Each borehole consists of a high-density polyethylene tube with a diameter of 40 mm. These vertical single U-type borehole heat exchangers were connected to a heat pump unit located in a house, constructed using national facilities. The U-pipe heat exchangers were installed in marl-type ground. To complete a closed loop, it is necessary to fill the space between the heat exchanger pipe and the borehole wall with material, such as grout or fill. The power input to the compressor, the evaporator's water antifreeze circulating pump, the condenser's water antifreeze circulating pump and the COP of the GSHP were calculated using the equations in the reference. The water-antifreeze solution flow rate passing BHE and BS or PS is set to 0.36 and 0.056 L/s, respectively as an optimum flow rate throughout the experiments.

HIGHLIGHTS

Snow/ice melting | Ground source heat pump | Bridge deck | Pavement

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from a geothermal borehole.

HEATING SYSTEM

Two prototype slabs (bridge-slab (BS) and pavement-slab (PS)), a circulation pump, and pipe circuits.

GEOTHERMAL HEAT SOURCE

Vertical drilling of Borehole Heat Exchangers (BHE) for a vertical Ground Source Heat Pump (GSHP) system.

Figure 3. Location of case studies analysed and related fact sheets

4.3 MODELLING APPROACHES

Modelling HPPS for snow melting and de-icing in infrastructure presents significant complexity due to a wide range of considerations. These systems can encompass various configurations, typically involving the following key components:

1. Pavement surface heating system, responsible for heat delivery.
2. Ground Source Heat Pump (GSHP), used to transfer heat.
3. Underground heat sources, which may serve to extract, store, or both. Examples include Ground Heat Exchangers, Borehole Thermal Energy Storage Systems (BTES), or Aquifer Thermal Energy Storage Systems (ATES).
4. System controllers and sensors, which regulate operations.

Not all configurations include every component—for instance, some systems may operate without a geothermal heat pump. Additionally, many systems aim to balance both heat extraction and storage concurrently.

A critical aspect of modelling these systems is determining the required heat flux at the heated surface, which must be calculated based on the desired operational outcomes. This heat flux depends on several factors, including:

- Climatic conditions and environmental heat transfer mechanisms, which influence the thermal load,
- Infrastructure construction details, such as materials, thickness, area, and orientation of the heated surface,
- Hydronic tubing characteristics, including material, diameter, spacing, and burial depth,
- System flow rates, affecting heat transfer efficiency,
- Properties of the heat transfer fluid, such as density and thermal characteristics,
- Supply temperature of the fluid, which drives the thermal performance (Han & Yu, 2017).

These factors in the initial modelling phase heavily influence the design and operation of the geothermal components. As evident from the analysed case studies, different approaches are employed depending on the system configuration and objectives.

The following chapters will focus on three key aspects of modelling geothermal systems: establishing reliable climatic conditions tailored to the specific case study, defining the required heat flux at the surface (thermal load), and evaluating the geothermal heat resource. Moreover, they will include an analysis of notable case studies from the compiled database, offering valuable insights into practical applications and advancements in this field.

DEFINITION OF CLIMATIC CONDITIONS

The effectiveness of a HHPS for de-icing, snow melting, or ice prevention relies heavily on its ability to accurately account for varying surface conditions and precipitation types. These factors are closely tied to the climatic conditions of the site, as will be elaborated below. Therefore, the initial step in designing the systems discussed in this study is the selection of reliable weather conditions.

Weather parameters typically serve as boundary conditions in mathematical models. However, for HHPS modelling, it is essential to describe the specific combination of weather variables that lead to surface ice formation. Snowfall thickness, for instance, can be prescribed using historical data. A common approach to defining weather conditions involves collecting and analysing meteorological data and the weather history of the region (Habibzadeh-Bigdarvish et al., 2021).

For example, Liu et al. (2019) utilized statistical data from Environment and Climate Change Canada on weather and snowfall events from 1981 to 2010 for several Canadian cities. Their findings showed that in Calgary, Edmonton, Montreal, Ottawa, Toronto, and Winnipeg, 97%, 97%, 91%, 92%, 93%, and 96% of daily snowfall events, respectively, were less than 10 cm. Designing for a more severe scenario, such as 20 cm of snowfall, would significantly overestimate the system's required power, leading to unnecessary cost increases. Instead, their study adopted a design scenario that covers at least 90% of snowfall events, corresponding to a daily snowfall of approximately 5–10 cm. These selected weather conditions (daily averages) were deemed representative of typical snowy conditions in the six cities examined.

Similarly, Ho et al. (2017) conducted a parametric study to determine the heat requirements for a snow-melting system in eastern North Dakota. Their analysis relied on climatic data averaged over fifteen years (2000–2015), measured by the National Oceanic and Atmospheric Administration and the World Data Centre for Meteorology. Specifically, their study included (a) fifteen-year averages of air temperatures during the coldest months of each year, (b) the distribution of precipitation magnitudes from November to January, (c) average wind speeds during the coldest months, and (d) average snowfall data for the same period.

More recently, Cao et al. (2024) refined the approach by filtering climatic data to focus on the coldest month for each city included in their study, covering the period from 1980 to 2020. They used the averaged values from these filtered datasets as input parameters for their models.

MODELLING OF THE REQUIRED HEAT FLUX

The thermal load required by HHPS represents a critical aspect of their design and operation. This load is determined by assessing the boundary heat conditions at the surface, atmospheric conditions, and the desired system performance. The effectiveness of a de-icing or snow-melting system model hinges on its capacity to accurately account for the wide range of surface conditions and precipitation scenarios encountered in practice. Modelling the snow-melting process on a heated surface involves several complexities:

- *Heat and mass transfer mechanisms*: The snow-melting process involves complex interactions between heat transfer and phase change phenomena, which must be accurately represented in the model.
- *Spatial and temporal variations*: Surface conditions during snow melting vary both over time, due to changing weather conditions, and across the surface, owing to the discrete arrangement of heat sources.
- *Dynamic weather conditions*: Storm events are characterized by rapidly changing weather variables, including precipitation intensity, temperature, humidity, wind speed, and solar radiation, all of which must be considered in the modelling process.

A primary measure of system performance is its ability to minimize the duration for which the pavement remains covered with snow, ice, or frost during a snowstorm or freezing event (Li et al., 2007). The transient nature of weather conditions and the dynamic response of both the pavement and hydronic system require the model to simulate the pavement's thermal state and surface conditions over a period leading up to the onset of precipitation.

To achieve this, the model must incorporate boundary conditions that reflect the full spectrum of weather conditions, not just those prevailing during snow events. This comprehensive approach ensures accurate predictions of system performance under various operational scenarios, and is shown in Figure 4 (Staudacher et al., 2022).

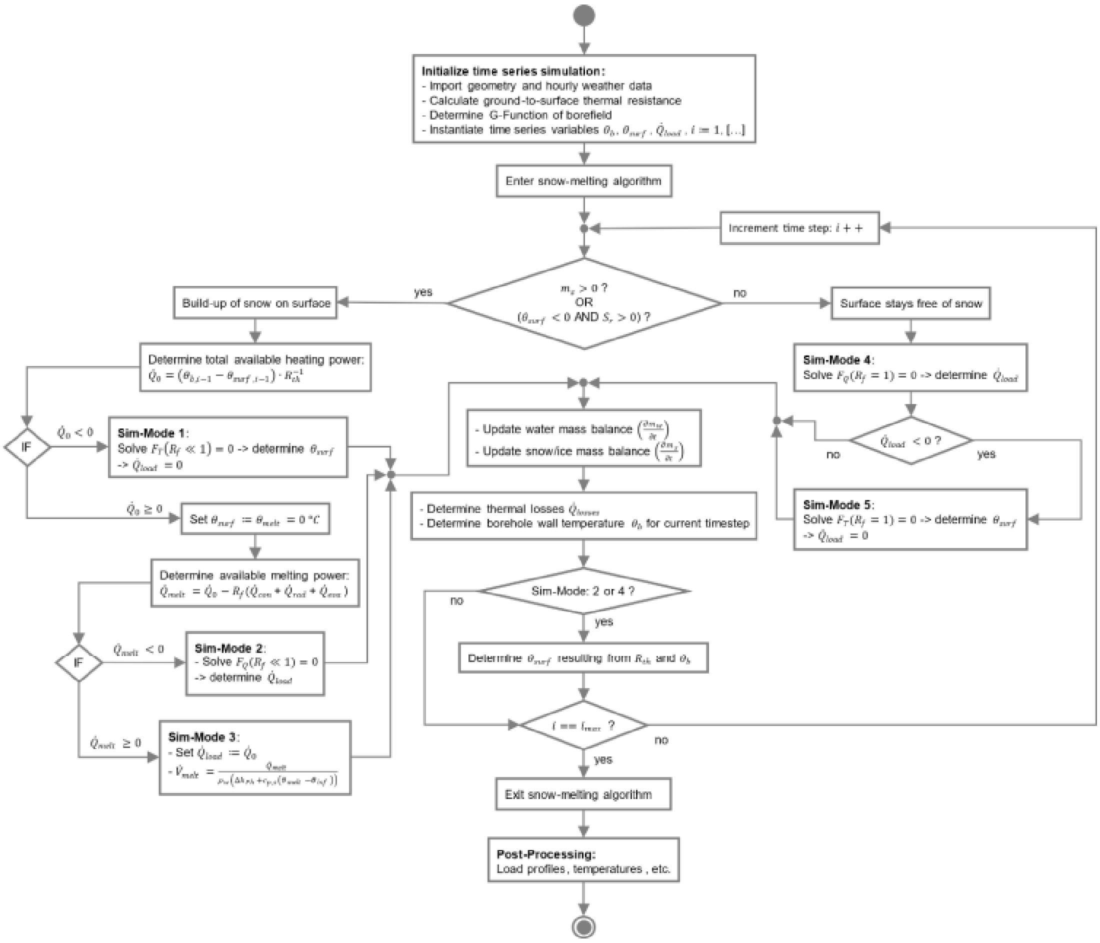


Figure 4. Flow chart of the snow melting calculation algorithm from Staudacher et al. (2022)

Building on the classification outlined by Rees et al. (2002), seven distinct surface conditions have been identified, as summarized in Table 1. Accurately determining the current condition of any part of the pavement requires not only an analysis of ongoing precipitation—considering its temperature, intensity, and form (rain or snow)—but also an understanding of the surface's preceding state.

Table 1. Classification and definition of surface conditions.

Surface Condition	Definition
Hoarfrost	The surface is covered with frost, which is due to the sublimation of water vapor in the ambient air on a cold surface. The pavement surface temperature must be below freezing.
Dry	The surface is free of liquid and ice. The pavement surface temperature may be above or below freezing.
Wet	The pavement surface temperature is above freezing and has some liquid water retained on it, but no ice. The liquid water can come from rainfall, condensed vapor, or the melted snow.
Dry snow	The surface is covered with dry snow without liquid water. The snow can be regarded as a porous matrix of ice. The pavement surface temperature is below freezing so that snow is not currently being melted.
Slush only	The surface contains ice crystals that are fully saturated with water. Water penetrates the porous matrix of ice from bottom to the upper surface. The pavement surface temperature is at freezing point.
Snow and slush	The surface contains snow that is partly melted. The lower part of the snow is saturated with water and the upper is as dry snow. The pavement surface temperature is at freezing point.
Solid ice	The ice on the surface is in solid form rather than porous like snow. The pavement surface temperature must be below freezing.

Various formulations for heat and mass balance have been utilized in the numerical case studies collected in this report, each stemming from diverse underlying assumptions.

Feasibility studies in North America have frequently employed the ASHRAE method for designing hydronic pavements. Early models of de-icing and snow-melting systems also relied on the guidelines provided by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1997), which recommended 1D steady-state methods. These approaches facilitated the calculation of the required heat flux for snow melting on bridge and pavement surfaces.

For example, Ramsey et al. (1999) developed a 1D steady-state analysis model capable of determining heat flux through energy balance calculations at the surface of bridge decks or pavements. This method was later adopted by Dupray et al. (2014) to define the geotechnical and energy design parameters of piles functioning as heat exchangers beneath a bridge deck (Figure 5). Their work incorporated thermo-hydro-mechanical simulations to evaluate the system’s performance.

$$q_0 = q_s + q_m + A_r\,(q_h + q_e) \tag{1}$$

Equation 1 represents the steady-state energy balance for the total heat flux required (power per unit surface area, W/m²) at the upper surface of a snow-melting slab during snowfall. This equation accounts for the various processes contributing to the heat flux requirements. Specifically, q_s represents the sensible heat flux, q_m denotes the heat required for snow melting, q_h accounts for convective losses to the ambient air at temperature t_a and radiative losses to the surroundings at a mean radiant temperature TMR, while q_e represents the heat flux necessary for evaporation.

This equation provides a framework for determining the heating requirements of a snow-melting system. However, accurate calculations necessitate incorporating real-time climatic factors, such as snowfall rate, wind speed, ambient temperature, and dew-point temperature (or an equivalent humidity indicator). By calculating the load for each hour of snowfall over several years, a frequency distribution of hourly loads can be developed. This approach is critical, as relying on annual averages or maximum values for climatic factors is unsuitable for system sizing, given the improbability of such conditions occurring simultaneously.

It is also important to note that this analysis focuses exclusively on the upper surface of the snow-melting system, excluding considerations of heat losses at the edges or through the underside of the slab. These additional losses should be addressed separately to ensure a comprehensive assessment of the system's thermal performance.

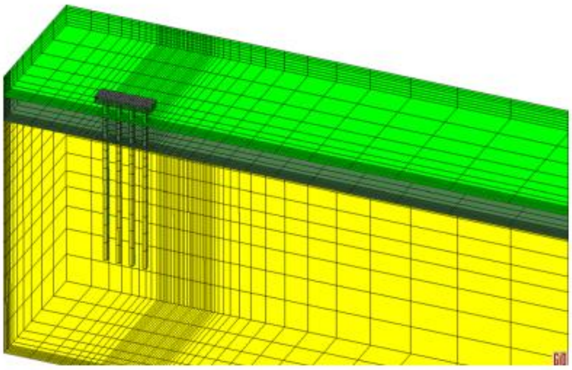


Figure 5. Transparent view of the model mesh (from Dupray et al., 2017)

In the study conducted by Liu et al. (2018), the thermal load due to snowfall was estimated by using steady-state boundary conditions in accordance with ASHRAE recommendations. The calculation of the required heat flux to maintain the average temperature of the bridge slab above 0 °C was based on a comprehensive energy balance, considering typical winter conditions during snowfall for each city analysed in the study.

Furthermore, the energy supplied by the geothermal energy piles was determined under the assumption that the coefficient of performance (COP) of the heat pump remained constant across all cities. This assumption, however, is not entirely realistic, as COP values can vary significantly depending on local climatic conditions and operational parameters.

Despite its strengths, this approach did not account for intermittent system operations or the impact of dynamic weather conditions, which are critical for accurately modelling real-world performance.

Another often-utilized procedure for roads involves considering mass and heat balance equations on the surface of the pavement. The summation of seven heat transfer processes is considered in the heat balance equation (Mirzanamadi, 2017): conductive heat from ground and pipes, $qcond$, convective heat flow from the ambient air, q_{conv}, sensible heat from rain, q_{rain}, sensible heat from snow, q_{snow}, long-wave radiation, q_{lw}, short-wave radiation, q_{sw}, as well as latent heat of evaporation and condensation, $q_{evp/cond}$. In Figure 6, the heat balance of the road surface is illustrated. The heat balance of the road surface is written as:

$$q_{cond} + q_{conv} + q_{rain} + q_{snow} + q_{lw} + q_{sw} + q_{evp/con} = 0 \tag{2}$$

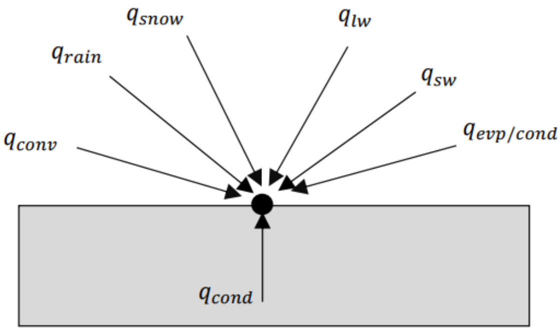


Figure 6. Heat balance of a road surface (from Mirzanamadi, 2017)

For example, Mirzanamadi et al. (2019) employed this approach with the primary objective of preventing hoar frost formation. The heating system was not designed to address snow melting or ice formation caused by rain. The study assumed a functioning drainage system and the absence of vehicular traffic. To simplify the numerical model, it was further assumed that all snowfall was immediately ploughed away from the road surfaces. However, in practice, falling snow before removal begins impacts the heat balance at the road surface.

The models discussed thus far have been employed during the design phase to calculate the heat flux required to melt all snow precipitation instantaneously. However, these models are not well-suited for simulating actual system performance, where snow accumulation on all or part of the surface is likely. As previously noted, the transient nature of weather conditions during storms, combined with the dynamic behaviour of the pavement and hydronic system, necessitates simulating the pavement's thermal state and surface conditions over a period preceding precipitation.

For instance, if snow begins to fall on a dry pavement at sub-freezing temperatures while the heating system is inactive, the heat flux from the system would initially contribute to sensibly heating the snow, delaying melting. Conversely, if the heat flux is sufficiently high, or the pavement slab temperature has been preheated to the freezing point, the snow may melt "instantaneously" (i.e., within a single time step), leaving the surface wet. Similarly, if the precipitation rate increases beyond the capacity of the heating flux, only a portion of the snow will melt, leading to snow accumulation. These scenarios underscore the importance of capturing dynamic interactions between the system and varying environmental conditions for accurate performance simulations.

Several numerical studies have incorporated both transient and two-dimensional (2D) analyses of HHPS. Rees et al. (2002) simulated a cross-section of the slab that included half of a heating element and extended to the midpoint between two adjacent heating elements. The slab was placed on soil, with its temperature determined using the analytical relationship proposed by Kusuda and Achenbach (1965). To establish initial conditions, the authors developed a one-dimensional (1D) model, which served as a simplified version of their 2D model but excluded the de-icing tube. This 1D model was subjected to boundary conditions over a two-week period prior to the activation of the heating system. The temperature gradient obtained at the end of this initialization period was then applied to the 2D domain six hours before heating commenced, allowing the simulation to capture the transient behaviour of the system. The operation continued under the specified boundary conditions until the heating system was activated. Surface boundary conditions were managed using a model that accounted for the seven possible surface states described in Table 1. This boundary condition model facilitated the prediction of the surface state at any given time and the calculation of the corresponding surface boundary heat flux. The primary advantage of this approach is its ability to accurately simulate the complex snow-melting process and predict the system's performance under varying conditions. However, its limitation lies in the use of a 2D domain, which represents only a small section of the heated slab, potentially restricting its applicability to larger-scale or three-dimensional scenarios.

Liu et al. (2003) expanded upon the model developed by Rees et al. (2002) to simulate the long-term hydronic heating of a bridge deck, rather than focusing solely on individual storm events. This enhanced model incorporated a ground-source heat pump and consisted of four interconnected sub-models: the hydronically heated bridge deck, ground loop heat exchanger, water-to-water heat pump, and system control. Experimental validation was performed using a ground source HHPS for bridge deck de-icing installed at Oklahoma State University. The setup featured an 18.3 m by 6.1 m bridge deck with 19 mm hydronic tubing spaced at 0.3 m intervals and embedded 89 mm below the surface. The system was designed to maintain the bridge deck temperature between 4.4–5.6°C (40–42°F) during periods of snowfall risk. The model effectively predicted the average bridge surface temperatures and fluid exit temperatures, although it slightly overestimated surface temperatures. The authors highlighted challenges in accurately accounting for long-wave radiation and convective heat fluxes in the numerical model.

Building on this work, Liu and Spitler (2004) conducted a parametric study using the Liu et al. (2003) simulation. They analysed the effects of idle time, pipe spacing, slab insulation, and control strategies on system performance. Their findings demonstrated that pre-emptive heating and maximizing heating capacity prior to snowfall significantly improved system performance. Subsequent studies by Liu et al. (2007a) further refined the model, and Liu et al. (2007b) validated its accuracy, contributing to its reliability for practical applications (Figure 7).

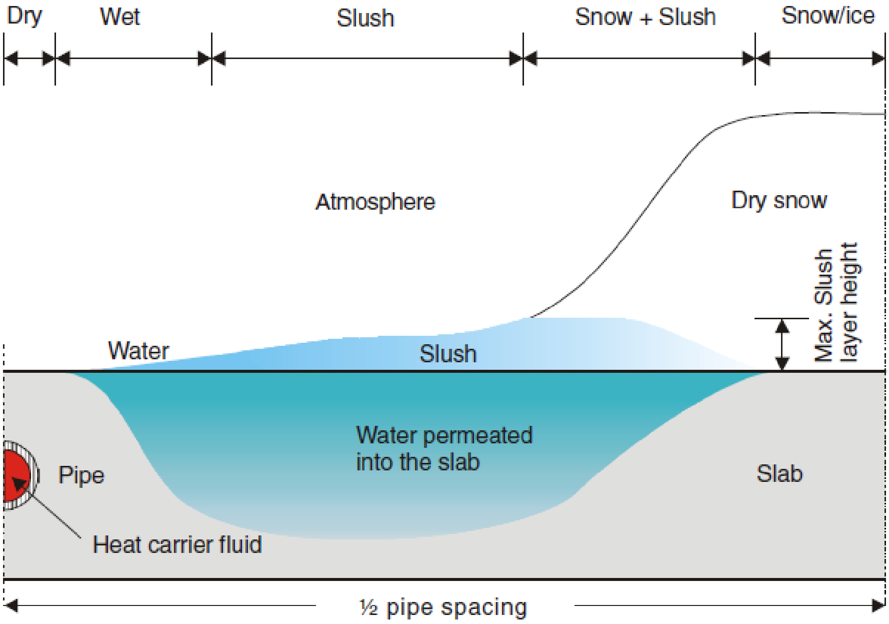


Figure 7. Variation of surface condition on a heated pavement slab during the snow melting process (from Liu et al., 2007)

Johnsson (2019) presents both experimental and numerical findings from a field station featuring a Hydronic Heating Pavement (HHP) designed to function as a pavement solar collector. The system, integrated with a BTES, was developed to assess the feasibility of deploying HHPS in Scandinavian climates. The analysed system faces several challenges that must be addressed to ensure its effectiveness. Seasonal variations in solar radiation necessitate reliance on BTES to provide consistent energy storage. For the BTES to function efficiently, heat losses must be minimized. This can be achieved by reducing the operating temperature of the HHPS, as heat loss is driven by temperature gradients. However, lower temperatures reduce the heat flow that can be extracted from the BTES, while the pavement requires sufficient heat flow to maintain the desired surface temperature. To mitigate this, adjustments can be made to the pipe layout, the thermal conductivity of the pavement, or the control system. The control system must account for the low supply temperature, which can be achieved by initiating the system proactively based on weather forecasts. By extending the operational duration of the system, a lower mean heat flux can be utilized, balancing the system's energy demands (for further details, refer to Technical Reports produced within the **SubTask_3** "*Development of system components for selected applications*" and **SubTask_4** "*Planning, construction and monitoring*" of the International Energy Agency Technology Collaboration Programme on Energy Storage Task_38 "Ground Source De-Icing and Snow Melting Systems for Infrastructure").

Thus, the study included a preliminary evaluation to estimate the potential energy harvestable through the system. To model the energy dynamics within the pavement, the HHP module employed the finite difference method, enabling detailed calculations of energy flows and thermal behaviour (Figure 8). This approach provided valuable insights into the system's performance and its applicability to energy-efficient infrastructure solutions in cold regions. The analysis explores the influence of key parameters, including albedo, fluid flow rate, and pipe spacing, on system efficiency. Additionally, it addresses the optimization of control strategies aimed at minimizing energy consumption. Lastly, the study examines the thermal properties of the materials employed and the performance of the subsurface thermal storage system. To validate the HHP module, the calculated thermal resistance between the pipe and the upper pavement surface was compared with results obtained using an analytical solution. Thermal resistance was chosen as a parameter because it is easily comprehensible and can be determined analytically.

The pavement surface is influenced by various heat transfer processes, as previously outlined by Mirzanamadi (2019). In this study, additional factors are considered, such as the sensible heat generated by traffic (q_{traffic}), latent heat due to the freezing and thawing of moisture on the road surface ($q_{\text{freeze/thaw}}$), and latent heat from sublimation and deposition ($q_{\text{sub/depo}}$):

$$0 = q_{\text{surface}} + q_{conv} + q_{\text{precipitation}} + q_{\text{lw}} + q_{\text{sw}} + q_{\text{evap/con}} + q_{\text{sub/depo}} + q_{\text{freeze/thaw}} + q_{\text{traffic}} \tag{3}$$

Various simplifications can be applied to HHP models depending on the specific phenomena under investigation, and the HHP module is designed to accommodate a range of assumptions.

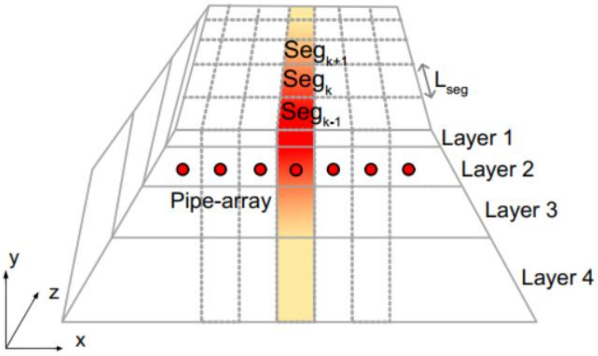


Figure 8. A sketch of the studied hydronic heated pavement with the HHP-model represented by the centrally shaded volume (from Johnsson, 2019)

One of the most used software platforms for studying these systems is COMSOL Multiphysics, which allows the input of thermal properties for individual components, enabling detailed analysis of heat flow under varying power supply conditions. In the study by Li et al. (2020), a novel externally heated hydronic bridge deck for retrofitting existing bridges was developed and modelled using a three-dimensional multi-physics approach in COMSOL Multiphysics. The simulation accounted for multiple heat transfer mechanisms, including conduction through the concrete slab, phase change processes (snow melting and water evaporation), solar radiation, thermal radiation, and surface convective heat transfer (Figure 9).

Furthermore, the model incorporated thermal contact resistance, defined as the reciprocal of thermal contact conductance. At the thermal interface, the contact conductance is represented by the sum of constriction conductance and gap conductance (Grujicic et al., 2005). Accurate simulation of the system required careful consideration of the thermal contact between the top surface of the cement layer and the base of the concrete slab, ensuring results consistent with experimental observations.

Due to the lack of sufficient experimental data for ambient temperatures below freezing within the environmental chamber of the corresponding prototype, the model developed by Li et al. (2020) was further employed to forecast and approximate the performance of the heating system under extreme winter conditions. These simulations provided valuable insights into the interplay between the thermal input and the system's heat transfer efficiency, enabling a more comprehensive evaluation of its behaviour across a range of challenging environmental scenarios. This predictive capability underscores the utility of advanced numerical modelling in addressing data limitations and optimizing system design for cold climates.

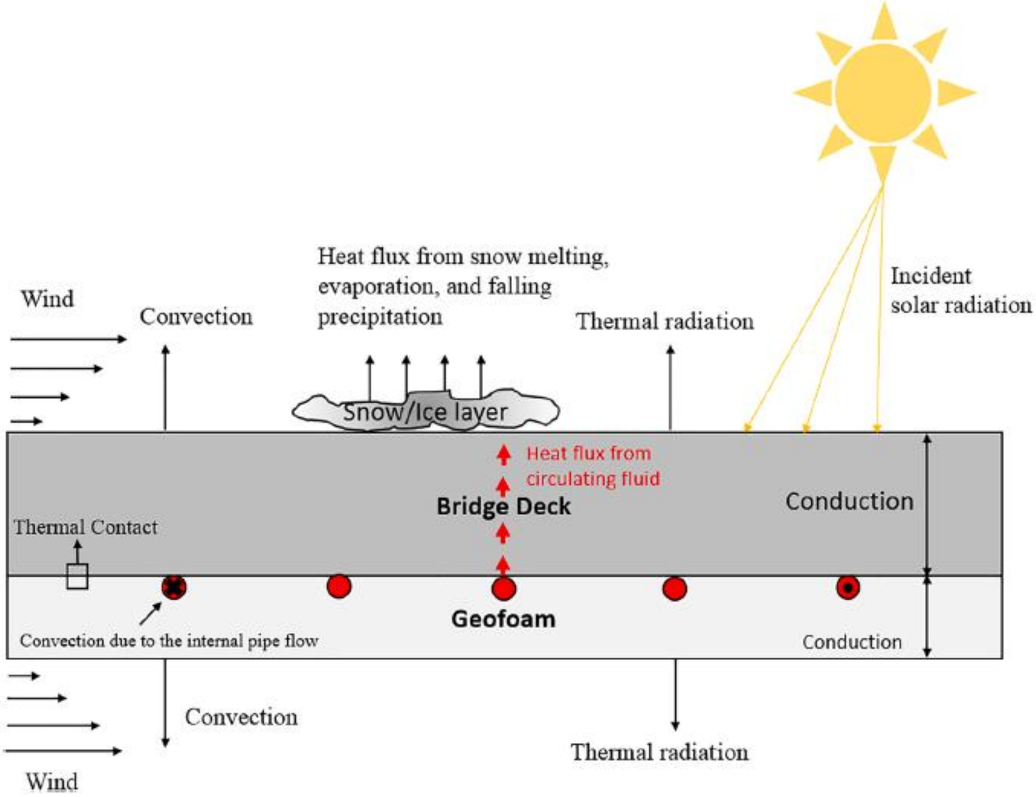


Figure 9. A cross-sectional view of heat transfer mechanisms in an externally heated bridge deck (from Li et al., 2020)

MODELLING OF THE GEOTHERMAL HEAT SOURCE

HHPS that utilize fluid to harness natural heat from the ground have emerged as one of the most effective and widely favoured methods for snow and ice removal through heat transfer. This approach leverages a readily available and renewable heat source, contributing to its popularity (Han & Yu, 2017).

The advantages of geothermal HHPS for snow melting are numerous: (*i*) they rely on renewable and sustainable energy sources, (*ii*) eliminate the need for chemical treatments, (*iii*) enhance safety in snow and ice removal operations, and (*iv*) significantly reduce CO_2 emissions. Furthermore, by maintaining surface temperatures above 0°C, these systems help mitigate damage caused by freeze-thaw cycles, resulting in substantial reductions in pavement maintenance costs.

One of the most renowned geothermal HHPS is the SERSO (Solar Energy Recovery from Road Surfaces) pilot plant in Switzerland. Operating since 1994, the SERSO system collects excess heat from solar warming during the summer, storing it underground in a rock-based storage volume. During winter, the stored heat is reused to maintain the road surface temperature slightly above 0°C, preventing ice formation and compacted snow freezing (Eugster, 2007). Notably, in the climate of central Europe, more heat is typically extracted from the roadbed in summer than is needed for the following winter, demonstrating the system's efficiency and sustainability.

Geothermal HHPS have also been implemented in other regions, including Japan (Morita & Tago, 2000; Nagai et al., 2009), Iceland (Ragnarsson, 2015), Poland (Zwarycz, 2002), and the United States (Han et al., 2018). However, the effectiveness of these systems varies significantly depending on local climatic conditions, geothermal resource availability, environmental factors, and geological characteristics. For optimal performance, systems must be tailored to the specific conditions of each region.

As highlighted earlier, geothermal de-icing and snow-melting systems encompass a wide variety of configurations. For example, the Gaia Snow Melting System utilizes the ground as both a heat source and a storage reservoir (Morita & Tago, 2000). This system incorporates Downhole Coaxial Heat Exchangers (Coaxial GHE), allowing solar heat absorbed by the pavement during summer to be captured and stored underground (Figure 10). In winter, the system combines geothermal and solar heat to effectively melt snow, showcasing its versatility and efficiency in leveraging multiple renewable energy sources.

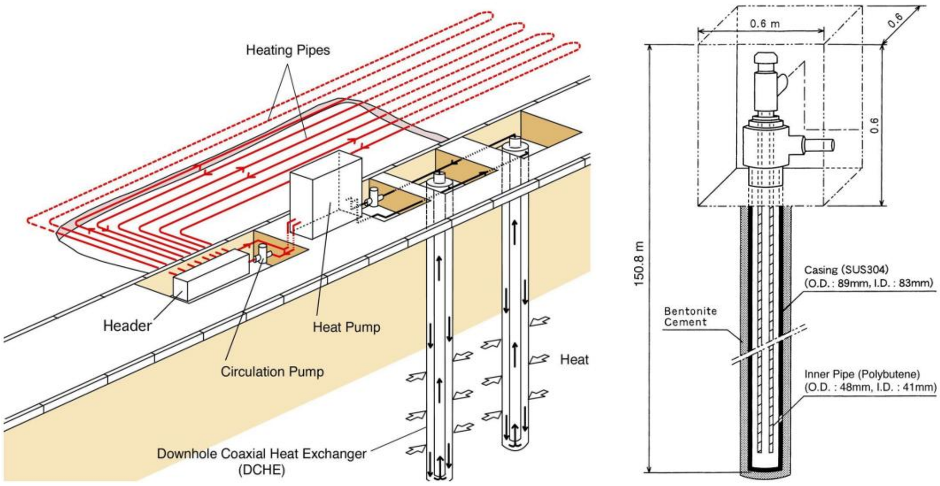


Figure 10. Conceptual scheme of the Gaia snow melting system (on the left); Structure of the DCHE (on the right) (from Morita & Tago, 2000)

The study by Balbay & Esen (2010) explores the feasibility of a ground-source heat pump (GSHP) system designed for snow melting on pavements and bridge decks. The system employs vertical single U-borehole heat exchangers of varying lengths as the primary heat source and utilizes hydronic heating within the bridge and pavement slabs (Figure 11).

The GSHP system analysed in this study comprises ground borehole heat exchangers with three different depths (30 m, 60 m, and 90 m), a water-to-water heat pump, and heating pipes embedded beneath the Bridge Slab (BS) and Pavement Slab (PS). This configuration enables efficient heat transfer from the ground to the surface, ensuring effective snow and ice removal while leveraging renewable geothermal energy. The heat extracted from BS or PS, Q, is calculated by the following equation:

$$Q = m_{wa} + C_{p,wa}\,(T_{wa,I} - T_{wa,o}) \tag{4}$$

The power input to the compressor $\dot{W}_c$, the evaporator's water antifreeze circulating pump $\dot{W}_{ep}$ and the condenser's water antifreeze circulating pump $\dot{W}_{cp}$ are calculated using the following equations:

$$W_c = I_c\,U_c \cos\varphi \tag{5}$$

$$W_{ep} = I_{ep}\,U_{ep} \cos\varphi \tag{6}$$

$$W_{cp} = I_{cp}\,U_{cp} \cos\varphi \tag{7}$$

The water-antifreeze solution flow rate passing BHE and BS or PS was set to 0.36 and 0.056 L/s, respectively as an optimum flow rate throughout the experiments.

Figure 11. Initial (first picture) and intermediate (second picture) snow melting process on slabs. (from Balbay & Esen, 2010)

In the economic feasibility study performed by Liu et al. (2019) to compare costs between a snow-melting system for a bridge deck using geothermal energy piles and an electricity-based heating system, the authors determined the energy requirements and inlet temperature for a hydronic system to heat and maintain the surface temperature of a bridge slab unit above 0°C during a standard snowfall event. This was done by conducting a transient energy balance analysis at the slab surface, considering the prevailing weather conditions for each city. The coefficient of performance (COP) of the heat pump for a bridge was then derived for each city based on its particular local geological conditions and heating demands. Specifically, during the design of the system, after assessing the boundary heat flux at the surface of the bridge slab, according to the ASHRAE method, the following steps consisted of i) calculating the heating loads (q_H) of the HHPS for snow melting necessary to sustain an average surface temperature above freezing for a bridge slab unit; ii) analysing the heat extraction rate (q_L) of the geothermal energy pile; and iv) determining the Coefficient of Performance (COP) and relative savings for a large-scale bridge project.

As for the determination of the heating loads (q_H), the heat transfer in the pipe and concrete materials used for the bridge slabs was considered. The governing equations of the heat transfer in the pipe and through the surrounding concrete slab were used to determine the temperature distribution profile of the fluid along the pipe and within the slab (Equation 7, from Liu et al., 2019), in which the term Q_{w1} represents the external heat source through the pipe wall). The product of Q_{w1} and the pipe's length is the energy output rate (q_H) from the condenser in the heat pump.

$$\rho_w A_{hf} C_{pw} \frac{\delta T_{hf}}{\delta t} + \rho_w A_{hf} C_p v_s \nabla T_{hf} = \nabla \cdot \left(A_{hf} k_w \nabla T_{hf} \right) + Q_{w1} \tag{8}$$

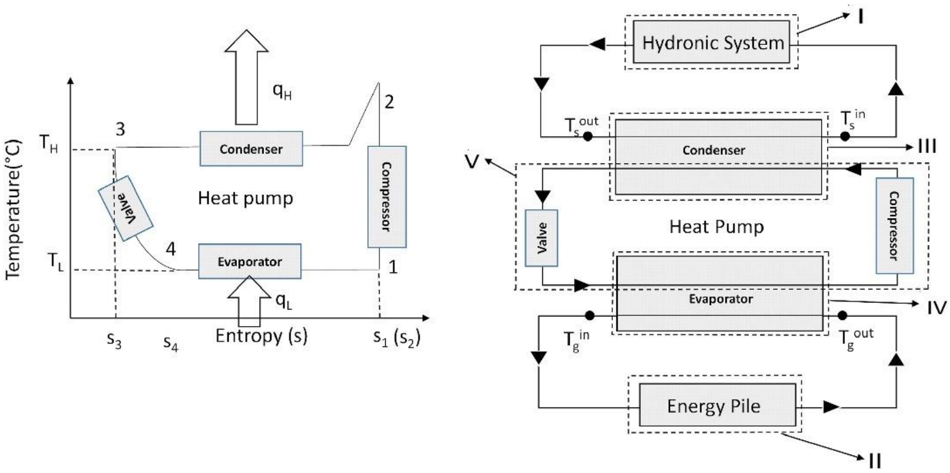


Figure 12. Initial (first picture) and intermediate (second picture) snow melting process on slabs. (from Balbay & Esen, 2010).

Subsequently, to evaluate the heat extraction rate, the governing equation for the heat transfer in geothermal heat exchanger fluid was considered:

$$\rho_w A_{gf} C_{pw} \frac{\delta T_{gf}}{\delta t} + \rho_w A_{gf} C_{pw} v_g \nabla T_{gf} = \nabla \cdot \left(A_{gf} k_w \nabla T_{gf} \right) + Q_{w2} \tag{9}$$

where A_{gf} (m^2) is the cross-sectional area of the geothermal heat exchanger; T_{gf} represents the temperature of the geothermal heat exchanger fluid; v_g (m/s) is the velocity of the geothermal heat exchanger pipe flow; Q_{w2} (W/m) is the heat sink term.

The heat transfer in the soil and concrete pile is described in Equation 4 which gives the temperature distribution due to the conduction mechanism:

$$\rho A C_p \frac{\delta T_{s/c}}{\delta t} = \nabla \cdot \left(kA\nabla T_{s/c}\right) - Q_{w2} \tag{10}$$

where $T_{s/c}$ represents the temperature distribution in soil or concrete; C_p (J/kg·K) is the heat capacity for concrete or soil; k (W/m·K) is the thermal conductivity for concrete or soil; ρ (kg/m^3) stands for the density of soil or concrete.

The constant underground temperature, sourced from Environment and Climate Change Canada, serves as the boundary condition in the analysis of geothermal energy piles. The heat exchanger pipe is modelled as polyvinyl chloride (PVC) with an inner diameter of 2 cm and a wall thickness of 4 mm. In this study, the heat transfer governing equations are solved using the COMSOL Multiphysics FEM software.

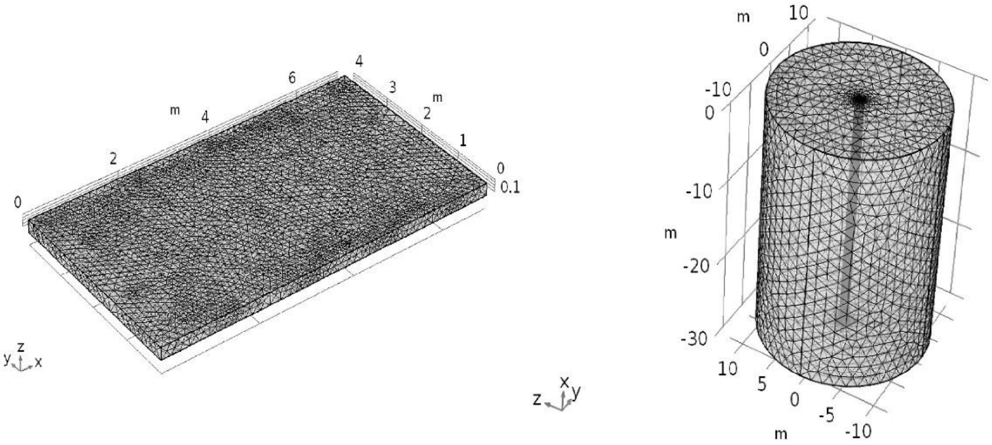


Figure 13. Mesh distribution for the bridge slab and geothermal energy pile (from Liu et al., 2019).

Lastly, as for the design of the heat pump, according to energy conservation principles, the energy absorbed by the evaporator of the heat pump equals the energy absorbed by the underground heat exchanger from the soil. Similarly, the energy released by the condenser of the heat pump equals the energy consumption of the concrete slab. It's important to highlight that the heat pump always necessitates electricity input to utilize energy at low temperatures. The COP of the heat pump can be calculated for the specific site by using the following equation:

$$\mathrm{COP} = \frac{q_H}{q_H - q_L} \tag{4}$$

In the study by Habibzadeh-Bigdarvish et al. (2021), which presents the design and implementation procedure of a novel external geothermal heating system on a full-scale bridge deck for de-icing operations in field conditions, the main objective in designing the Ground Heat Exchanger (GHE) was to determine the smallest size that could provide sufficient heat output for melting the snow and ice. Firstly, the design weather conditions were determined. This involved collecting weather data and examining the historical weather patterns of the region. Subsequently, the necessary heat flux for melting snow/ice on the bridge deck was calculated based on the weather data. Then, the peak hourly and monthly heating loads were computed, taking into account the area of the bridge deck and the duration of snowfall hours, respectively. For the calculation of the monthly heating load, it was assumed that 64 hours of snowfall per year occurred only during the three months of the winter season (i.e., 21.3 hours each in December, January, and February). Following this, a heat pump capable of operating within a system with the calculated heating load was selected. EWT and flow rates were specified, and the heating loads for both the heat pump and the GHE were determined from the heat pump heating performance data sheet. Subsequently, the design and operational parameters were chosen, with reasonable assumptions made if necessary due to unavailable data. Finally, all data were input into the design software tool, such as GLHEPro, to compute the size of the GHE.

In the study conducted by Mirzanamadi et al. (2019), the feasibility of the coupled HHP system to a Horizontal GHE for harvesting solar energy during summer and anti-icing road surfaces during winter was examined. A hybrid 3D numerical simulation model was employed to depict the transient heat transfer processes during both the harvesting and heating periods of the coupled HHP system and Horizontal GHE. This model was constructed by integrating 2D vertical cross-sections of the HHP system and the Horizontal GHE, with these cross-sections connected sequentially to one another through convective heat transfer in fluids. Utilizing FEM, the hybrid 3D numerical simulation model computed the heat fluxes emanating from the pipes while simultaneously estimating the decline in fluid temperature along the pipes, employing a quasi-steady state assumption. Specifically, this study employs four 2D vertical cross-sections to simulate the HHP system and an additional four 2D vertical cross-sections to simulate the Horizontal GHE. Furthermore, as can be seen in Figure 10, there is symmetry analysis region between the pipes in the domains of HHP and Horizontal GHE. It was assumed that the lines of A-B and C-D in the HHP system and the lines of G-H and I-J in the Horizontal GHE are adiabatic, so as the outgoing heat from boundaries and incoming heat to the boundaries are the same. In order to reduce the computation time, the region of A-B-C-D was selected to numerically simulate the HHPS and the region of G-H-I-J was selected to numerically simulate the Horizontal GHE.

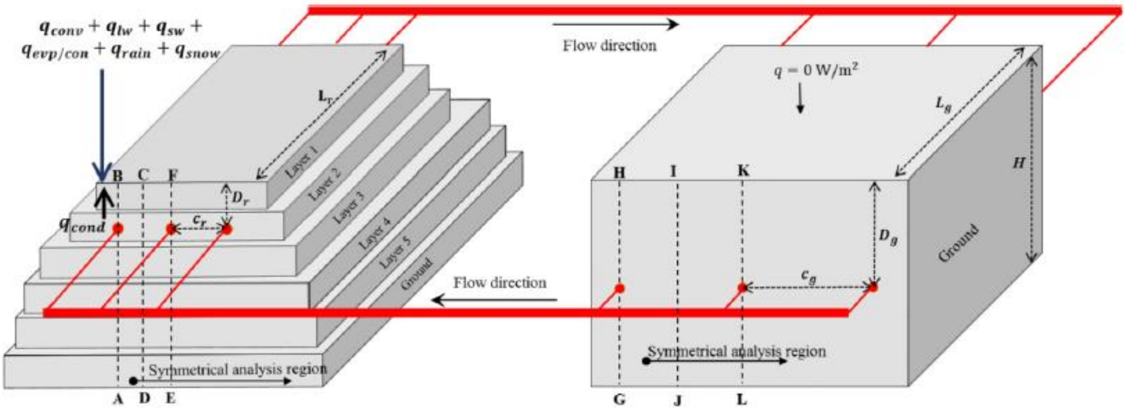


Figure 13. Schematic view of the HHP (left side) coupled to the Horizontal Ground Heat Exchanger (right side) (from Mirzanamadi et al., 2019)

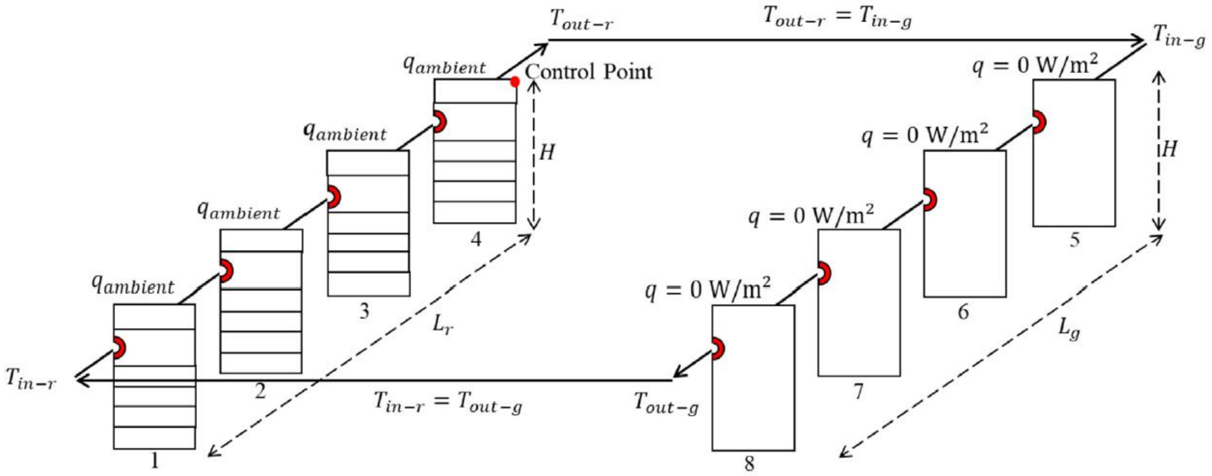


Figure 14. A scheme of the hybrid 3D numerical simulation model of the coupled HHP system (left) to the Horizontal GHE (right). The 3D model is represented by 2D vertical cross sections which are serially connected through the convective heat transfer in the fluid (from Mirzanamadi et al., 2019)

By accounting for the steady-state longitudinal temperature distribution of the fluid along the pipes and assuming that the length of the pipe between two vertical cross sections at positions n and n+1 is Ln (m), the inlet temperature of the fluid for section 1 at time t is a known value, and the outlet temperature of one section can be regarded as the inlet temperature of the subsequent section. Consequently, it is feasible to compute the outlet temperature of the fluid for the entire length of the pipework.

The hybrid 3D numerical simulation model is validated by the results of another numerical simulation model from the literature. In addition, the following assumptions are made: i) The surface of the Horizontal GHE is fully insulated and the boundary condition at the surface of the Horizontal GHE is adiabatic, ii)The total depth of the HHP and the Horizontal GHE is truncated to five times the periodic penetration depth of the ground, iii) The boundary condition at the bottom of the ground is set to be adiabatic, iv) The inlet temperature of the HHP system is equal to the outlet temperature of the Horizontal GHE, v) The outlet temperature of the HHP system is equal to the inlet temperature of the Horizontal GHE.

REQUIREMENTS FOR SOLAR ENERGY COLLECTION

Various criteria, including ambient air temperature, solar radiation, and road surface temperature, can be employed to activate or deactivate solar energy harvesting. However, for the sake of simplicity in this study, only the air temperature was considered for activating or deactivating solar energy harvesting. Based on climate data from the specific site, there was no risk of ice formation on the road surface if the air temperature remains above 4°C. However, considering a lower air temperature such as 4 °C to start harvesting solar energy can result in heating the road surface for the periods during which the road surface is colder than the inlet temperature of the fluid. Thus, by considering that the maximum air temperature in the case study area is 25 °C, the air temperature of 10 °C was arbitrarily selected as a criterion to start harvesting solar energy. Furthermore, to ensure that the temperature of the fluid circulating in the Horizontal GHE does not cause a temperature decrease within the Horizontal GHE domain during the harvesting period, it is assumed that solar energy harvesting commences only when the inlet temperature of the fluid in the Horizontal GHE, Tin-g, exceeds the average temperature of the inner surface of the pipe walls in the Horizontal GHE, T_{ave-g} (°C). The harvesting of solar energy will cause a decrease in the temperature of the road surface. The temperature decreases on the road surface during the harvesting period, $T_{decrease}$ (°C), can be calculated as the difference between the temperature at the surface of an unheated road and the temperature at the surface of the HHP system during harvesting at a specific control point.

It is important to underline that the fluid initiates circulation in both the HHP system and the Horizontal GHE whenever the harvesting or heating system is activated. Conversely, when either system is deactivated, the boundary conditions at the inner surface of the pipe walls for all 2D vertical cross-sections are configured to be adiabatic.

SELECTION OF THE OPERATIONAL PARAMETERS

As emphasized repeatedly, the definition of operational parameters for effectively modelling such systems depends on many factors. The various components of these systems should be designed and modelled interdependently, following approaches that, as seen, vary from case study to case study. In this paragraph, we aim to analyse the most important operational parameters for the modelling and design of snowmelt and thawing systems for infrastructure using geothermal energy. Specifically, we will address the description of the surface system, followed by discussing the part related to the geothermal resource of the system.

GEOTHERMAL COMPONENT DESIGN

The performance of a Geothermal Heat Exchanger (GHE) is highly dependent on a comprehensive understanding of ground temperature distribution at varying depths. One of the defining characteristics of soil is its high thermal mass, which results in a slow response to surface temperature fluctuations (Liu et al., 2019). The geothermal heat source is a fundamental component of the system, as it extracts thermal energy from the surrounding ground. Therefore, an accurate assessment of the energy extraction rate is crucial, as it directly influences the energy available for snow melting and bridge deck de-icing. Several factors affect the selection of parameters for modeling the geothermal component of the systems analyzed in this study. These factors are detailed in Table 2.

Table 3 provides a summary of the key parameters used in modeling multiple case studies presented in this report. Ground properties—such as undisturbed temperature and thermal conductivity—are particularly significant in determining the amount of heat exchanged with the structure. Additionally, soils with high thermal conductivity and specific heat capacity are preferable for optimizing heat collection efficiency.

A comparison of similar case studies, like those by Liu et al. (2019) and Cao et al. (2024), reinforces this point, as even comparable structures can exhibit significantly different heat extraction rates, primarily influenced by the average undisturbed temperature of the ground.

Table 2. Geothermal component modeling parameters.

Typology and geometry	Operational conditions	Environmental conditions
Diameter of the borehole/pile ($D_{borehole}$/D_{pile}) [m]	Grout/concrete thermal conductivity (K_{grout}) [W/mK]	Undisturbed soil formation temperature (T_{ground}) [°C]
Diameter of pipe (D_{pipe}) [mm]	Flow regime	Soil thermal conductivity (K_{ground}) [W/mK]
Borehole/Pile depth [m]	Flow rate	Groundwater depth [m]
Heat carrier fluid	Heat pump heating capacity (CAP) [kW]	
Heat pump size	GHE heat extraction (HE) [kW]	
HP COP	Inlet temperature (T_{in}) [°C]	

Table 3. Geothermal component modelling parameters listed for the selected case studies.

Reference	Parameters	Value(s)
Morita & Tago (2000)	Borehole depth	150.8 m
	CAP	15 kW
	D_{pipe}	16 mm
	Thermal capacity	50 kW_t
Balbay & Esen (2010)	Borehole depths	30, 60, 90 m
	$D_{boreholes}$	15 cm
	K_{ground}	1.70 W/mK
	D_{pipe}	35.2 mm
	HP COP	1.99 (30m), 2.66 (60m), 3.05 (90m)
Dupray et al. (2014)	Pile depth	18 - 44 m
	D_{pile}	1 m
	K_{ground}	2.44, 1.59, 2.02 W/mK
	$K_{concrete}$	1.56 W/mK
	T_{in}	/
	T_{ground}	11 °C
	Design power (W/m)	37 (Scenario 1), 53 (Scenario 2)
Ho & Dickson (2017)	Exchanger surface depth	6 m
	D_{pipe}	24.5 mm
	K_{ground}	0.5 - 5.0 W/mK
	T_{in}	7 °C
	T_{ground}	5 - 10 °C
	HP Power	4 kW

Liu et al. (2019)	Pile depth	30 m
	D_{pile}	0.6, 1.2, 1.8 m
	D_{pipe} (inner)	2 cm
	K_{ground}	1.8 W/mK
	$K_{concrete}$	1.6 W/(mK)
	T_{in}	-4 °C
	T_{ground}	12 - 15 °C
	Average heat extraction rate (kW)	3.2 - 3.8 (per pile)
	HP COP	3.0 - 4.9
Cao et al. (2024)	Pile depth	30 m
	D_{pile}	0.6 m
	D_{pipe}	30 mm
	K_{ground}	2 W/mK
	$K_{concrete}$	1.65 W/mK
	T_{in}	-4 °C
	T_{ground}	1.7 - 17.5 °C
	Average heat extraction rate (kW)	1.5 - 5.5 (Double U parallel conf.)
	HP COP	3
Habibzadeh-Bigdarvish et al. (2024)	Borehole depth	131 m
	$D_{boreholes}$	146 mm
	D_{pipe}	34.5 mm
	K_{ground}	0.2-1.5 (varies with water content)
	T_{in} (average)	16.7 °C
	Average heat extraction rate (W/m)	6.5 (test 1), 20.7 (test 3)
	HP SPF (COP)	1.1 (test 1), 2.9 (test 3)

Another observation that can be made is that the types of geothermal heat sources can be very different and heterogeneous. Apart from energy piles technology, studied initially by Dupray et al. (2014) and more recently by Liu et al. (2019), Cao et al. (2024), Morita & Tago (2000), Balbay & Esen (2010) and Habibzadeh-Bigdarvish et al. (2024) explored the more traditional borehole system, while Ho & Dickinson (2017) focused on heat production modelling and the simulation of heat collection pipes in a stabilized subsurface temperature zone. In this study, the heat collection pipes are embedded horizontally in the constant-temperature layer, with fluid circulating through them to the pavement surface via a heat pump. The warm fluid transfers heat to the pavement, melting the snow, and then returns underground to absorb and extract heat once more. Moreover, this work emphasizes the importance of the thermal conductivity of the soil and the volumetric flow rate of the fluid in the pipes in the evaluation of the efficiency of a heat collection system: High thermal conductivity values of the soil into which the heat collection pipes are embedded are recommended and a high degree of saturation of the soil in the stabilized temperature layer is desirable, while the volumetric flow rate should be controlled at or below 1.0 l/s, to avoid higher pressure in the pipes that leads to exceeding the strength of pipes materials.

Lastly, in most case studies, the use of a heat pump was found to be essential. The temperature variation achievable from a geothermal heat source is relatively limited, and when direct use of geothermal hot water is either unavailable or the fluid temperature is too low, a heat pump is needed to raise the temperature for effective operation. The coefficient of performance (COP), which indicates energy efficiency, varies significantly across cities due to differing weather conditions. However, in the majority of cases analysed, typical COP values were around 3. It can be calculated using various methods (Liu et al., 2019; Cao et al., 2024).

SURFACE COMPONENT DESIGN

Many design parameters, including geometric configurations, material properties, operational factors, control scenarios, and environmental circumstances, can affect the HHPS heating performance and its life-cycle cost.

The geometric configuration of a HHPS system mostly relies on pipe embedded depth, spacing, and inner radius. The pipe works in a serpentine configuration, perpendicular to the traffic direction on the road pavement. Some of these parameters, which are fundamental in modeling the heated surface of HHPS, are listed in Table 4, referencing specific case studies analysed in this report.

According to the ASHRAE Handbook (ASHRAE, 1997), placing the pipe at least 50 mm from the top and bottom of the slab in concrete pavements is recommended. In the study of Mehrabi et al. (2022), 75 mm depth is assumed as a typical clear cover for concrete bridge decks. In this study, the modelling was nonetheless extended to a shallower pipe placement depth of 50 mm, which mitigated thermal-induced damage, captured by plastic tensile strains. It should be emphasized that the impact of the traffic loads on the pipe is more significant in the case of a shallower placement. Concerning the pipe spacing, according to Spitler & Ramamoorthy (2000) it typically ranges from 150 mm to 300 mm. Similarly, in the modelling approach proposed by Liu et al. (2007), pipe spacing ranging from 100 to 300 mm was investigated. Such parameters were related to the duration of the pre-heat stage, namely the idling time. As pipe spacing is reduced, shorter idling times are required to provide the same snow-melting performance. Besides, according to Zhu et al. (2022), increased spacing was found to increase the shear strength of the pipe.

Concerning the thickness of the pipe, in the experimental activity carried out by Li et al. (2020), a 6 mm thick pipe was employed to circulate heat-carrying fluid within a bridge deck. A smaller thickness of 2.3 mm was instead set in the numerical simulation models presented by Mirzanamadi et al. (2020), in which the materials, thickness, and diameter of embedded pipes in the HHP system and the geothermal heat source are considered to be the same.

The recommendations for nominal pipe diameters are 18 – 25 mm (Spitler & Ramamoorthy, 2000). As pointed out by Mirzanamadi et al. (2020), as well as pipe spacing and inner radius, the pipe length affects the temperature difference between the inlet and outlet fluid and in turn the annual required energy for anti-icing the road surface. However, such energy consumption is also strictly related to fluid features, i.e. its density and specific heat capacity.

Since HHPS aim at providing surface temperatures higher than both freezing and dew temperature (Mirzanamadi et al., 2020), the heat transfer process is noticeably affected by thermic parameters of pavement materials such as thermal conductivity, density, and specific heat capacity. It is to be stressed that materials' parameters are frequently chosen based on the published literature (Mehrabi et al., 2022). Furthermore, to maintain surface conditions at a level no worse than wet, it is necessary to achieve surface temperatures above the freezing point of water before the accumulation of snow or ice, and to sustain these temperatures until the completion of snow or ice buildup. The heating strategy is thus governed by several local environmental factors including snowfall rate, air temperature, relative humidity, and wind speed (Mehrabi et al., 2022).

Polyethylene is the prevalent material utilized in the fabrication of heating pipes. Specifically, cross-linked polyethylene (PEX) tubing featuring an oxygen barrier layer is preferred for HHPS applications. This choice is attributed to its capability to prevent the infiltration of air or oxygen into the radiant heating system, as Li et al. (2020) highlighted.

The temperatures of the fluid and the surrounding environment assume significant importance in assessing the heat transfer performance of the adopted system and ascertaining the stable temperature conditions of the heated pavement. Li et al. (2020) carried out a numerical analysis in which they explored a range of water temperatures spanning from 21.1 to 37.8 °C, alongside ambient temperatures varying from 4.4 to 16.7 °C.

Table 4. Heated surface component modelling parameters listed for some of the selected case studies.

Parameter	Reference	Value min	Average/Typical value
Pipe embedment depth	ASHRAE (1997)	50 mm	50 mm
	Mehrabi et al. (2022)	50 mm	75 mm
Pipe spacing	Liu et al. (2007)	100 mm	300 mm
Pipe diameter	Spitler and Ramamoorthy (2000)	18 mm	18 – 25 mm
Pipe thickness	Mirzanamadi et al. (2020)	2.3 mm	2.3 mm

4.3 CONCLUSIONS

Recently, the use of **Shallow Geothermal Energy (SGE)** to support **Hydronic Heating Pavement Systems (HHPS)** for winter maintenance of paved surfaces—such as viaducts, roads, walkways, airport aprons, and helicopter pads—**demonstrated considerable potential** as an alternative to conventional heat sources.

This technical report aimed to analyze the availability, development, and capabilities of models required for the effective design and control of geothermal energy storage, de-icing, and snow-melting systems for rail, pavement, and bridge deck applications. To achieve this, an overview of the **modelling methods for HHPS** was provided, incorporating **over 20 illustrative examples** from existing literature, which were compiled into a dedicated database. This database served as a valuable resource, enabling the extraction of detailed information about the components of the analyzed systems and the **most prevalent and effective modelling approaches**. Furthermore, it facilitated the creation of **detailed fact sheets** for each case study, thereby establishing a **practical tool** to support the **efficient design and implementation** of these systems, considering their broad potential.

The analysis conducted on the select case studies permitted us to evaluate the most common approaches utilized in the different phases of the modelling processes of these systems and to draw the following remarks:

- The collected **climatic data** are crucial for calculating the heat required to de-ice or melt snow on the heated surface. However, the phenomena governing this energy demand are highly complex for several reasons: the heat and mass transfer mechanisms involved in the snow melting process are intricate and require the treatment of phase change phenomena; during the snow melting process, surface conditions can vary not only temporally due to changing weather conditions but also spatially at a given moment because of the discrete arrangement of heat sources; weather conditions during storm events are highly variable. Any model must account for changes in precipitation, temperature, humidity, wind speed, and solar radiation. This complexity has led to the development of various models for calculating heat flux, some more advanced than others. After analysing the case studies selected for this work, it was found that the most commonly used approach is the 1D steady-state analysis model. This model calculates heat flux through energy balance equations on the surface of a bridge deck or pavement, using a simple formula that incorporates different contributions to the supplied heat flux: q_s, the sensible heat flux, q_m, which accounts for the heat required to melt snow, q_h, which represents convective losses to the ambient air at temperature, and radiative losses to the surroundings that maintain a mean radiant temperature, while q_e accounts for the heat flux required for evaporation.
- Geothermal-based HHPS offer significant advantages by utilizing the ground as a renewable heat source. Ground-source heat exchangers capture and store excess solar heat from the summer, which is then used during winter to prevent freezing. These systems, such as Switzerland’s SERSO, demonstrate how geothermal energy can efficiently maintain surface temperatures above 0°C, reducing the formation of ice and

snow accumulation. By leveraging underground thermal energy, geothermal heat exchangers ensure consistent and sustainable heating, while minimizing energy consumption and environmental impact.

- The selection of operational parameters for geothermal systems is complex, as it depends on multiple interrelated factors that must be considered in conjunction to effectively model snow-melting and de-icing geothermal systems. A key element is the geothermal heat exchanger, whose performance is influenced by the thermal properties of the ground, such as thermal mass and its consequent relatively slow response to temperature changes. The geothermal heat source plays a central role by extracting heat from the ground and facilitating heat transfer through a heat pump to the system. Accurate parameter identification—such as the ground temperature distribution, soil thermal conductivity, and heat exchanger/sink configuration—is essential for assessing the energy extraction rate, which determines the system's efficiency in snow melting and de-icing operations.

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5. MODELLING OF GEOTHERMAL ENERGY STORAGE AND DE-ICING SYSTEMS, SUBTASK 2, DELIVERABLE 2.2: ASSESSMENT OF MODEL CAPABILITIES AND VALIDATION PROCESSES

Hydronic Heated Pavement Systems (HHPS) for de-icing and snow-melting are a highly effective solution for keeping infrastructure's surfaces such as walkways, driveways, bridge decks, and road pavements free from snow and ice during winter. These systems operate by circulating a heated fluid—typically a mixture of water and antifreeze—through a network of embedded tubing. The fluid transfers heat to the surface, melting snow and preventing ice formation. The performance and durability of such systems depend on careful design, efficient energy sourcing, proper installation, and diligent maintenance. Modern approaches to hydronic systems focus on environmental and economic sustainability, integrating innovative energy solutions. For instance, pavements can serve as solar collectors during summer, storing thermal energy seasonally through geothermal heat exchange. This method reduces reliance on conventional energy sources like electricity, gas, or district heating, enhancing both cost-effectiveness and environmental benefits.

To further explore and optimize the use of renewable and geothermal energy in de-icing systems, the International Energy Agency (IEA) initiated a technology collaboration project. This initiative focuses on leveraging direct geothermal heating systems and ground-source heat pumps for snow melting and de-icing applications in transportation infrastructure.

This report focuses on analysing a series of numerical modelling studies and experimental prototypes of ground source de-icing systems. The main objective is to identify the most commonly adopted approaches to effectively address the calibration and validation of numerical models used in assessing the mechanical and energy performance of this system.

5.1 INTRODUCTION

Methods for thermal de-icing, snow melting, and ice prevention on transportation infrastructure offer several key benefits. These include maintaining safe surface conditions through automated systems, reducing the use of harmful chemicals and their environmental impact, and prolonging the lifespan of the infrastructure itself.

Hydronic systems can harness solar energy during the summer and store it seasonally through geothermal heat storage for later extraction (Figure 1). By utilizing renewable resources and incorporating efficient energy storage technologies, these systems can significantly reduce primary energy consumption. Within this context, shallow geothermal energy (SGE) stands out as a highly effective alternative to conventional energy sources, particularly for seasonal storage and subsequent energy retrieval.

Ground-source, de-icing, snow-melting, and ice-prevention systems typically function as closed-loop configurations. These systems comprise several key components: the heat transfer fluid, the network of piping embedded in the paved surface, the heat pump, pipe loops for circulation in the ground, and sensors to monitor real-time weather conditions. These elements are managed by a centralized control system to ensure efficient and responsive operation.

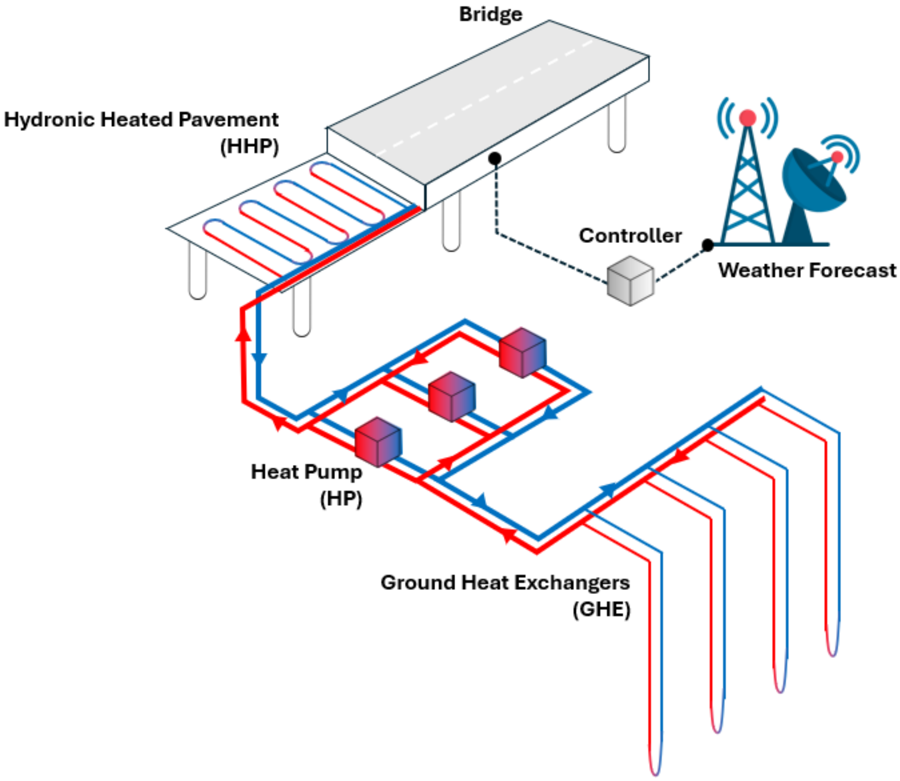


Figure 1. Diagram of a hydronic heated pavement system installed on a bridge.

This report examines the potential of numerical models in reproducing the operational behaviour of the ground source de-icing and snow melting systems by exploring documented case studies of prototypes alongside their associated numerical modelling. Specifically, **it focuses on identifying the**

key elements and methodologies adopted for the calibration and validation of numerical models, with a strong emphasis on the **strategies to ensure their precision and dependability**. To assist in identifying the key modelling aspects for this purpose, technical fact sheets have been prepared for 4 selected case studies.

5.2 CAPABILITIES OF NUMERICAL MODELS

A wide range of numerical models have been developed for simulating the thermal and mechanical performance of de-icing geothermally heated bridge decks and pavements (refs. Report D2.1). Generally, they aim to include in a single model the various components of the analysed system including, the heating system (i.e., pipe loop, heat transfer fluid, etc…), the structural elements (i.e., deck, paved surface, etc…), the surrounding soil volume, and boundary elements (e.g., climatic conditions, inlet/outlet temperatures, etc…), the ground-source system for exploitation or storage (Borehole Heat Exchangers, Energy Piles, etc…).

These models vary in their complexity (i.e., 1D to 3D) and account for both steady-state and transient conditions, incorporating initial and boundary conditions defined by specific operational or environmental scenarios. The earliest numerical models, recommended by ASHRAE (Vaughn, 2018), were 1D steady-state methods. These models were designed to calculate the heat flux required for snow melting on bridge or pavement surfaces (Chapman & Katunich, 1956). Ramsey et al. (1999) developed a 1D steady-state model based on energy balance to calculate the heat flux at the top surface of a bridge deck or pavement. However, their model did not account for intermittent system operations or dynamic weather conditions. Additionally, some of the initial studies focused on developing transient models (Leal & Miller, 1973). A comprehensive review of these models is reported in the report D2.1 "The state of the art in system modelling and design load assessment" of the Task 38- "Ground Source De-Icing and Snow Melting Systems for Infrastructure".

Advancements in computational tools have enabled the development of 3D numerical models capable of accurately representing geometrical properties and heat transfer mechanisms within bridge decks. These models are particularly effective in capturing the interactions at the interfaces between different materials and their surrounding environments. However, to ensure their accuracy and reliability, it is crucial to address the challenge of calibrating and validating these models against experimental data and real-world conditions.

This review examines strategies for model calibration and validation, drawing insights from four recently published reference case studies that represent distinct applications and configurations of ground-source de-icing systems. These case studies were carefully selected to provide a comprehensive overview of different structural types, modelling approaches, and validation methods. Specifically:

- Two studies focus on bridge decks, investigating hydronic heating systems with different operational conditions and system configurations. These studies provide insights into the thermal performance of bridge deck de-icing and highlight key factors affecting energy efficiency.

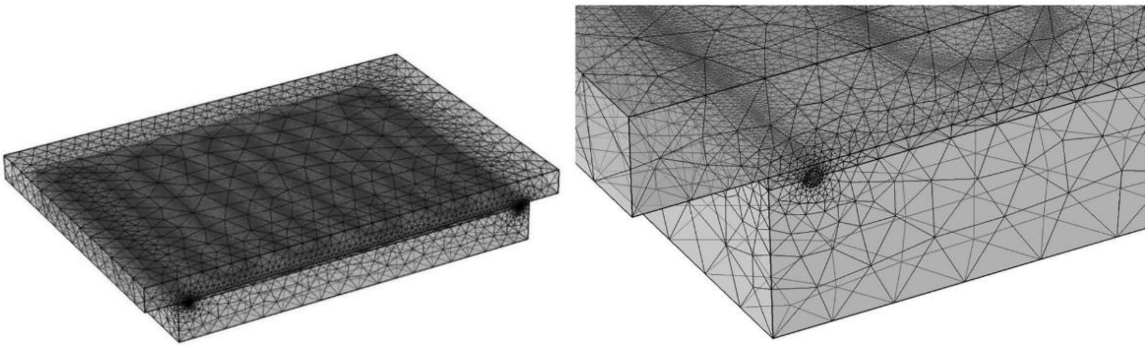
- One study analyzes an asphalt pavement system, exploring the feasibility of shallow geothermal energy for snow melting and evaluating the system's thermal response under varying climatic conditions.
- One study examines energy piles with a thermo-mechanical modeling approach, emphasizing the interplay between thermal energy extraction and structural behavior in foundation systems.

These studies were chosen because they combine experimental, analytical, and numerical investigations, using lab-scale prototypes and advanced simulation techniques to validate model performance. Additionally, they offer a diverse range of temperature supply conditions, spanning from low-temperature systems (~40°C) to high-temperature applications (~100°C), which further enhances the comparative assessment of different system configurations.

A detailed breakdown of these case studies, including their distinctive aspects, is provided in the Appendix D2.1 and summarized below, with a particular focus on model capabilities and validation approaches. To further clarify their unique characteristics, a schematic representation of the case studies is included, highlighting their key differences in system configuration, structural type, and operational parameters.

Figure 2. Location of the selected case studies, withing the global database (described in report D2.1).

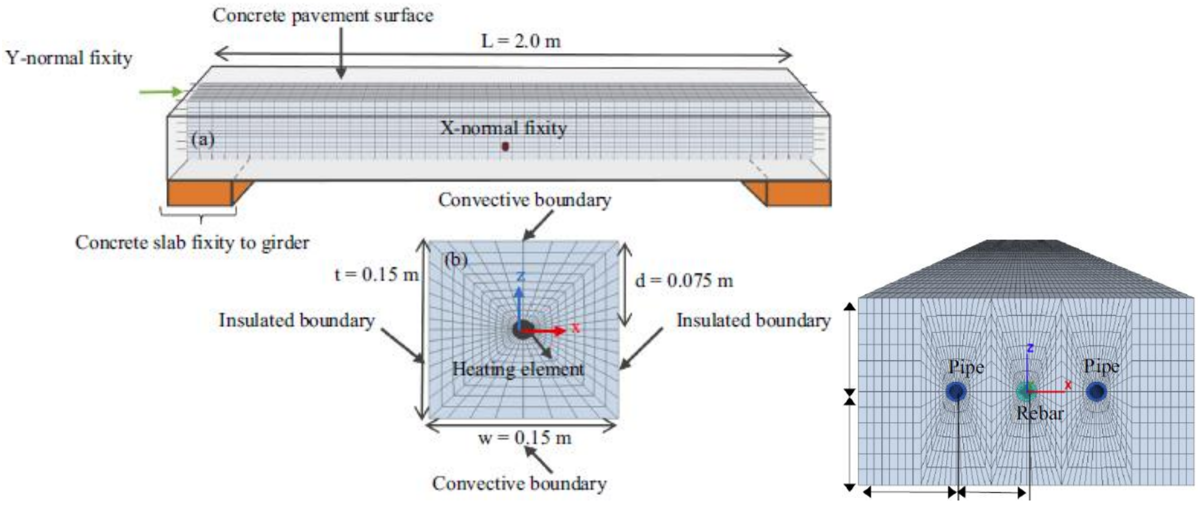
1) Li et al. (2020) developed a 3D Finite Element (FE) model of an externally heated deck in COMSOL Multiphysics (Figure 3), and its transient simulation was calibrated using the experimental results acquired in the laboratory prototype. The calibrated FE model was further validated using steady-state results from 15 environmental chamber tests. The FE model facilitated a comprehensive analysis of the heat transfer mechanisms and energy balance.



(a) *(b)*

Figure 3. Finite element mesh of the bridge deck model: (a) Entire slab; (b) Zoom of pipe elements (from Li et al., 2020).

2) Mehrabi et al. (2022) presented a novel thermo-mechanical assessment of a heated bridge deck subjected to cyclic internal thermal loads implemented through three different heating elements: pipe, cable, and rebar. A new finite difference based numerical model was developed and calibrated against small scale laboratory experiments (Figure 4). The primary goal of this study is to gain a fundamental understanding of the thermo-mechanical behaviour of a large-scale heated bridge deck subjected to internal cyclic thermal loading in HHP and EHP systems. The analysis incorporates realistic mechanical and thermal boundary conditions, along with the effects of thermal degradation on concrete properties.



(a) *(b)*

Figure 4. Schematic of the mesh geometry: (a) Transverse strip, depicting mechanical fixities with X-Z cross-section, depicting thermal boundaries; (b) cross section of the modified deck strip with heated pipe system (from Mehrabi et al., 2022).

3) Chen et al. (2024) developed a numerical model using the ANSYS Fluent module to investigate the impact of pipe spacing, pipe diameter, and fluid flow rate on the heat flux density of asphalt surfaces. The model was validated using experimental data. In real-world road de-icing and snow-melting applications, numerous variable and uncontrollable factors contribute to the complexity of thermal convection, conduction, and radiation on the road surface and the environment. To address these challenges, the study considered both controlled indoor experiments and practical engineering scenarios, particularly in simulations of geothermal fluid circulation heating for road surfaces. Recognizing the susceptibility of smaller road systems to boundary condition influences and temperature instability in concrete, several assumptions were made:

- The thermal properties of the circulating fluid, heat exchange pipes, concrete, and aluminum foil tape are isotropic; the fluid is incompressible and flows steadily.
- Contact thermal resistance between the heat exchange pipes and both the concrete and aluminum foil tape are neglected.
- The initial temperatures of the concrete, heat exchange pipes, and aluminum foil tape are assumed to be equal.
- Boundary and bottom temperatures of the concrete are constant, and the surface boundary is treated as a convective boundary. Solar radiation is disregarded as the experiment was conducted in a cold storage facility.
- The effect of air humidity on surface temperature rising is ignored.

The heat transfer process in the model is represented as a three-dimensional, unsteady-state conduction process, with the k-epsilon (k-ε) turbulence model selected for heat transfer control.

4) The primary objective of Zhou et al. (2024) was to investigate the thermal effects of energy piles on system performance using a simplified model of an energy pile-reinforced foundation beneath an embankment (Figure 5). Their proposed model incorporates the thermo-mechanical stress–strain behaviour of both the piles and foundation soil, focusing on stress continuity and settlement compatibility between the embankment, reinforced foundation, and underlying soil. The study examines how thermal variations influence load-transfer behaviour in pile-supported embankments. Validation of the model is conducted through comparisons with numerical simulations. A simplified 2D axisymmetric finite element (FE) model, developed using Plaxis 2D, is employed to simulate the energy pile-supported embankment within a unit-cell framework.

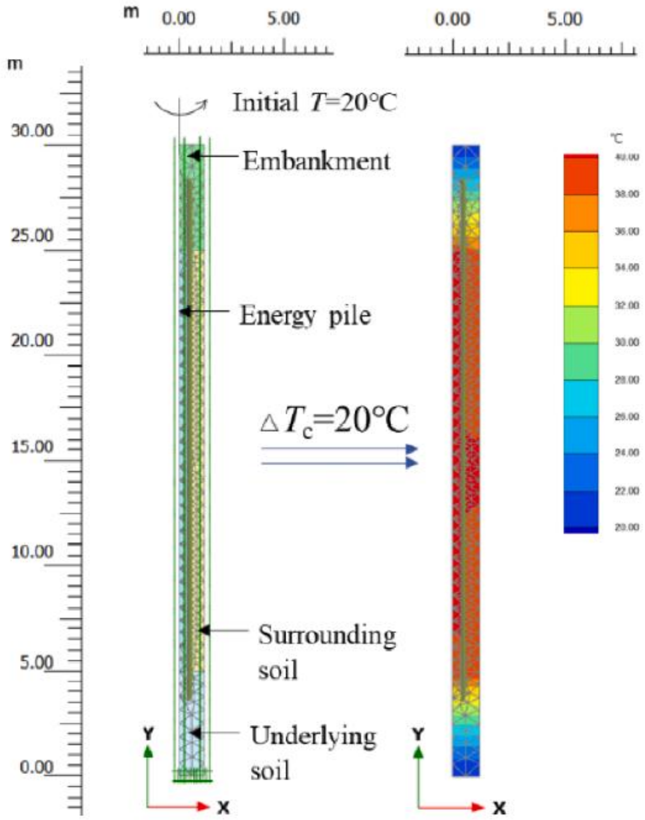


Figure 5. Mesh of Plaxis modelling for the pile and the embankment (from Zhou et al., 2024).

In the following sections, each case study will be examined in detail, with a particular focus on the modelling approach used for thermal exchange processes, followed by an analysis of the strategies employed for model calibration and validation.

5.3 HEAT TRANSFER PROCESS MODELS

A thorough understanding of the heat transfer mechanisms in a hydronic de-icing or snow-melting system is essential for developing an accurate and practical model. In this section, various approaches in modeling heat transfer processes in hydronic de-icing and snow-melting systems will be examined. The objective is to gain a broader understanding of the different methods, allowing for a comparison of their strengths and limitations. By analyzing these diverse approaches, the aim is to identify the most effective strategies for accurately modeling heat transfer mechanisms and to better understand their potential applications and challenges.

Li et al. (2020) investigated the heat transfer processes occurring along the pathway from the fluid inside the pipes to the bridge deck surface. These processes encompass several stages: fluid-solid conduction at the pipe wall, conduction through the pipe material, thermal contact resistance at the pipe-to-deck interface, and conduction through the concrete slab (Figure 6). At the interface between the concrete and the air, various mechanisms come into play, including convection, phase changes of ice or snow, thermal radiation, and solar radiation. Within the solid domains—comprising the concrete slab, pipes, and geofoam block—conductive heat transfer predominates, occurring both within and between the circulation tubes, the concrete slab, and the geofoam block. Furthermore, conduction occurs between falling precipitation and either the bridge deck surface or any accumulated precipitation on it.

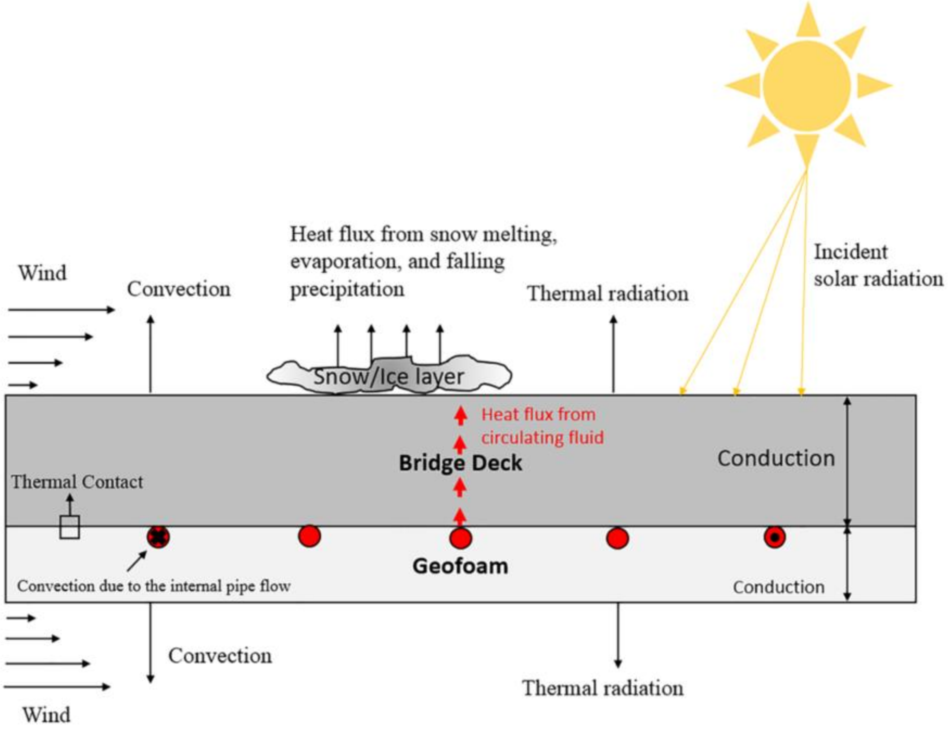


Figure 6. A cross-sectional view illustrating the heat transfer mechanisms in an externally heated bridge deck (Li et al., 2020).

The **conduction** heat transfer can be evaluated by the following equations:

$$\rho C_p \frac{\delta T}{\delta t} + \nabla \cdot \boldsymbol{q} = Q \tag{1}$$

$$\boldsymbol{q} = -k \cdot \nabla T \tag{2}$$

Heat transfer in the water flow along the pipe is governed by **convection**. The fluid flow problem is addressed using the momentum and continuity equations proposed by Barnard et al. (1966). To account for convection heat transfer within the water, three additional terms are incorporated into Eq. (1), refining the energy balance to describe the fluid temperature field, as expressed in Eq. (3). The coupled heat transfer between the fluid and solid domains is solved using the conjugate heat transfer approach available in COMSOL.

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p \boldsymbol{u} \cdot \nabla T = \alpha_p T \left(\frac{\delta p_A}{\delta t} + \boldsymbol{u} \cdot \nabla p_A \right) + \tau : S + \nabla \cdot (k \cdot \nabla T) + Q \tag{3}$$

The third heat transfer mechanism evaluated in this study is **thermal contact resistance**, which reflects temperature variations caused by conductive heat transfer across the air-filled gaps at the interface between two solid materials. These gaps result from surface roughness, typically filled with air. In COMSOL, thermal contact is modelled using the concept of "micro-contact heat transfer," incorporating parameters such as microhardness, surface roughness, surface roughness slope, microscopic distance between mean planes, and gas rarefaction. However, to simplify the analysis, this study excludes these micro-scale parameters. Instead, the interface between the cement layer's top surface and the concrete slab's base is treated as a "pseudo-material" with negligible thickness and significantly lower heat transfer efficiency than concrete or cement paste. Thermal contact behaviour is evaluated solely using the constriction conductance (h_c) and gap conductance (h_g) parameters, defined as inputs in COMSOL.

External convection in this study is induced by air circulation from a fan in the evaporator coil within the environmental chamber, simulating the effects of external wind on the bridge deck. The heat flux at each exposed surface of the bridge deck can be determined, enabling further heat flux analysis and validation of the model against experimental data, using Eq. (4):

$$q_0 = h(T_{ext} - T_s) \tag{4}$$

where h is the convection heat transfer coefficient [W/m^{2}K], while T_{ext} and T_s are the external surrounding and the surface temperatures [°C], respectively. The energy from **radiation** is emitted in the form of electromagnetic waves of all surfaces with a finite temperature. All surfaces of a bridge deck experience radiation heat transfer that is affected by surface emissivity and is dependent upon materials. The energy exchange, in the form of radiation, between the bridge deck and the environment can be expressed in Eq. (5):

$$-\boldsymbol{n} \cdot \boldsymbol{q} = \varepsilon\sigma(T_{sky}^4 - T_s^4) \tag{5}$$

where ε is the surface emissivity of the concrete bridge deck, σ is the Stefan-Boltzmann constant, and T_{sky} is the sky temperature [°C]. In this study, the sky temperature was set equal to the room temperature, and the effects of solar radiation were not considered, as the bridge deck was tested inside an environmental chamber. The conjugate heat transfer module was employed to couple heat transfer and fluid flow through a multiphysical interface. A transient model was used to analyse the time-dependent heating processes, while a steady-state model was applied to determine the final equilibrium temperature.

Mehrabi et al. (2022) assumed isotropic heat **conduction** as the main heat transfer mechanism. The primary factors influencing thermo-mechanical stresses and strains are temperature and the three components of heat flux. These variables are interconnected through the energy balance equation and governed by Fourier's law of heat conduction. A one-way coupling scheme was implemented, in which temperature gradients influence mechanical strains and stresses, but the latter do not affect temperature changes. The general equation describing temperature variations in concrete is expressed in Eq. (6):

$$-q_{i,i} + -q_v = \rho C_v \frac{\delta T}{\delta t} \tag{6}$$

where q_i [W/m^2] is the heat-flux vector; q_v [W/m^3] is the volumetric heat-source intensity; ρ [kg/m^3] is the mass density of the medium; and C_v [J/kg° C] is the specific heat at constant volume.

The mechanical response of an isotropic elastic continuum subjected to thermal loading is expressed as Eq. (7):

$$\sigma_{ij} = E_o/(1+\vartheta)\left(\varepsilon_{ij} - \alpha_t T\delta_{\ ij}\right) + \frac{E_o\vartheta}{(1+\vartheta)(1-2\vartheta)}\left(\varepsilon_{kk} - 3\alpha_t T\right)\delta_{\ ij} \tag{7}$$

where σ_{ij} [Pa] and ε_{ij} are thermal-induced stresses and strains respectively, ϑ is the Poisson ratio of the material, E_o [Pa] is the original elastic modulus of the body, α_t [$^\circ$C^{-1}] is the linear thermal expansion coefficient of the solid matrix, and δ_{ij} is the Kronecker delta. In this study, concrete failure was modelled using the Mohr-Coulomb yield criterion. The stress state on the failure envelope is governed by a non-associated flow rule in the case of shear failure and an associated flow rule in the case of tensile failure.

Chen et al. (2024) modelled the heat transfer through a three-dimensional, **unsteady-state conduction** process. The k-epsilon (k-ε) turbulence model has been selected for heat transfer control. The relevant equations are presented as follows:

$$\frac{\delta\rho}{\delta t} + \nabla\cdot(\rho\boldsymbol{u}) = 0 \tag{8}$$

$$\frac{\delta(\rho u)}{\delta t} + \nabla\cdot(\rho\boldsymbol{uu}) = -\nabla p + \nabla\cdot(\mu\nabla\boldsymbol{u}) + \nabla\cdot(\tau_t) + \boldsymbol{F} \tag{9}$$

$$\frac{\delta(\rho E)}{\delta t} + \nabla\cdot[\boldsymbol{u}(\rho E + p)] = \nabla\cdot\left(k_{eff}\nabla T\right) + \Phi \tag{10}$$

The following assumptions were made in this study: *1*) The thermal properties of the circulating fluid, heat exchange pipes, concrete, and aluminium foil tape are isotropic. The circulating fluid is assumed to be incompressible and flows in a steady-state regime; *2*) Thermal contact resistance between the heat exchange pipes and the concrete, as well as between the pipes and the aluminium foil tape, is neglected; *3*) The initial temperatures of the concrete, heat exchange pipes, and aluminium foil tape are assumed to be identical; *4*) The boundary and bottom temperatures of the concrete are considered constant, while the surface boundary is treated as a convective boundary. Solar radiation is excluded due to the experimental setup being conducted in a cold storage environment; *5*) The effect of air humidity on the temperature rise of the road surface is neglected.

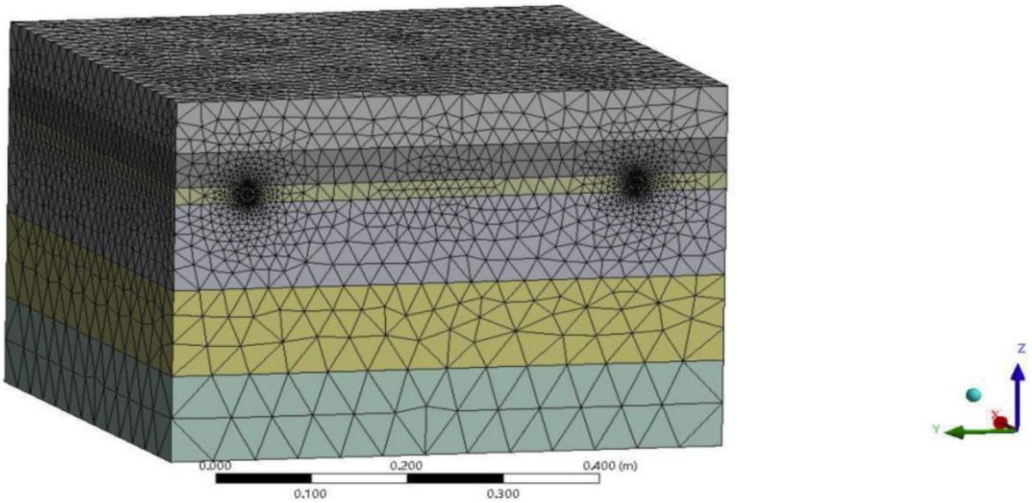


Figure 7. A schematic diagram of numerical model meshing (Chen et al., 2024).

In the computational model proposed by Zhou et al. (2024), the following assumptions were made:

I. Heat transfer is analyzed within the piles and the surrounding soil, while temperature variations in the embankment and the underlying soil are neglected.
II. The dissipation of pore water pressure and its effects on pile deformation are excluded.
III. A unit cell model is employed to represent the effective influence zone of an energy pile within a group.

It is assumed that temperature changes in the surrounding soil equilibrate with those in the piles when a thermal load is applied for a sufficiently long duration. The fundamental properties of the foundation soil are considered unaffected by temperature variations. The unit cell modeling approach for the reinforced foundation associates each pile with a corresponding effective influence zone. When all energy piles in a group are operational, this influence zone is utilized to simulate heat transfer interactions among the piles. For an isolated unit cell, its boundary is treated as a no-heat-flux boundary.

Traditional heat transfer models, such as the line source model (Man et al., 2010) and the semi-analytical isolated infinite heat source model (Bergman et al., 2011), are applied to analyze heat transfer for a single pile under the assumption of an infinite heat transfer zone. The temperature field is presumed to extend radially from the pile shaft into the surrounding circular soil. Additionally, the following assumptions are made:

- The heat exchanger has infinite length.
- The thermal properties of the soil are uniform, isotropic, and invariant with temperature.

Under these conditions, the temperature distribution in the surrounding soil mass can be expressed as:

$$\frac{\partial^2\theta}{\delta r^2}+\frac{1}{r}\frac{\delta\theta}{\delta r}=\frac{1}{a}\frac{\delta\theta}{\delta t}\ (r_c \le r \le r_{e,}\ t > 0) \tag{11}$$

where, a is the thermal diffusion coefficient, and $a=\frac{\lambda}{C}$, λ is the thermal conductivity coefficient, C is the volumetric heat capacity, and $\theta(r,t)$ is the excess temperature at any point of the soil mass, $\theta = T - T_0$; T and T_0 is the temperature after and before applying thermal load. At a given time t_0, the temperature distribution in the soil surrounding a single pile, as predicted by traditional line source models, and the temperature distribution in the soil within the unit cell are illustrated in Fig. 8a:

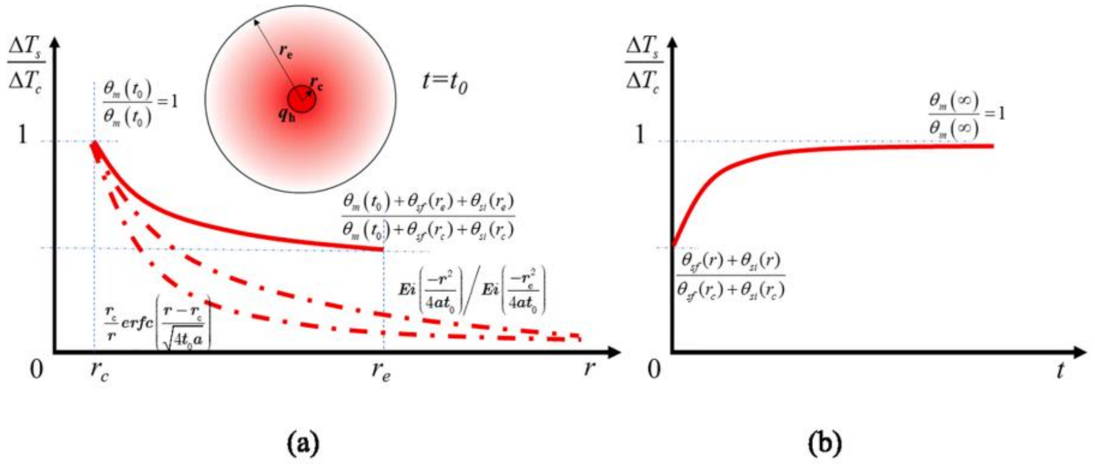


Figure 8. Diagram showing the temperature distribution as a function of radial distance and time. (Zhou et al., 2024).

It can be observed that, after a sufficiently long period, the temperature change of the pile and the surrounding soil ($\triangle Ts$) within the effective zone converges to the same value (as shown in Fig. 8b). To simplify the analysis, this uniform temperature change in the pile and soil is assumed to evaluate the thermally induced behaviours of the foundation.

5.4 CALIBRATION AND VALIDATION PROCEDURES

The aim of this paragraph is to critically review different adopted approaches used for the calibration and validation of the numerical models simulating the operating of ground source HPPS. Among the collection described in the D2.1, the 4 selected case studies already presented in the previous sections referring to both numerical modelling and laboratory testing, constitute a valuable collection to discuss the strategies adopted.

- **Case Study N-01**

Li et al. (2020) conducted an integrated numerical and experimental study to validate a heat transfer model for a small-scale bridge deck, incorporating heating tests performed within a controlled environmental chamber at the University of Texas at Arlington (Figure 9).

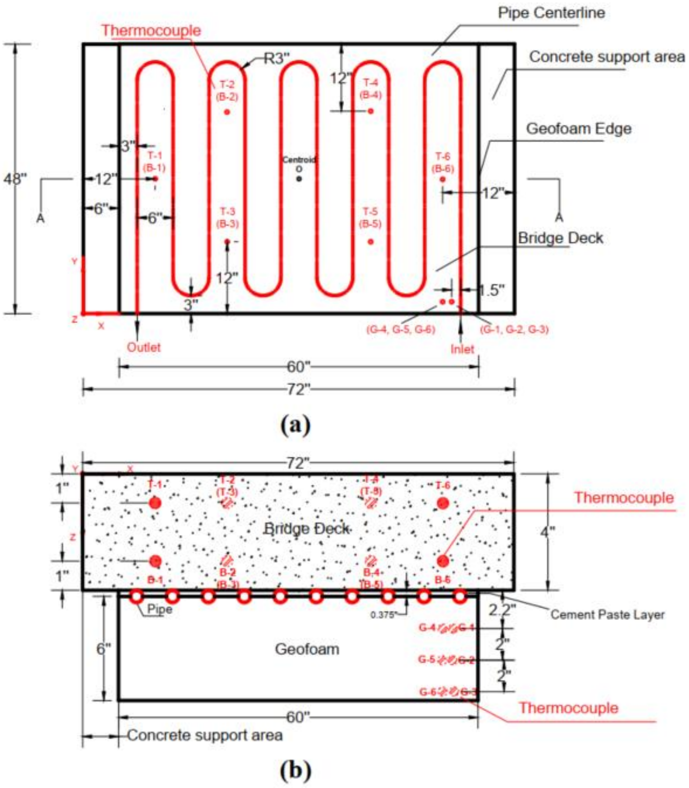


Figure 9. A schematic diagram of the experimental prototype with location of sensors in the concrete slab (Li et al., 2020)

Experimental Setup and Methodology

The experimental program utilized a small-scale bridge deck installed in an environmental chamber at the University of Texas at Arlington, capable of maintaining a minimum temperature of 4.4 °C (40 °F) (Figure 9). Sixteen heating tests were performed under different combinations of water and ambient temperatures. Key aspects of the setup include:

1. **Controlled Initial Conditions.** The concrete slab was first cooled to equilibrium with the chamber temperature, while the water tank was heated to a desired temperature (*e.g.*, 21.1 °C). The water pump was then activated to circulate warm water through the deck until a steady state was achieved.
2. **Validation with Numerical Modeling.** The COMSOL software was employed to develop a FE model and simulate the thermal behavior of the bridge deck. Experimental inlet and ambient temperatures were used as input parameters to ensure consistency between the laboratory and numerical conditions.
3. **Time-Dependent Measurements.** Thermocouples installed in the deck and surrounding geofoam provided time-resolved temperature data, which were compared with the transient and steady-state results of the numerical model (Figures 10–13).

Key Observations from the Study

1. **Agreement Between Numerical and Experimental Results**. The study reports a close alignment between numerical simulations and laboratory measurements for inlet and ambient temperatures, as well as for thermocouple responses at various locations within the deck and geofoam. However, some discrepancies were noted, particularly during the initial heating phase.
2. **Impact of Material Assumptions on Results.** Discrepancies between experimental and numerical results are attributed to assumptions made in the numerical model:
    - **Homogeneity of Materials:** COMSOL assumes uniform thermal conductivity, whereas the experimental materials exhibit inherent heterogeneity and porosity, leading to localized variations in heat transfer.
    - **Air Gaps:** Resistance from air gaps between the cement paste and the concrete slab in the experimental prototype may have slowed heat transfer, creating differences in initial heating rates.
3. **Geometric and Material Variations.** Deviations in the geometry of the heating loop from its design could have introduced additional variations between the experimental and numerical results.
4. **Steady-State Comparison.** At steady state, the differences between numerical and experimental results were less pronounced, particularly for thermocouples installed deeper within the slab (*e.g.*, B-1 to B-6). This suggests that the numerical model is effective in capturing the long-term thermal behavior of the system.

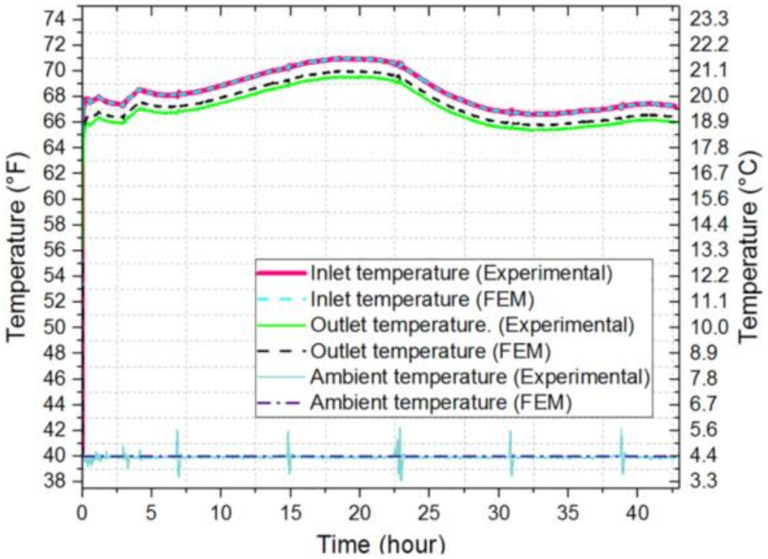


Figure 10. Comparison of laboratory and numerical results for inlet, outlet, and ambient temperatures (Li et al., 2020).

Observations on Methodology and Applications

- **Strength of Validation Approach.** The combination of experimental testing and numerical modeling provides a robust framework for evaluating heat transfer performance. Time-resolved comparisons at multiple thermocouple locations enhance confidence in the model's predictive capabilities.

- **Limitations in Numerical Assumptions.** While the numerical model simplifies the representation of material properties and interface resistances, these assumptions highlight the need for further refinement to improve the accuracy of transient predictions.
- **Practical Implications.** The study demonstrates the utility of the numerical model for simulating heat transfer in bridge decks under controlled conditions. This capability is crucial for optimizing heating designs in cold climates, particularly for snow and ice removal applications.

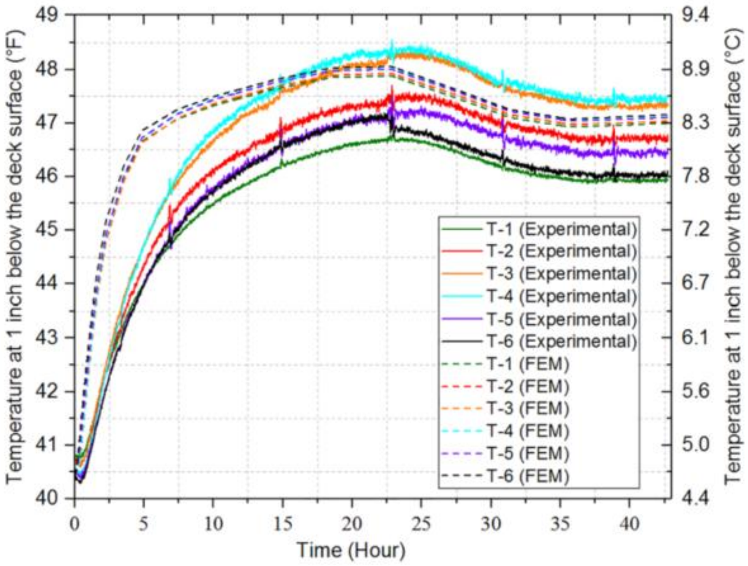


Figure 11. Comparison of temperature responses from experimental data and numerical analyses for thermocouples T-1 to T-6 (Li et al., 2020).

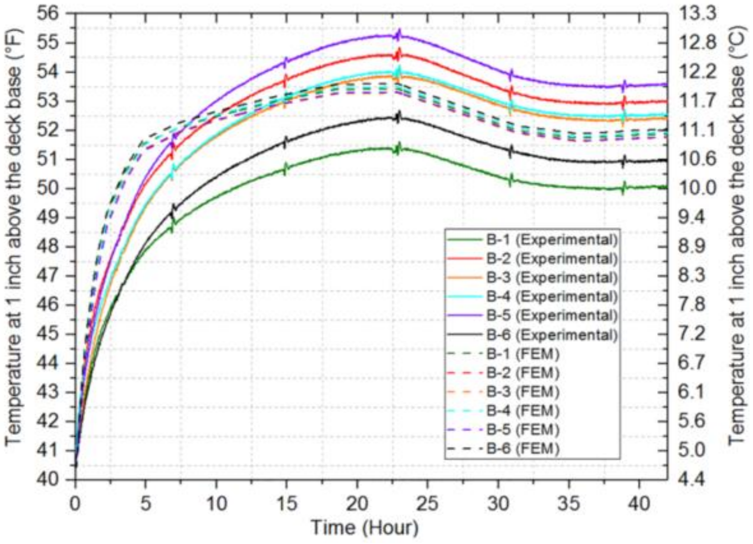


Figure 12. Comparison of experimental results and numerical analyses final temperature responses for thermocouple set B-1 to B-6 (Li et al., 2020).

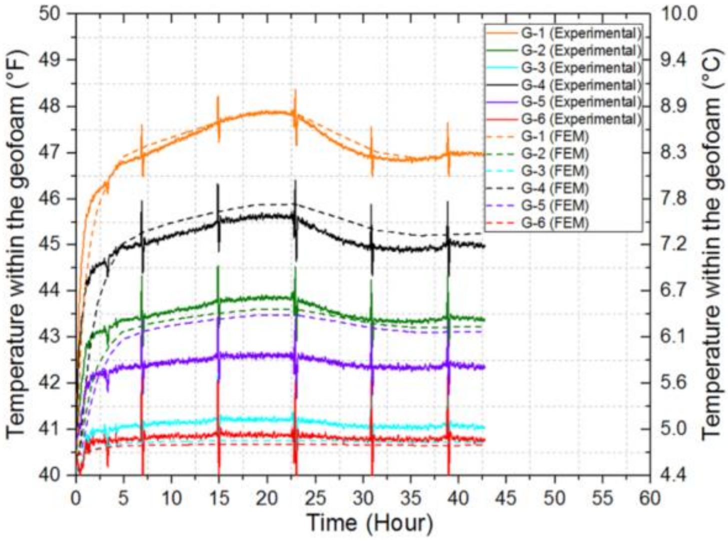


Figure 13. Comparison of experimental results and numerical outputs of final temperature responses for thermocouple set G-1 to G-6 (Li et al., 2020).

- **Case Study N-02**

Mehrabi et al. (2022) conducted a comprehensive thermo-mechanical assessment of a heated bridge deck subjected to cyclic internal thermal loads applied through three different heating elements: pipes, cables, and rebars. Their study combines experimental and numerical methods, with a finite difference-based numerical model calibrated against laboratory experiments. This dual approach provides a detailed understanding of the thermal and mechanical responses of concrete under internal heating conditions.

Experimental Setup and Methodology

The laboratory experiments involved a cylindrical concrete specimen, 150 mm in diameter and 300 mm in length, with a 400 mm long, 16 mm (US #5) rebar embedded longitudinally at its center (Figure 14). Key aspects of the experimental protocol include:

1. **Heating and Measurement Configuration**
   - Boiling water (100 °C) served as the heat source, directly heating the rebar through immersion in a steel pot.
   - Type-K thermocouples measured the temperature distribution over time, with five thermocouples embedded near the rebar-concrete interface and five placed along the outer surface of the cylinder. Additional thermocouples monitored the temperature of the rebar and heating water.
2. **Heating-Cooling Protocol**
   - The rebar was initially immersed in room-temperature water (21 °C).
   - Over 30 minutes, the water temperature was ramped to 100 °C and maintained for 2.5 hours, followed by natural cooling to room temperature.

3. **Monitoring and Data Collection.** Temperature histories were recorded to assess heat transfer behavior and temperature distribution within the specimen during both the heating and cooling phases.

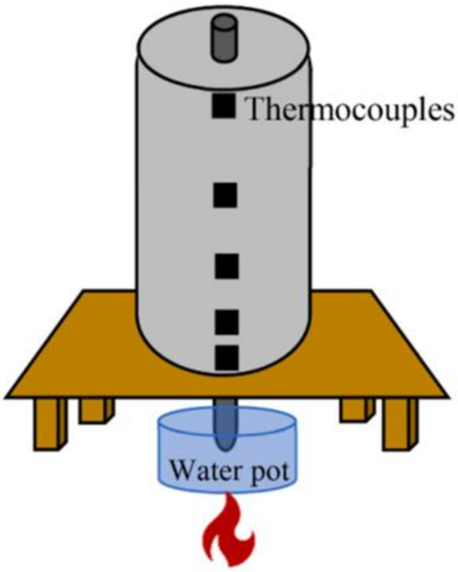


Figure 14. Schematic of experimental setup (Mehrabi et al., 2022).

Numerical Modeling and Calibration

The finite difference-based numerical model was developed to replicate experimental conditions. The calibration phase focused on determining accurate thermal properties by simulating the cylindrical specimen's behavior under identical conditions. Key elements of the modeling include:

1. **Material Properties and Heat Transfer Parameters**
   - Thermal properties such as linear thermal expansion, specific heat, and thermal conductivity for both concrete and steel rebar were incorporated.
   - Convective heat transfer coefficients accounted for heat exchange between the concrete and the environment.
2. **Boundary and Initial Conditions**
   - The ambient lab temperature (21 °C) was set as the initial condition.
   - The temperature variation recorded by thermocouple "TR-0" was applied as a heat flux source.
3. **Calibration and Validation**
   - Temperature readings from the numerical model were compared against experimental data at multiple locations (*e.g.*, rebar-concrete interface and external surface).
   - Calibrated thermal properties were cross validated with values from published literature to ensure consistency.

4. **Results.** The temperature profiles from the calibrated model closely matched the experimental results (Figures 15a and 15b), indicating reliable simulation of the thermal response during both heating and cooling phases.

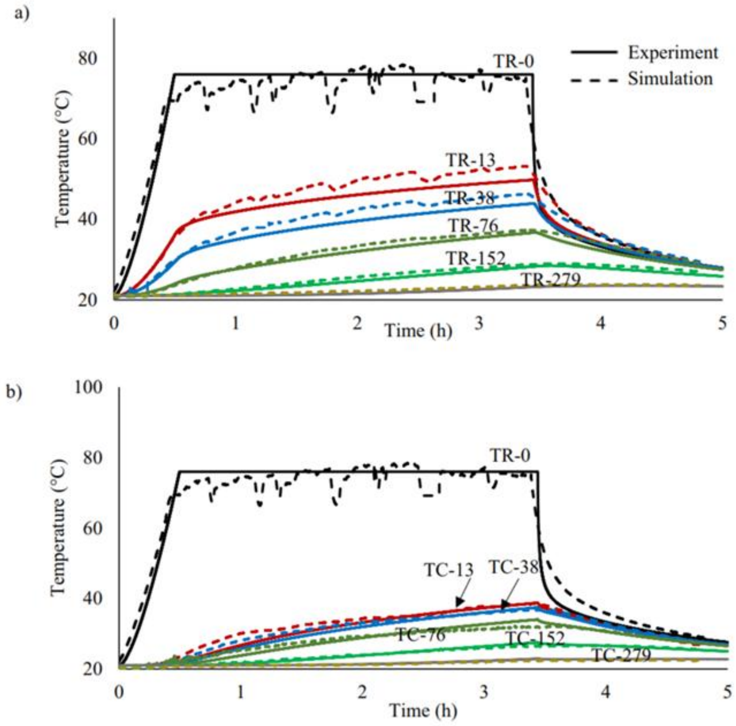


Figure 15. Temperature histories: (a) along rebar-concrete interface; (b) along concrete surface (Mehrabi et al., 2022)

Observations on Methodology and Findings

Mehrabi et al.’s approach effectively integrates experimental and numerical methods to capture the complex thermal behavior of concrete subjected to internal heating. The following observations highlight the study's contributions:

1. **Comprehensive Experimental Design**
   - The use of multiple thermocouples along the rebar-concrete interface and the external surface ensures detailed spatial and temporal data on temperature variations.
   - Boiling water as a heat source provides a controlled and replicable environment for testing.
2. **Accurate Calibration of Numerical Model**
   - The calibration process, based on independent temperature data, enhances confidence in the numerical model's ability to replicate real-world scenarios.
   - Cross-referencing thermal properties with literature values further strengthens the model's reliability.
3. **Thermo-Mechanical Insights**

  - The study demonstrates how internal heating affects the temperature distribution within concrete, particularly near the rebar-concrete interface.
  - These findings are relevant for understanding thermal stresses and potential degradation mechanisms in heated bridge decks.

- **Case Study N-03**

Chen et al. (2024) present a detailed experimental and numerical study on road de-icing using a geothermal energy system coupled with a ground source heat pump. The research evaluates the performance of a fluid-circulation heating system integrated into asphalt road surfaces, focusing on temperature distribution, system performance, energy consumption, and optimal design parameters for practical engineering applications.

Experimental Setup and Methodology

The geothermal de-icing system comprises underground heat exchange pipes, a heat pump unit, and embedded heat exchange pipelines within the road (Figure 16). During operation, the system circulates a heat transfer fluid through the pipes to absorb heat from the soil or groundwater and transfer it to the road surface.

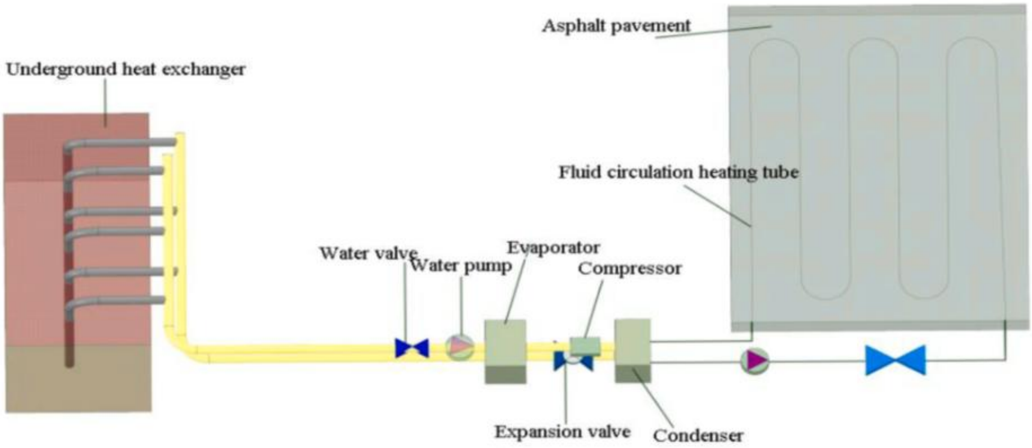


Figure 16. Schematic structure of the road heating system using Geothermal Fluid Circulation (Chen et al., 2024).

Key aspects of the experimental setup include:

1. **Preheating and Ice Melting Tests**
   - The preheating test was conducted under ambient temperatures of -5 °C and -10 °C, with water temperatures of 40 °C and 50 °C. Measurements included the temperature of road layers, supply water, and power consumption over a 6-hour heating period.
   - The ice melting test was performed under ambient temperatures of -2 °C, -5 °C, and -8 °C. A 5 mm ice layer was applied to the road surface, and system performance was monitored during 8 hours of heating.

2. **Instrumentation and Data Collection.** A Keysight temperature measurement device, operating within -40 °C to 125 °C, was used to record temperature profiles, supply water temperatures, and ice melting rates.

Numerical Modeling and Validation

A finite element numerical model was developed to replicate the experimental setup. The model included all key layers of the road system: heat exchange pipes, asphalt, concrete, and aluminum foil tape. Computational refinements included:

1. **Meshing and Accuracy Improvements**
    - Wall surfaces of underfloor heating pipes were finely meshed for higher accuracy.
    - An expansion grid was applied for the circulating fluid, while tetrahedral meshing was used for other structural layers.
2. **Material Properties and Boundary Conditions.** The model incorporated material properties such as density, specific heat capacity, and thermal conductivity, consistent with experimental data. The numerical setup replicated the conditions of the experimental Case 1 (ambient temperature of -5 °C, inlet water temperature of 40 °C).
3. **Model Validation.** The temperature field was validated by comparing simulated and experimental results for temperature points across four layers of the asphalt model. Root Mean Square Errors (RMSEs) for these layers were calculated as 0.78, 0.44, 0.23, and 0.12, indicating good agreement between experimental and numerical data (Figure 17).

Observations and Insights

The study demonstrates the feasibility and effectiveness of geothermal energy systems for road de-icing. Several key observations highlight the strengths and implications of the work:

1. **Comprehensive Experimental Protocol.** The indoor tests provide a controlled environment for evaluating system performance under varying ambient and water temperatures. The inclusion of preheating and ice melting phases allows for a holistic assessment of the system's capabilities.
2. **Accurate Numerical Model.** The numerical model is robust, with RMSE values demonstrating its ability to replicate experimental conditions. The close alignment between simulated and measured data confirms the model's suitability for design and optimization purposes.
3. **Design Recommendations.** The research identifies critical parameters, such as fluid flow rate, inlet water temperature, and pipe arrangement, which influence system performance. These findings can inform practical implementations of de-icing systems.
4. **Energy Efficiency Considerations.** By analyzing power consumption alongside temperature distributions, the study provides insights into the energy requirements for de-icing under different conditions. This is crucial for balancing performance and sustainability.

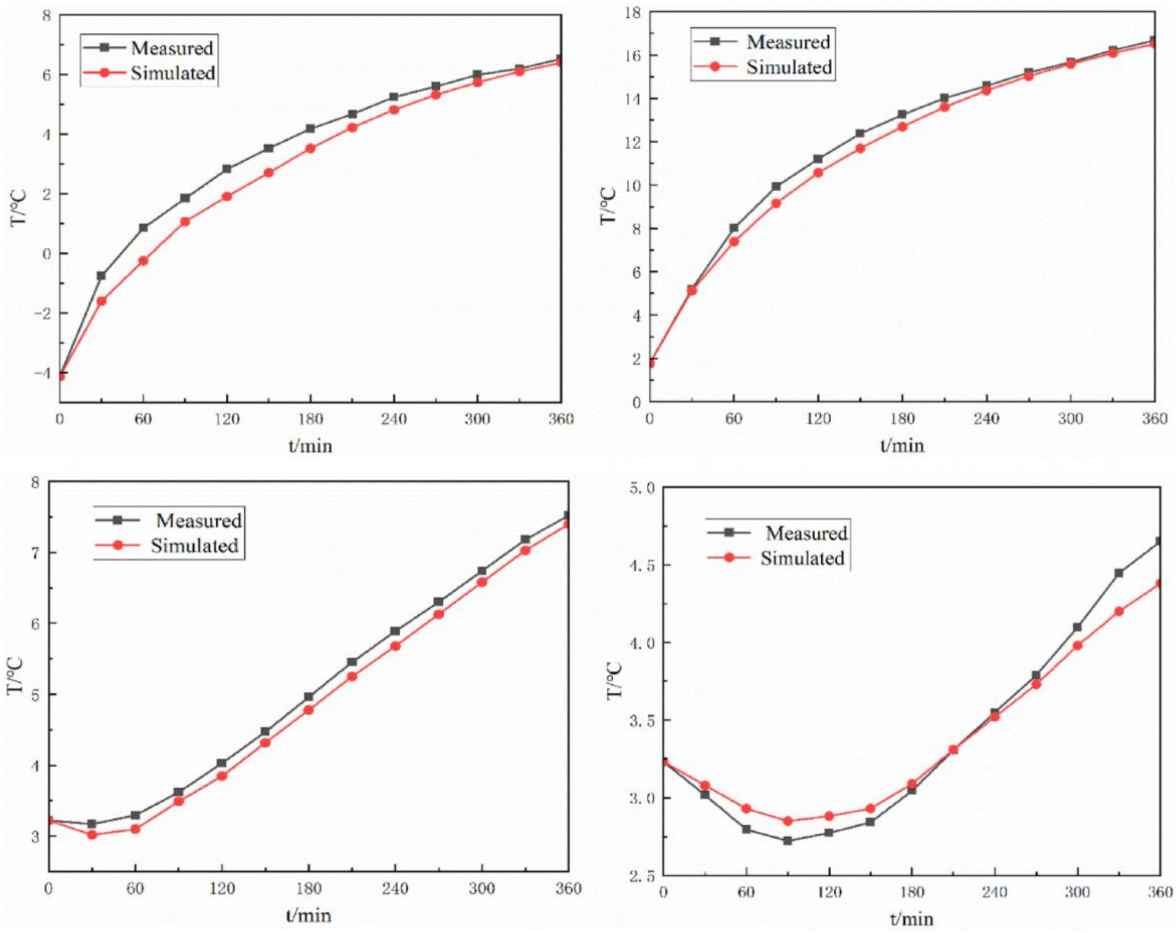


Figure 17. Comparison between experimental and simulated temperature values across the four layers of the asphalt pavement model. (Chen et al., 2024)

- **Case Study N-04**

Zhou et al. (2024) present a simplified analytical model to predict the behavior of energy pile-supported embankments, emphasizing the impact of thermal changes on load transfer and settlement. By integrating thermo-mechanical interactions, stress continuity, and settlement compatibility, the model provides insights into the complex interplay between embankments, reinforced foundations, and underlying soil. The study includes validation against numerical simulations and applies the model to a hypothetical case, demonstrating its utility for analyzing thermal effects in energy pile systems.

Model Framework and Assumptions.

The proposed model is designed to predict key behaviors of energy pile-supported embankments under thermal loading. Major elements include:

1. **Thermo-Mechanical Interactions**. The model incorporates thermal expansion and temperature variations in the soil and pile, allowing for an assessment of their influence on settlement and load distribution.

2. **Simplified Settlement Analysis.** Settlement predictions are based on uniform settlement analysis, providing an efficient yet practical approach to estimating foundation behavior.
3. **Validation through Numerical Simulations.** The model's results are compared to numerical analyses, with normalized settlement, stress profiles, and shear stress distributions showing good agreement with computational outputs.

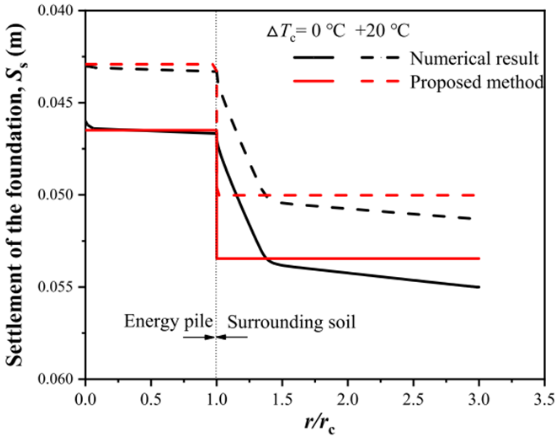
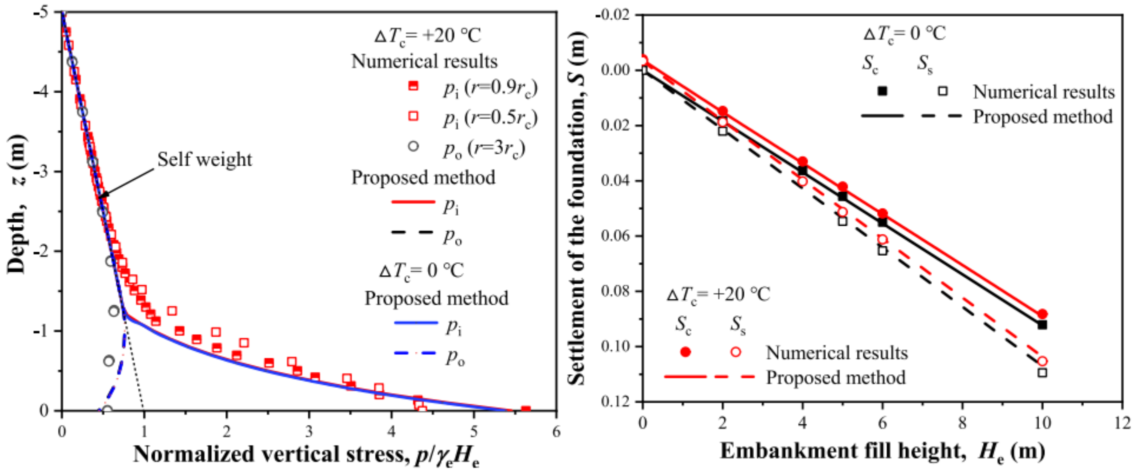


Figure 18. Settlement at the surface of the foundation under 5 m embankment fill. (Zhou et al., 2024)

Key Findings

1. **Settlement and Stress Analysis**
   - Settlement Predictions: The model captures the settlement at the surface of the foundation, with calculated settlements closely matching numerical results. However, a slight discrepancy of approximately 0.009% L_c is observed at the edge of the unit cell, likely due to the uniform settlement assumption.
   - Impact of Thermal Loading: A thermal load of +20 °C reduces foundation settlement by 0.016% L_c, highlighting the potential for thermal effects to influence pile behavior.
2. **Vertical Stress Distribution**
   - The model predicts vertical stress distributions in the embankment fill with reasonable accuracy (Figure 19a). Stress increases above the pile due to the soil arching effect, aligning well with numerical simulations.
   - In the inner cylinder near the pile, vertical stress distributions under thermal loading closely follow the self-weight line, reflecting the influence of thermal expansion.
3. **Shear Stress and Skin Friction.** The model provides insights into shear stress and skin friction along the pile, which also shows strong consistency with numerical predictions. This agreement underscores the reliability of the proposed method for analyzing load transfer mechanisms in energy pile systems.
4. **Embankment Height and Settlement Relationship**. The relationship between settlement and embankment height, as predicted by the model, aligns closely with numerical results (Figure

19b). This consistency demonstrates the model’s ability to capture key trends in foundation behavior.



(a) (b)

Figure 19. (a) Distribution of vertical stress with depth in the embankment fill; (b) Settlement at the foundation surface as a function of embankment fill height. (Zhou et al., 2024)

Observations on Methodology and Application

The research focuses on the interaction between the pile, the soil, and the embankment, considering thermo-mechanical stress. Although the study does not directly address HHP systems, the model's principles can be extended to analyze such systems. In particular, understanding the temperature distribution in the soil and the thermo-mechanical interaction between the pile and the ground can be applied to the design and analysis of heated pavement systems, providing insight into the interactions between hydronic pipes, the surrounding soil, and the pavement itself. The analyses presented on heat transfer and soil deformations are relevant to heated pavement systems, as they may share similar mechanisms of heat transfer and material-soil interactions.

The study’s combination of analytical modeling and numerical validation offers a robust framework for analyzing thermal effects in energy pile-supported embankments. The following observations highlight the study’s contributions and potential extensions:

1. **Strengths of the Model**
   - The simplified framework is computationally efficient, making it suitable for preliminary design applications.
   - By incorporating thermo-mechanical interactions, the model provides a nuanced understanding of the influence of temperature on settlement and load transfer.
2. **Validation and Agreement**
   - The strong alignment between the model’s predictions and numerical results enhances confidence in its accuracy.

- Discrepancies, such as the slight overestimation of settlement at the edge of the unit cell, are minor and stem from inherent simplifications.

3. **Design and Engineering Applications**
    - The model can be applied to optimize energy pile configurations and predict long-term performance under thermal loads.
    - Insights into stress profiles and skin friction are particularly valuable for designing pile systems to withstand combined mechanical and thermal effects.

5.5 CLOSING REMARKS: COMPARATIVE ANALYSIS OF REFERENCE CASES

This report has analyzed four case studies focused on energy pile-supported systems, heated bridge decks, geothermal de-icing systems, and the integration of thermo-mechanical modeling approaches. Together, these studies provide valuable insights into the design, performance, and potential optimization of thermal and thermo-mechanical response of HHP systems. Below, we summarize the key findings and overarching themes identified across the reviewed cases, along with considerations for future research.

KEY INSIGHTS FROM THE CASE STUDIES

1. **Integration of Experimental and Numerical Approaches**. Across the reviewed case studies, numerical models are central to analyzing thermal systems. Advances in computational tools have enabled the development of high-dimensional models (1D, 2D, and 3D) capable of representing complex geometries and heat transfer mechanisms:
   - Case Study N-01 (Li et al., 2020): Time-dependent heating curves in a heated bridge deck were successfully simulated using COMSOL, with discrepancies attributed to material homogeneity assumptions and experimental air gaps.
   - Case Study N-02 (Mehrabi et al., 2022): Calibration of a model for heated bridge decks incorporated thermal degradation effects on concrete. Strong alignment between simulated and measured temperature profiles confirmed the reliability of thermal property assumptions.
   - Case Study N-03 (Chen et al., 2024): A 1:1 numerical model was used to replicate a geothermal road de-icing system, capturing multi-layer temperature distributions. Root mean square errors (RMSE) across asphalt layers ranged from 0.12 to 0.78, validating the model's accuracy for preheating and ice-melting scenarios.
   - Case Study N-04 (Zhou et al., 2024) leverages numerical validation to enhance the reliability of their simplified analytical model for energy pile systems.

This combination ensures that theoretical models remain grounded in real-world behavior, offering both predictive accuracy and practical applicability.

2. **Thermal Behavior and Design Implications.** The studies highlight the dominance of conduction as the primary heat transfer mechanism in geothermal de-icing and snow-melting systems. Thermal processes span multiple domains:
   - **Conduction**: Heat transfer through pipe walls, concrete slabs, and geofoam blocks, conduction governs interactions between circulating fluid and solid materials. For example, in Case Study N-03, conduction facilitated heat transfer within and between the asphalt and underlying layers.
   - **Convection and Contact Resistance**: Secondary mechanisms like convection (within circulating fluid) and thermal resistance at material interfaces, such as pipe-to-concrete junctions, also influence system performance.

  - **Radiation and Precipitation Effects**: Though less emphasized, radiation and heat exchange with precipitation impact surface temperature regulation, as observed in the snow-melting system in Case Study N-01.

3. **Discrepancies and Refinement of Models.** Validation of numerical models often reveals discrepancies with experimental results, providing opportunities for refinement:
  - **Discrepancies Due to Simplifications**: In Case Study N-01, deviations in initial heating rates were linked to assumptions of uniform material properties and thermal conductivity. Similarly, air gaps and geometric variations in experimental setups contributed to errors in early heating predictions.
  - **Calibration Adjustments**: Case Study N-02 refined thermal properties based on independent thermocouple data, ensuring accurate predictions of heat transfer along the rebar-concrete interface.
  - **Boundary Condition Variations**: Assumptions about uniform settlement in Case Study N-03 caused minor differences in predicted settlement patterns but provided a computationally efficient framework for load transfer analysis.

The iterative process of comparing numerical and experimental data ensures robust models capable of addressing real-world complexities.

4. **Practical Applications and System Optimization.** Validated models serve as powerful tools for system optimization and design enhancement:
  - **Pipe Arrangements for Efficiency**: In Case Study N-03, simulations identified optimal pipe configurations to maximize energy efficiency in de-icing systems.
  - **Steady-State Predictions**: Case Study N-01 utilized numerical models to determine steady-state temperatures in heated bridge decks under different operational conditions.
  - **Durability Assessments**: Calibrated models in Case Study N-02 supported durability evaluations of heated concrete under cyclic thermal loads.
  - **Predictive Tools for Load Transfer**: Case Study N-04 provided simplified analytical tools for predicting settlement and stress distributions in energy pile-supported embankments under thermal effects.

These applications highlight the role of numerical modeling in enabling data-driven design decisions, improving system performance, and reducing operational costs.

5. **Validation and Error Considerations.** Discrepancies between experimental and numerical results are observed across studies, often linked to simplifying assumptions:
  - Material homogeneity assumptions (Case Study N-01) and uniform settlement analyses (Case Study N-04) lead to minor deviations but remain within acceptable error margins.
  - Air gaps, thermal resistance, and material heterogeneity emerge as common factors requiring further refinement for improved predictive accuracy.

OVERARCHING THEMES AND FUTURE DIRECTIONS

1. **Dimensional Advances in Numerical Models**. The evolution from 1D steady-state models, such as those used in ASHRAE guidelines (Vaughn, 2018), to modern 3D models has significantly enhanced the ability to simulate material interactions and environmental conditions. Future work should further explore transient scenarios, such as seasonal variations, to capture long-term system behavior.
2. **Coupled Multi-Physical Systems**. Integrating thermal, mechanical, and hydraulic processes into multi-physical models would provide a more comprehensive understanding of infrastructure systems. For example, pore water pressure dynamics could complement the settlement analysis in Case Study N-04.
3. **Field Validation and Scaling**. Extending validated models to field-scale implementations will bridge the gap between laboratory conditions and real-world scenarios. Long-term monitoring of operational systems, such as those studied in Case Studies N-01 and N-02, can provide critical insights into system durability and efficiency.
4. **Energy Efficiency and Sustainability**. As sustainable design becomes a priority, optimizing energy consumption in geothermal and heating systems will remain a focus. Simulations like those in Case Study N-03 demonstrate the potential for reducing energy requirements while maintaining performance.

The reviewed studies collectively highlight the potential of integrating thermo-mechanical systems into infrastructure design, offering insights into energy efficiency, structural performance, and system optimization. By combining experimental validation with advanced numerical modeling, these works lay a strong foundation for future developments. To address current limitations, future research should focus on field-scale validation, multi-physical coupling, and the development of robust design frameworks that prioritize long-term performance and sustainability. This comprehensive approach will ensure that thermo-mechanical systems continue to advance as a cornerstone of modern engineering solutions.

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Summary of Activities for Subtask 2

The objective of **Subtask 2** was to study the **availability, development, and capabilities** of models required for the **design and control** of geothermal energy storage, de-icing, and snow-melting systems. The work aimed at identifying and classifying **different modelling approaches**, focusing on their applicability to **railways, pavements, and bridge decks**. The analysis included a review of model approaches to assess **climatic conditions**, energy demand estimation, geothermal heat sources, and operational parameters.

The activities officially commenced in **November 2022**, with a **delay** compared to other subtasks due to a **change in the Subtask Leader**. Despite an initial delay, **Subtask 2** successfully met its objectives by **compiling and analyzing** key modelling approaches for geothermal energy storage and de-icing systems. This was obtained through participation in key meetings and the preparation of technical reports summarizing state-of-the-art research and model validation techniques.

MEETINGS AND COLLABORATIVE EFFORTS

During the execution of **Subtask 2**, several international meetings were attended, fostering collaboration among research groups and industry stakeholders. The participation included:

- **November 2022** – Attendance at the **Istanbul meeting** to define research goals and identify key modelling methodologies.
- **March 2023** – Organization of the **Perugia meeting**, which focused on discussions regarding database structuring and validation strategies.
- **May 2023** – Participation in the **Antwerp meeting**, where findings from **numerical and experimental models** were reviewed.
- **November 2023** – Final participation in the **Göteborg meeting**, where the conclusive results of **Subtask 2** were presented and discussed with all the expert partners.

These meetings played a **crucial role** in shaping the direction of **model assessment**, ensuring that the selected methodologies aligned with real-world applications.

Summary of Activities from Deliverable 2.1: The State of the Art in System Modelling and Design Load Assessment

This report provided a **comprehensive review of modelling techniques** used for geothermal energy storage and **hydronic heating pavement systems (HHPS)**. The key activities included:

- **Compilation of over 20 case studies** from literature, covering numerical modelling, laboratory experiments, and full-scale prototypes.
- **Definition of models for climatic conditions,** crucial for system performance evaluation and control.
- **Classification of modelling approaches for HPPS,** including steady-state and transient simulations**.**
- **Assessment of geothermal heat sources,** such as Borehole Thermal Energy Storage (BTES), Ground Heat Exchangers (GHE), and Aquifer Thermal Energy Storage (ATES).

- **Selection of operational parameters,** with an emphasis on optimizing system efficiency for different infrastructure types.

This deliverable laid the groundwork for understanding **design constraints and thermal load requirements**, helping to refine future modelling strategies.

Summary of Activities from Deliverable 2.2: Assessment of Model Capabilities and Validation Processes

The **second deliverable** focused on **model calibration and validation**, ensuring that numerical models could accurately **simulate real-world geothermal de-icing and snow-melting systems**. Key activities included:

- **Selection of four reference case studies**, each representing a different structural type and modelling approach:
    - Two **bridge deck models** (hydronic heating systems under different operational conditions).
    - One **asphalt pavement model**, analyzing the thermal response to shallow geothermal energy.
    - One **energy pile model**, examining thermo-mechanical interactions in foundations.
- **Numerical Models**: Various numerical models have been developed to simulate the thermo-mechanical performance of snow and ice melting systems. These models vary in scale (1D, 2D, 3D) and account for both steady-state and transient conditions. Three-dimensional models are particularly effective in capturing interactions between different materials and the surrounding environment.
- **Calibration Processes**: Calibration and validation of numerical models are essential to ensure their accuracy and reliability. These processes involve comparing numerical simulation results with experimental data and prototype outcomes using parameters such as temperature profiles, energy consumption, and root mean square error (RMSE). Discrepancies between numerical and experimental results were analysed to refine the models and improve their accuracy. The *D2.2* document examines four specific case studies to illustrate different validation methodologies.

6. DEVELOPMENT OF SYSTEM COMPONENTS FOR SELECTED APPLICATIONS, SUBTASK 3, DELIVERABLE 3.1& 3.2

The development of system components for Hydronic Heated Pavements (HHPs) plays a crucial role in optimizing their performance, durability, and adaptability for various applications. This document, as part of Subtask 3 within the framework of the Technology Collaboration Programme on Energy Storage (ES TCP) of International Energy Agency (IEA) '*Task 38 - Ground Source De-Icing and Snow Melting Systems for Infrastructure*', focuses on advancing key components of HHP systems to enhance their efficiency, structural integrity, and feasibility across different environments and use cases.

A primary objective of this report is to refine the selection and design of materials, including pipes, surface heat exchangers, and thermal conductive layers, to improve heat transfer and ensure long-term durability. Pipe material selection is particularly important, as it influences thermal distribution, mechanical stability, and resistance to mechanical loads over time. The impact of pipe placement on pavement performance, including compaction quality, rutting deformation in warmer months, and potential cracking due to stiffness variations, is also a critical consideration.

Furthermore, this deliverable explores innovations in system integration to expand the applicability of HHPs. The adaptability of these systems to different climates, infrastructure types, and functional requirements is essential for their widespread adoption. From high-priority areas such as airport runways and emergency access routes to bicycle lanes and pedestrian pathways, system components must be adapted to meet the specific demands of each application.

This document provides insights into the technical advancements and strategic approaches necessary to facilitate the further development of HHP components, ultimately contributing to safer, more efficient, and sustainable pavement heating solutions.

6.1 State of the art in system components developments for selected applications

Recent research efforts are geared towards reducing dependence on traditional fossil fuels to combat global warming and address climate change. The focus on harvesting solar energy from asphalt pavement has intensified, driven by the need for sustainable solutions amid global population growth and urbanization. Hydronic Heated Pavement Systems (HHPS) are designed to extract thermal energy from asphalt surfaces exposed to intense solar radiation in various infrastructural settings like roads and parking lots.

Asphalt's dark colour causes surface temperatures to rise, reaching up to 70°C during summer, creating substantial potential for solar energy extraction. HHPs incorporate a heat exchanger layer within the asphalt structure, allowing the harvested thermal energy to be extracted by circulating fluid through the system. This extracted energy can be stored for applications such as providing snow- or ice-free asphalt surfaces in winter or contributing to clean energy uses like domestic hot water (DHW), residential heating, and industrial processes. Additionally, heat extraction during summer moderates asphalt temperatures, mitigating pavement distresses such as top-down cracking and rutting.

Globally, interest in large-scale HHP projects has grown, with notable examples like the Solar Energy Pilot Project in Switzerland (1994) and Road Engineering Systems (RES) in the Netherlands. Commercial projects have been implemented to showcase the potential of HHP systems on a larger scale. However, technical specifications may vary, including parameters like pipe material, spacing, placement technique, grid support, and bitumen spraying. HHP structures may employ a heat exchange layer made of porous asphalt or a pipe network with a heat-carrying medium, where circulating fluid carries absorbed heat to regulate asphalt layers effectively. (refer to figure, see figure 1)

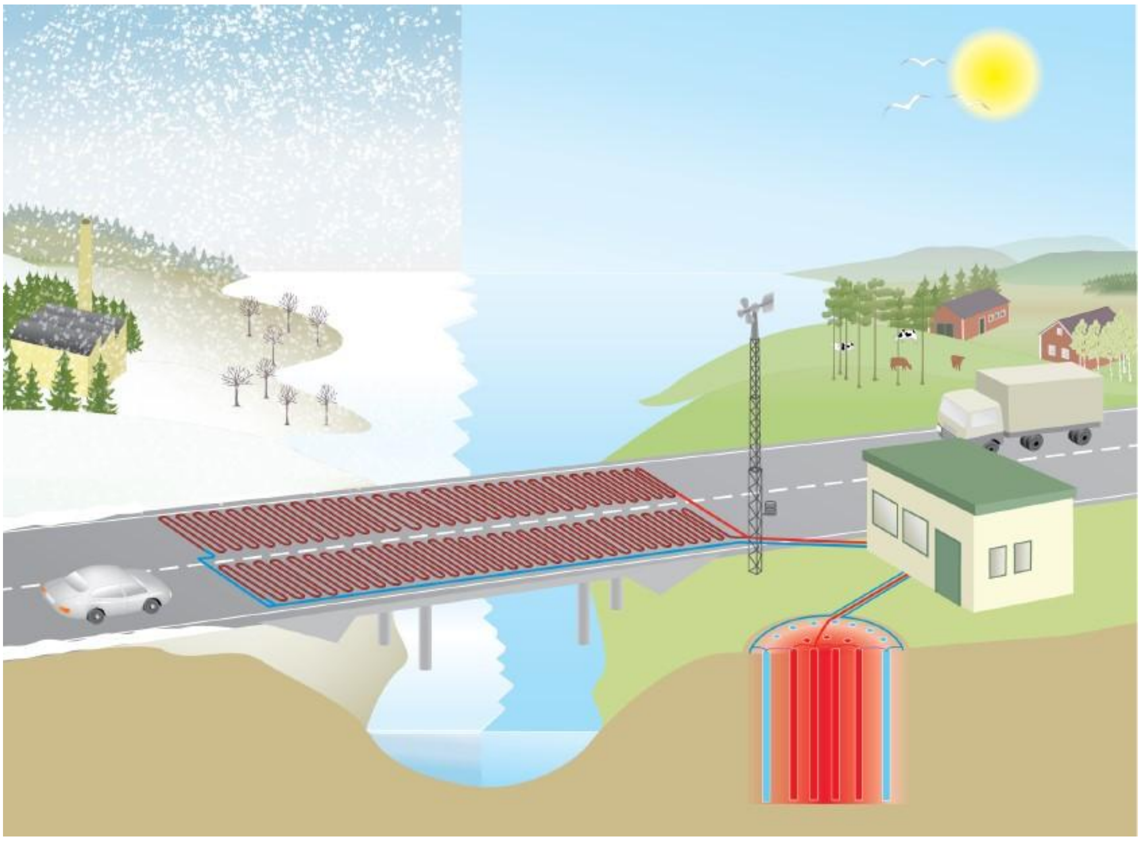

Figure 2. General schematic of snow melting system components constructed on a bridge (annotated from (Johnsson 2019))

HHP technology demonstrates versatile applications in various infrastructural elements. It aids in snow melting and de-icing for roads, parking lots, walking/biking paths, ramps, stairs, and entrances, ensuring enhanced safety and accessibility during winter. Tunnel entrances, bridge decks, and road parts between tunnels benefit from HHPs by maintaining optimal temperature conditions and minimizing the impact of temperature fluctuations. Railway switches experience smoother operations as HHP technology prevents ice formation. Platforms, sensitive slopes, parking lots, and aircraft parking areas utilize HHPs to efficiently address weather-induced challenges, contributing to improved functionality and safety. The adaptability of HHPs extends even to sports fields, ensuring playability in diverse weather conditions. Overall, HHP technology emerges as a comprehensive solution, showcasing its efficacy across several infrastructural components for resilient and safe urban environments.

In this Work Package (WP), HHPS are categorized based on two key factors: the magnitude of applied mechanical loads and the criticality of maintaining a snow- and ice-free surface. Figure 3 presents a schematic diagram illustrating this categorization within the scope of this WP.

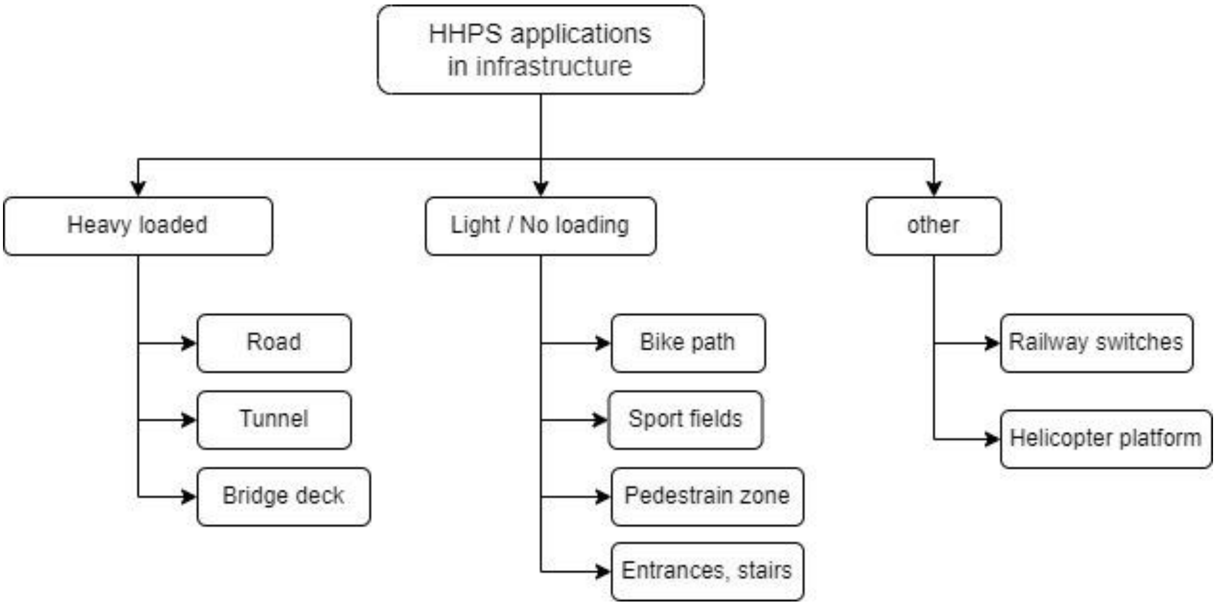

Figure 3. Schematic of HHP categories in WP3.

Roads (heavy load)

HHPs find diverse applications in various infrastructure settings, including roads, streets, tunnels, bridge decks, sensitive slopes, and entrances. In road and street networks, HHPs serve as innovative solutions for snow melting and de-icing, enhancing safety and usability during winter months. By embedding a network of pipes beneath the asphalt surface and circulating heated fluid, these systems efficiently melt snow and ice, preventing hazardous road conditions. Similarly, in tunnels and bridge decks, where temperature differentials can exacerbate ice formation and compromise safety, HHP systems provide reliable snow melting and de-icing capabilities, ensuring smooth traffic flow and reducing the risk of accidents. Sensitive slopes and entrances, prone to ice buildup and challenging to access for traditional de-icing methods, benefit from the targeted and effective snow melting capabilities of HHPs. By maintaining optimal surface conditions, these systems enhance accessibility and safety in areas with steep gradients.

Bicycle lanes, parking spaces and sport fields (light/no loading)

Utilization of a HHPS on bicycle lanes for snow melting and de-icing presents a promising solution for cities with dense bike lane networks, such as Antwerp or Amsterdam. By maintaining clear and safe pathways during winter, this technology enhances cyclist safety and promotes year-round bicycle usage, especially in colder regions (e.g., Scandinavia) where winter conditions limit cycling activity. During winter, the HHP system can utilize stored thermal energy to melt snow and prevent the ice formation , ensuring safer and more accessible pathways for cyclists. This proactive approach to snow removal and de-icing significantly reduces the risk of accidents and injuries caused by slippery road conditions, improving overall bike lane safety during the colder months. The implementation of HHPS on bicycle lanes not only demonstrates a commitment to sustainable infrastructure but also prioritizes the well-being and mobility of cyclists, encouraging more individuals to choose biking as a viable transportation option year-round. As cities continue to promote active transportation and address climate-related challenges, the adoption of HHP technology on bicycle lanes emerges as a practical and effective solution for creating safer and more resilient urban environments.

By providing a reliable and eco-friendly means of snow removal, HHPs on bicycle lanes align with the broader goals of reducing environmental impact and promoting sustainable practices in urban planning. As cities continue to explore innovative solutions for climate-resilient and user-friendly transportation networks, the application of HHPs on bicycle lanes emerges as a promising strategy to enhance winter mobility and safety for cyclists.

The benefits of HHPs can be extended beyond roads and streets, finding practical applications in parking lots, walking paths, and sports fields (e.g., football pitches). In parking lots, HHPS offers efficient snow melting and de-icing solutions, ensuring safe access and manoeuvrability for vehicles even during harsh winter conditions. In parking lots, the expansive asphalt surface area presents a significant opportunity for the application of HHPS. Beyond its primary function of snow melting and de-icing in winter, the large space availability allows for efficient harvesting of heat during summer months. The vast expanse of asphalt serves as an ideal collector of solar energy, which can be harnessed and stored for various purposes. Walking paths in hotspots of city centres, often used by pedestrians and cyclists, benefit from HHP systems' ability to maintain clear surfaces, reducing the risk of slips and falls. Additionally, sports fields, particularly those used for activities like football, can be maintained in playable conditions in cold weather using HHPs, minimizing disruptions to training sessions and matches. By integrating HHP technology into these environments, safety hazards associated with snow and ice accumulation are mitigated, contributing to enhanced usability and comfort year-round.

Figure 4. The PowerRoad project in Egletons (photo from facebook page of Eurovia France)

Railway switches, ramps, stairs, and entrances (Other)

Snow melting and de-icing systems have been utilized for many years to ensure the reliable operation of railway switches and other critical infrastructure during winter. Unlike most other applications, where occasional snow accumulation may be acceptable, switch heating systems must maintain a complete snow- and ice-free surface at all times. This requirement necessitates significantly higher heating power, typically around 300 W/m, which corresponds to approximately 1000 W/m².

In Germany, electrical resistance heating is the predominant method for switch heating, while in particularly harsh environments, such as mountain passes and northern climate regions, gas burner systems are also employed. In recent years, efforts have been made to replace conventional heating methods with more sustainable geothermal systems. These include:

1. Pumped systems with borehole heat exchangers or wells and heat pump
2. Thermosiphon systems in direct operation
3. Thermosiphon systems with heat pump

Several of these systems have already been implemented in real-world conditions, as documented in the report "STATE-OF-THE-ART: GERMANY - GROUND SOURCE DE-ICING AND SNOW MELTING SYSTEMS FOR INFRASTRUCTURE."

This technology has been widely implemented in various infrastructure applications, including ramps, stairways, and entrance areas. Common use cases include underground parking ramps, high-traffic staircases in train stations, and the entrances of commercial buildings such as department stores. By integrating hydronic heated pavements, the risk of accidents caused by black ice can be significantly reduced, ensuring safer and more accessible pedestrian and vehicular pathways during winter conditions.

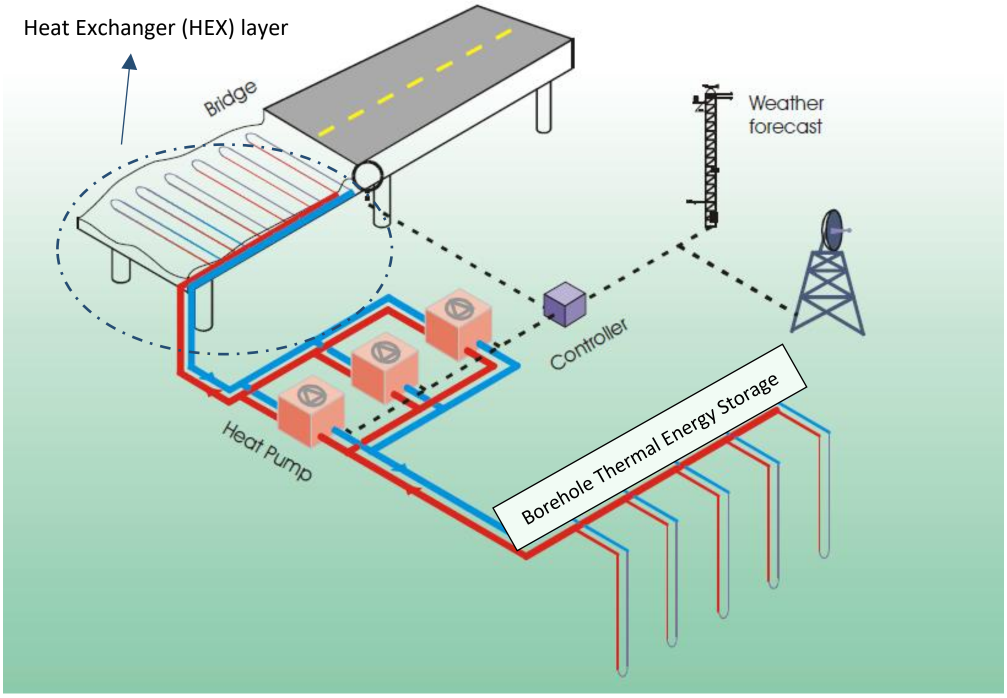

Figure 5. Schematic of a hydronic snow melting system in a bridge (Liu 2005)

6.2 Thermal development of the heating surfaces

The configuration of HHPS incorporate three primary components: the HHP, Borehole Heat Exchanger (BHE), and control system (Figure 5). The Heat Exchanger (HEX) or HHP section serves dual purposes, facilitating both heat collection and rejection, depending on project requirements. While some projects solely utilize heat rejection for snow melting or de-icing, others tap into additional heat sources like geothermal or waste heat for enhanced functionality.

Heat exchanger layer

The HEX section of HHPs comprises several key components that collectively influence its performance. These include the pipe configuration (e.g., serpentine or reverse layouts), pipe characteristics such as depth, diameter, and material, as well as the properties of the circulating fluid. Additionally, the materials used in the pavement, such as asphalt, and the incorporation of insulation layers are crucial factors in optimizing heat exchange efficiency and system effectiveness.

Pipe network: The primary component of HHPS is the HEX, consisting of an asphalt layer integrated with an embedded pipe network. In various projects, grid support has been implemented to ensure the precise positioning of pipes during construction. This support serves multiple purposes: safeguarding embedded pipes from damage caused by paving and compaction machinery, maintaining their structural integrity, and mitigating stress concentration around the pipes. The heat exchanger section may utilize bituminous asphalt or concrete as its primary material, while the pipes themselves can be composed of copper or PE (polyethylene). Additionally, certain projects have adopted innovative approaches such as laying pipes within grooves in previously installed layers or connecting the pipe network to a steel square mesh using metal pins (Figure 6-Figure 11).

Figure 6. Pipe and grid placement in HEAL project at the University of Antwerp

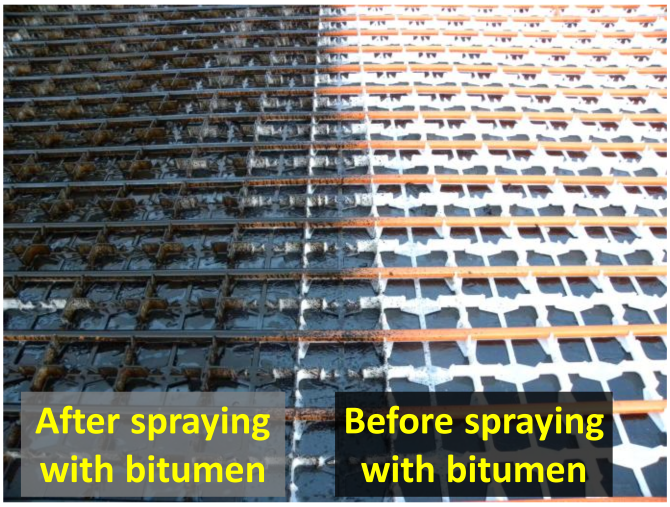

Figure 7. Pipe and grid network

Figure 8. The construction stage of HHP with grid support in a RES project (Lieshout 2017)

Figure 9. The construction stage of HHP without grid support (left) Power Road where the tubes are placed in grooves in the previously installed layer (Vinci 2019), (right) ICAX TRL project where the pipe network is connected to a steel square mesh using metal pins (ICAX)

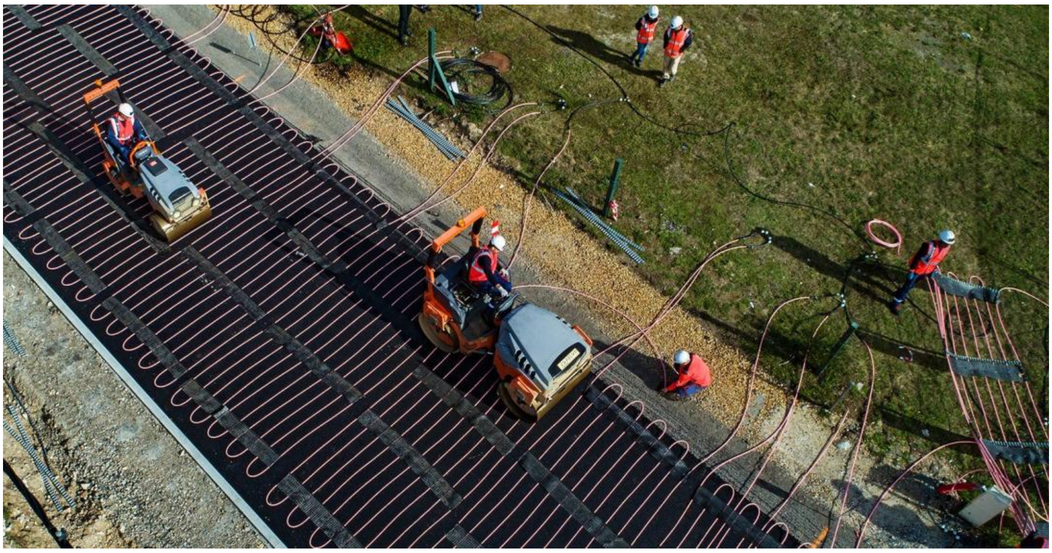

Figure 10. Pipe placement in Power Road project (Power Road website)

Figure 11. Pipe placement using metal spacers (from Eurovia Germany website)

To provide a concise overview of the material characteristics utilized in large-scale HHPS, different pipe materials, considering the trade-off between heat transfer efficiency, resistance to medium temperatures during compaction (in bituminous asphalt), and cost-effectiveness have been investigated. Historically, embedded pipes in HHPS predominantly comprised metal or plastic materials. In early HHPS like those in Klamath Falls, US, wrought iron pipes installed in bridge decks experienced corrosion-related leakage issues, prompting replacement with high-density polyethylene (HDPE) pipes during reconstruction. Additionally, concrete pavement pop-outs in large-scale pipe heating systems were attributed to water leakage from pipe joints. Although metal pipes are uncommon in large-scale projects due to cost constraints, lab-scale experiments and recent HHP installations have utilized copper and stainless steel pipes. Polyethylene pipes, on the other hand, have seen widespread use in various projects due to their affordability and corrosion resistance. In conclusion, plastic pipes like polyethylene or cross-linked polyethylene emerge as the preferred option, balancing cost considerations and corrosion resistance. A histogram detailing the distribution of pipe materials used in large-scale HHPs is depicted in Figure 12. The information of pipe material in the projects from the RES (with over 10 projects) is counted as one in the histogram.

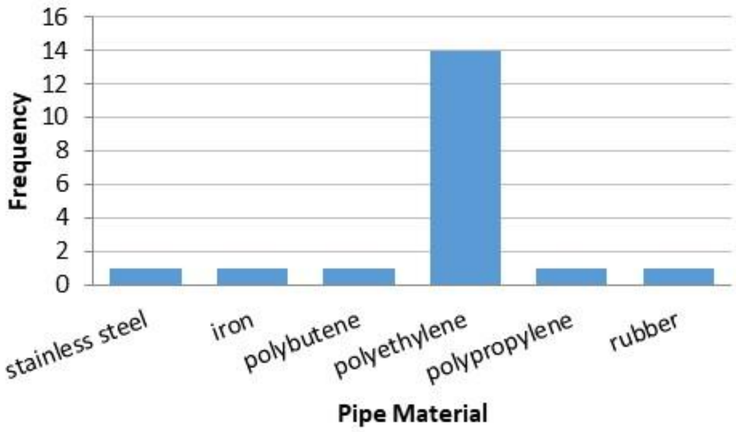

Figure 12. Pipe material histogram (Ghalandari et al. 2021)

Material characteristics: The thermal behaviour of asphalt in HHPs is pivotal for their efficiency in harvesting solar energy and snow melting applications, focusing on heat absorption, storage, and transfer capabilities. These materials' capacity to absorb, store, and transfer heat directly impacts their performance, with thermal conductivity, heat capacity, and absorption being key evaluated properties. Additionally, the temperature distribution of asphalt through its depth, influenced by material choice and system configuration, underlines the significance of thermal properties. Sensitivity analyses further reveal how thermal conductivity, specific heat, and emissivity/absorptivity directly impact asphalt's temperature, emphasizing their crucial role in optimizing HHPs' effectiveness across various environmental settings (Bobes-Jesus et al. 2013).

The selection of circulating fluid for hydronic pavement systems, such as asphalt solar collectors, hinges on specific requirements: high specific heat, stability within the operating temperature range, compatibility with pipes, abundance, and cost-effectiveness. While water is ideal for systems operating at lower temperatures (between 25°C and 90°C), its solidification temperature must be lower than the expected minimum temperature at the collector. Hence, water-antifreeze mixtures, typically utilizing glycols for their moderate cost, high specific heat, low viscosity, and corrosion resistance, are commonly used. In experimental tests, water serves as the primary circulating fluid, with antifreeze often added in colder environments to prevent freezing. Laboratory settings typically maintain water temperatures between 15°C and 25°C for solar energy collection and between 25°C and 50°C for snow melting. Flow rate regulation in HHP applications involves considering both the thermophysical characteristics of the material and the method of pipe arrangement. Higher flow rates accelerate heat transfer, reducing the time needed to achieve stable thermal exchange, and can enhance fluid velocity, heat transfer coefficient, and exchanged energy. However, while increasing the flow rate can reduce temperature differentials, its impact on heat transfer efficiency is less pronounced compared to pipe parameters. Thus, while higher flow rates may decrease temperature differentials, they may not necessarily improve overall heat transfer efficiency (Bobes-Jesus et al. 2013, Pan et al. 2015).

Control system and data measurement devices

The control system (i.e., heating centre) in the technical unit of the HHPs may comprises various components including a reversible Heat Pump (HP), buffer storage, water pump, expansion tanks, weather station, control computer, flow transmitters, temperature sensors, pressure manometers, control valves, and regulators. The control system operates by monitoring input and output parameters and making necessary adjustments, like activating or deactivating heat exchanger sections. Measurement devices record supply and return temperatures, flow rates, and pavement temperatures, etc. all connected to a system for real-time monitoring and control. The control system can be adjusted manually or automatically (based on defined criteria).

Depending on the necessity of the project, a HP can be installed in the HHPs. During winter, the HP transfers stored heat from the Borehole Thermal Energy Storage (BTES) to the heat exchanger section. In cases where the stored heat is insufficient for the HHP system's requirements, such as during harsh snow conditions, the HP can increase fluid temperature through compression and expansion processes. The buffer storage, is crucial for activating the HHPS at alternative supply temperatures and ensuring stable runtime for the HP. In large-scale projects with limited BTES thermal power, additional auxiliary buffer storage may be necessary. The buffer tank regulates water temperature by utilizing energy from the HP through coils inside, minimizing the frequency of HP ON/OFF cycles and prolonging its lifespan. By integrating the HP and BTES, the system can achieve higher supply temperatures during winter.

Measurement devices, including weather stations and embedded sensors, are integral for monitoring and controlling various parameters such as asphalt temperature, fluid pressure, flow rate, and fluid temperature, etc. These devices enable real-time data collection for both large and small-scale prototypes, contributing to effective system operation and post-performance analysis. The inclusion of temperature sensors and flow meters is vital for large-scale projects, facilitating heat loss measurement and power consumption analysis for heat pumps in the HHPs. The flow of the system is controlled using flow transmitters as these sensors can adjust the flow, with automatic or manual switching capabilities. To monitor temperature profiles and weather parameters, thermocouples can be embedded in different layers of asphalt/concrete pavement (Ghalandari et al. 2022). Additionally, a mixing valve can be installed to sets the supply temperature by mixing water from the buffer storage and BTES controlled by the water pump through the control system.

The weather station plays a pivotal role within the control system of HHPS, serving as a critical component for monitoring and analysing environmental conditions. Equipped with sensors to measure parameters such as air temperature, relative humidity, wind velocity and direction, solar irradiation, and barometric pressure, the weather station provides essential data for optimizing HHPS performance. By continuously monitoring weather conditions, the control system can dynamically adjust operational parameters, such as fluid flow rates or heat exchange rates, in response to changing environmental factors. This proactive approach allows HHPS to effectively respond to fluctuations in weather patterns, ensuring efficient operation and enhancing overall performance. Additionally, the data collected by the weather station facilitates comprehensive analysis and modelling of system behaviour, enabling further refinement and optimization of HHP installations to meet specific performance objectives and environmental requirements.

Heat storage becomes crucial for projects relying on harvested solar energy, with options for both horizontal and vertical seasonal heat storage systems based on available space. While a heat pump is recommended for efficiency, smaller-scale solar collectors may not necessitate a complex control system.

Heat source and storage

This section explores the integration of geothermal heat as a renewable energy source within HHPS and its role in heat storage. Geothermal energy serves as a sustainable heat source for snow melting and de-icing applications in HHPS. Various projects have demonstrated the feasibility of utilizing geothermal energy for snow melting, requiring external electric power solely for pump operation, thus minimizing reliance on conventional energy sources (Iwamoto et al. 1998).

Geothermal heat, despite being a low-temperature resource, has been extensively investigated for integration into HHPS due to its cost-effectiveness and widespread availability across numerous countries. It serves as a primary heat source for large-scale snow melting systems (SMS) via ground source heat pumps (GSHP), either independently or in combination with supplementary heat sources like electric heaters or fuel boilers. Notable examples include its use in the Gaia snow melting projects in Japan, FHWA initiatives in the United States (Texas, Colorado, and Nebraska), Klamath Falls projects, and 25 SMS installations on Honshu Island in Japan (Boyd 1999, Lund 1999, Chiasson and Spitler 2001, Boyd 2003, Nagano et al. 2006, Brown 2007, Yu et al. 2017).

Ground-coupled HHPS have been implemented to heat airport aprons and aircraft parking areas in notable locations such as Greater Binghamton Airport, Oslo International Airport, and Stockholm Arlanda Airport (Figure 9). At Greater Binghamton Airport, the HHPS integrates twenty vertical geothermal storages (approximately 150 m deep) and two horizontal storages (around 40 m) to provide winter heating for aprons and summer cooling for the terminal. In contrast, Oslo International Airport employs HHPS paired with an aquifer thermal energy storage system to heat aircraft parking stands while also facilitating terminal heating and cooling (Eggen and Vangsnes 2005, Midttømme et al. 2008, Ziegler 2009, Ceylan et al. 2014, Anand 2015, Olgun 2016, Abdualla et al. 2018, Abdualla et al. 2018, Daniels 2018, Daniels and Heymsfield 2019).

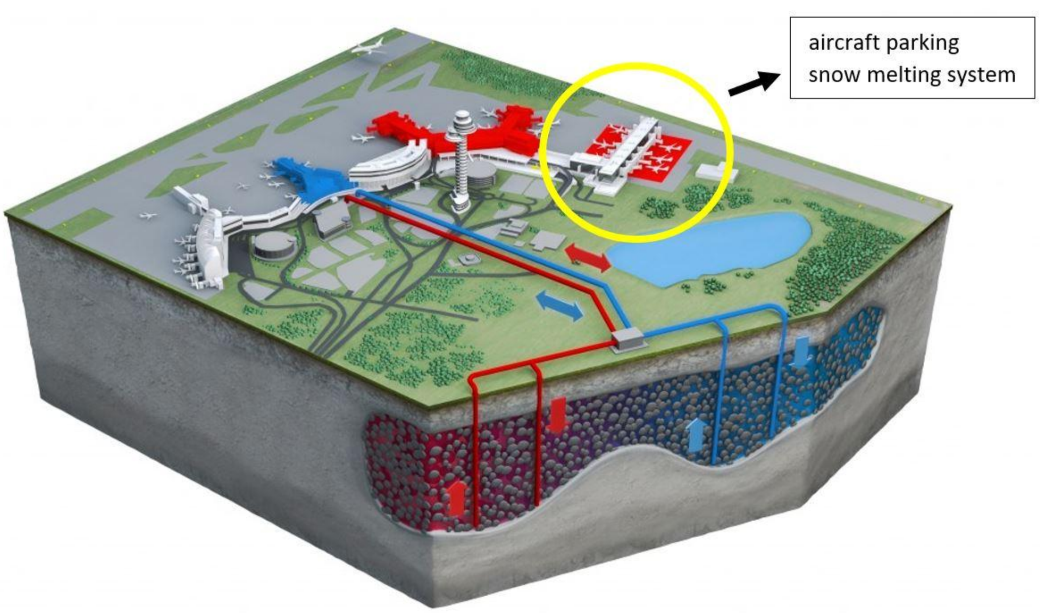

Figure 13. Aquifer thermal energy storage system coupled with HHP in Stockholm Arlanda airport (Wigstrand 2009, Ghalandari et al. 2021)

In projects with heat harvesting capacity (pavement solar collectors), heat storage is essential to store the harvested heat in summertime until its application during the cold months. Several projects implemented horizontal ground heat exchangers into HHP (Carder et al. 2007, Siebert and Zacharakis 2010, Guldentops 2014, Saleh et al. 2019), where the ground-coupled HHP with asphalt is connected to heat storage to keep the inlet temperature of the circulating fluid constant, bringing about temperature balance between pavement and the fluid (Johnsson and Adl-Zarrabi 2019, Saleh et al. 2019, Ghalandari et al. 2022).

6.3 Impact of various parameters on thermal performance of HHPs

In recent years, significant attention has been directed towards exploring the feasibility and performance optimization of HHPs, prompting various experimental studies categorized into small/lab scale and large-scale or actual size setups. Experimental studies have been conducted at both small/lab scale and large-scale or actual size setups, with numerical simulations often employed to understand HHPS behaviour due to the higher cost and complexity associated with large experimental setups. The simulation tools developed in the literature studies (refer to WP2 for various models and their accuracy) utilized to predict thermal behaviour, conduct parametric studies, assess long-term performance, predict energy output, and evaluate asphalt surface temperatures. Large-scale HHPs are constructed in various sizes depending on the application and area to be covered, with geometrical specifications such as pipe spacing, pipe configuration, and embedment depth varying across projects. Operational conditions such as supply temperature, flow regime, flow rate, thermophysical properties of the asphalt, and geometrical specifications significantly impact HHPS performance, see D4.1. Several studies have highlighted the influence of geometrical parameters, operational parameters, and asphalt properties on HHP efficiency, with pipe spacing, embedment depth, and pipe diameter identified as remarkably influential (Ghalandari et al. 2023).

Geometrical specifications

As discussed earlier the HHPs can act as solar collectors in the summer or solely de-icing and snow melting systems in wintertime. As a result, the thermal performance of HHPs can be defined as their capacity to harvest heat in summer or keep surface ice/snow-free in the winter. The findings indicate that the anti-icing effectiveness of the HHP is enhanced by reducing the distance between pipes, decreasing the depth of embedded pipes, utilizing larger pipe sizes, and lowering the emissivity value of the road surface. Among these factors, the spacing between pipes exhibits the most notable impact on enhancing anti-icing performance.

In the wintertime, closer spacing between pipes significantly enhances HHP system's effectiveness, reducing slippery road conditions by nearly fourfold when distances decreased from 400 mm to 50 mm. Additionally, shallower embedment depths of pipes proved beneficial, correlating with a 25% reduction in slippery conditions when varied from 150 mm to 60 mm. Moreover, employing larger pipe diameters effectively decreased the risk of slippery road surfaces, with a diameter increase from 10 mm to 40 mm resulting in a substantial 45% reduction in such conditions. These findings underscore the importance of optimizing pipe layout and dimensions within HHPS to maximize their efficacy in maintaining safe road conditions (Mirzanamadi et al. 2018).

In terms of heat harvesting, the findings indicate that smaller pipe spacing not only results in lower temperatures throughout the pavement but also leads to a more homogeneous temperature distribution, which is beneficial for reducing thermal stresses within the pavement. Studies highlight the importance of pipe depth, showing that closer surface pipes result in lower temperatures directly above, yet the surface temperature between pipes remains largely unaffected as depth increases.

Larger pipe diameters were found to be more effective in reducing pavement temperatures compared to smaller diameters, although smaller diameters heat the water to a higher degree (Saleh et al. 2019). In a similar study, the impact of pipe depth variation on system performance shows a decrease in thermal gains from 21% to 14% as the pipe depth increases from 25 mm to 105 mm. Evaluations were conducted considering depths below 75 mm, aligning with a typical tertiary road structure with an asphalt concrete thickness of 130 mm (Guldentops et al. 2016).

The sensitivity analysis indicates that pipe spacing, flow rate, and inlet supply temperature significantly influence heat harvesting capacity, with pipe embedment depth and diameter demonstrating marginal sensitivity. Consequently, optimizing the system's response can be achieved by placing pipes deeper in the asphalt pavement to shield them from structural damage, prioritizing the more sensitive factors. Additionally, surface temperature exhibit high sensitivity to pipe spacing, flow rate, and inlet supply temperature, while the impact of pipe embedment depth and asphalt thermal conductivity is minimal (Ghalandari et al. 2023).

(Zhao et al. 2020) investigated the snow melting capacity of HHP and concluded that embedded pipe depth, supplied fluid temperature and pipe spacing are the most influential parameters for reaching maximum melting rate. It should be noted that the applied control strategy in the conducted experiments was that the supplied fluid temperature was variable between 25 and 35 °C. Although the snow melting system is coupled with geothermal source, a HP was integrated to increase the supplied temperature in harsh snow conditions. Compared with the heating rate of for embedded pipe depth, the influence degree of pipe spacing was lower than that of pipe depth (Figure 14) (Zhao et al. 2020).

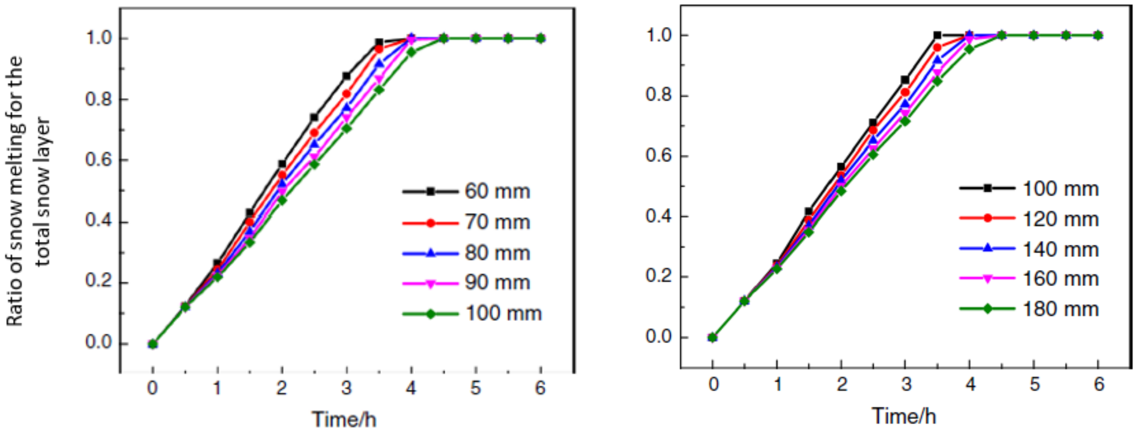

Figure 14. Melting ratio of the snow at different (left) embedded pipe depths (right) pipe spacings (Zhao et al. 2020)

A comparison of the free-area ratio under different pipe spacing configurations highlights the critical role of spacing in determining melting time. For instance, increasing the pipe spacing from 200 mm to 300 mm can extend the melting time by up to 3.5 times (Figure 15). Wang et al. identified the influence of operational parameters in the following order of significance: pipe spacing > burial depth > fluid temperature. Therefore, optimizing pipe spacing is essential for an efficient snow-melting system. Excessively wide spacing can significantly prolong melting time, while excessively dense spacing leads to higher installation costs. Generally, a recommended spacing range of 100 mm to 250 mm balances performance and cost-effectiveness (Wang and Chen 2009).

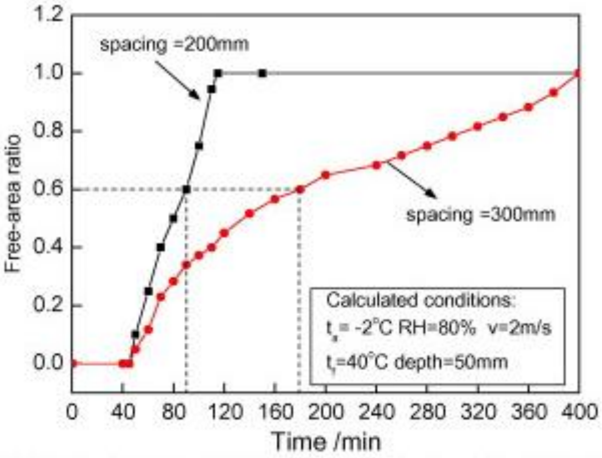

Figure 15. Impact of pipe spacing on the melting process at various spacing configurations (Wang and Chen 2009)

A comparative analysis of different pipe arrangements for calculating heat requirements in snow-melting systems was conducted, focusing on the ratio of pipe spacing to pipe diameter (S/D), which ranged from 6.0 to 10 (Ho and Dickson 2017). This ratio was applied to estimate heat production on pavement surfaces at varying fluid temperatures. The study revealed that water heated to 20 °C could provide 335.8 BTU/hr.m² (98.41 W/hr.m²) for an S/D ratio of 10, while water at 80 °C could deliver 2238.94 BTU/hr.m² (656.16 W/hr.m²) for an S/D ratio of 6.0. In regions where the fluid temperature is insufficient, a heat pump may be necessary to enable the direct use of geothermal hot water for optimal performance.

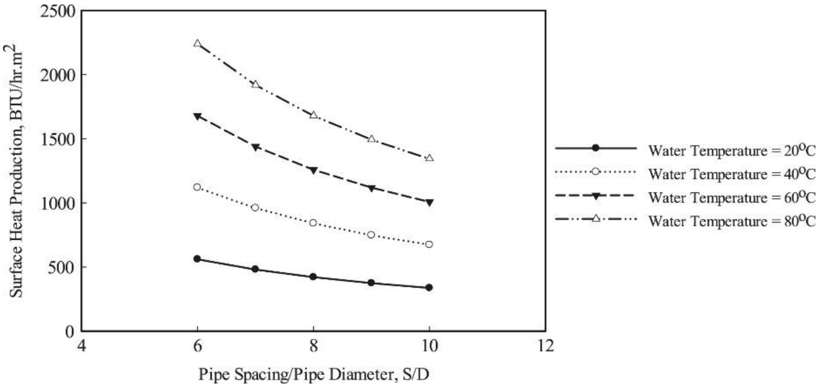

Figure 16. Heat demand in relation to pipe spacing-to-diameter ratios (100 BTU = 29.30 W) (Ho and Dickson 2017)

Thermophysical properties

The thermophysical properties of asphalt concrete significantly influences the efficiency of HHPs as demonstrated by practical experiments. Factors such as binder percentage, air voids content, and aggregate type within asphalt pavement significantly affect its thermophysical properties, thereby impacting the thermal efficiency of HHPs. Therefore, accurately identifying and determining the material properties of HHPs is imperative for developing realistic simulation models and enhancing comprehension of their thermal dynamics. Higher thermal conductivity leads to faster thermal gains in the working fluid, enhancing collector efficiency. Numerical modelling reveals that the collector's efficiency increases from 17% to nearly 20% as thermal conductivity rises from 1.0 to 2.0 W/mK. Despite asphalt concrete's high solar absorptivity, aging causes its colour to lighten, resulting in decreased absorptivity and collector efficiency over time. This highlights the need to investigate how aging affects asphalt concrete's thermal conductivity and absorptivity to optimize HHP design and material selection. Cementitious concrete structures may offer comparable long-term performance since their solar absorptivity slightly increases with age, contrasting with asphalt concrete's significant decrease over time (Guldentops et al. 2016).

The impact of thermally conductive asphalt concrete (CAC) on snow melting performance and pavement temperature distribution was assessed by incorporating graphite as a partial replacement for mineral fillers. The analysis revealed a strong correlation between the thermal conductivity of asphalt layers and the initiation time for ice melting. As illustrated in Figure 17, higher thermal conductivity in the asphalt pavement results in a shorter time to initiate ice melting at a given pipe embedding depth. Conversely, for a fixed thermal conductivity, deeper pipe embedding leads to a longer initiation time (Chen et al. 2011).

Furthermore, Figure 17 demonstrates that both conventional asphalt concrete and CAC exhibit effective snow-melting performance. When heating pipes are embedded within the middle layer or between the middle and top layers, the snow melting process is highly efficient, typically completing within 0.5 hours. Notably, when the thermal conductivity reaches 3.0 W/m·K, the melting time can consistently be maintained within this 0.5-hour threshold, further underscoring the benefits of enhanced thermal conductivity in HHP systems (Chen et al. 2011).

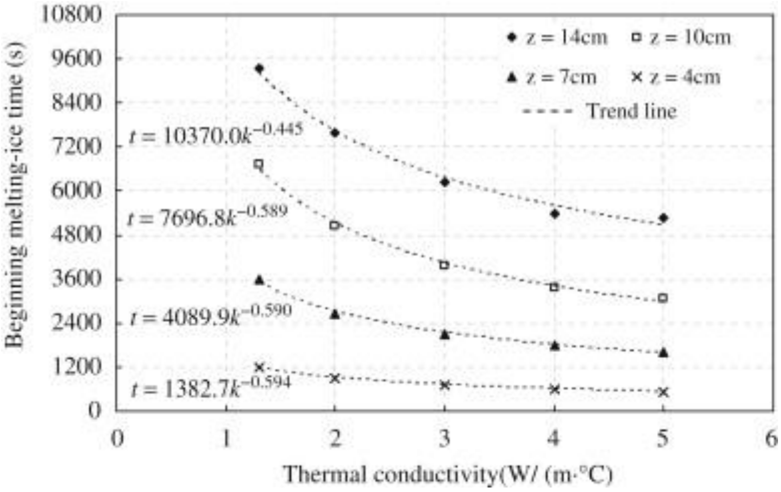

Figure 17. Correlation between snow melting initiation time and thermal conductivity at different pipe embedding depths (Chen et al. 2011)

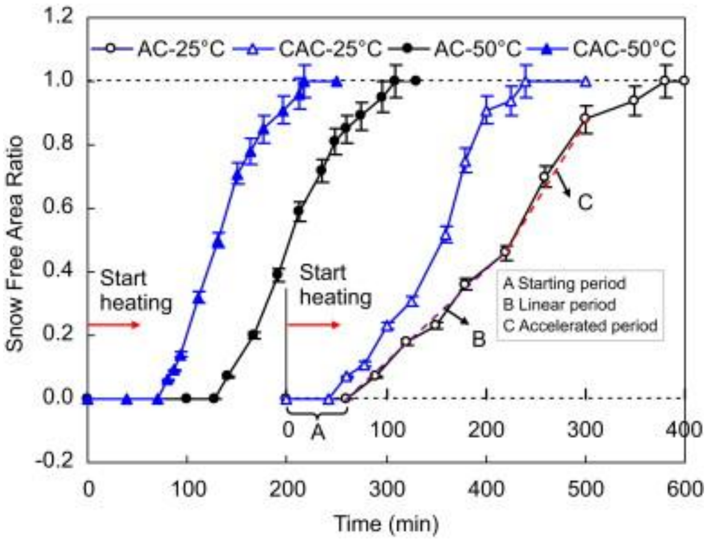

Figure 18. Asphalt concrete surface condition on slabs during the snow melting process (Chen et al. 2011)

The use of CAC has been shown to significantly enhance heat transmission and improve snow melting performance. One key indicator of snow melting efficiency is the total time required for complete snowmelt. Compared to conventional asphalt concrete slabs, CAC slabs exhibit a noticeable reduction in melting time (Chen et al. 2011). Specifically, when the thermal conductivity of asphalt concrete increases from 1.531 to 2.309 W/m °C, the snow melting time decreases by approximately 30%. This demonstrates that CAC effectively accelerates heat transfer from the heat source to the pavement surface, resulting in more efficient and faster snow removal Figure 18.

A comparison between the thermal conductivities of pipes and pavement shows that while pipe materials can vary widely in conductivity, the efficiency of heat transfer in HHPs is ultimately limited by the conductivity of the pavement itself. It is suggested that rather than investing in high-conductivity pipes, enhancing the pavement's thermal conductivity—even marginally—would yield better efficiency in thermal performance of these systems. This could be achieved by incorporating materials such as graphite into the asphalt mix (Saleh et al. 2019).

Operational conditions

The examination of flow rate is crucial in understanding the dynamics of HHPs, given its close correlation with system efficiency. Through an analysis of various studies in the literature, several key observations emerge. Firstly, higher flow rates correspond to increased surface temperatures, however, these variations in flow rate do not significantly affect temperature profiles at different depths within the HEX. Notably, increasing flow rate while maintaining a constant pipe diameter results in elevated fluid velocity, thereby enhancing the heat transfer coefficient and the overall energy extraction/injection potential. Additionally, in case of using HHP as pavement solar collector, with rising flow rates, the temperature rise of water circulating through the collector diminishes, necessitating longer pipes for the fluid to attain pavement temperature at specific depths. Lastly, higher flow rates lead to a quicker realization of steady-state conditions in the collector, a phenomenon observed to be independent of the inlet water temperature.

The sensitivity analysis of flow rate in HHPs reveals notable effects on power consumption. Transitioning from laminar to turbulent flow rates, leads to significant increases between 34% - 49% of power consumption, respectively. Interestingly, the impact of flow rate varies depending on the flow regime. Elevating the flow rate from laminar to transient regimes results in a 21% increase in power consumption, while the subsequent transition to turbulent flows sees less pronounced increases of approximately 10%. Conversely, during summertime, boosting the flow rate from laminar to transition flow enhances cumulative power harvesting capacity by 48%, with marginal gains of 12% and 2% observed when transitioning to higher flow rates. These findings underscore the role of flow rate in influencing the heat transfer efficiency of HHPs, as confirmed by existing literature (Ghalandari et al. 2022).

The recommended fluid temperature for snow melting systems typically ranges from 25°C to 50°C (Pan et al. 2015). While effective, this temperature range is relatively high for anti-icing purposes, leading to increased annual energy consumption. The impact of using ultra-low supply temperatures on the thermal response of HHPs and the duration of slippery road conditions is illustrated in Figure 19. As expected, higher fluid temperatures result in elevated road surface temperatures, thereby reducing the risk of slippery conditions. Notably, increasing the fluid temperature from 4°C to 20°C reduces the duration of slippery conditions by approximately 35% during system operation, highlighting the significant influence of supply temperature on system performance.

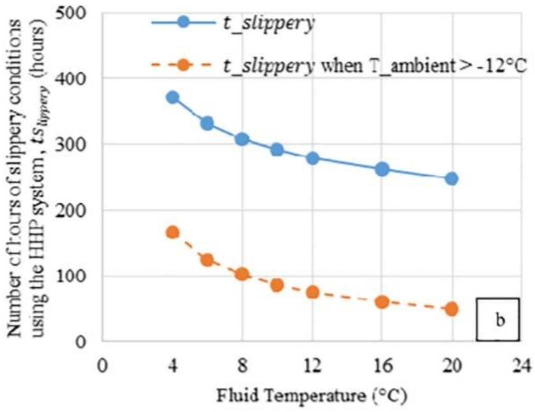

Figure 19. The effects of different (ultra-low) fluid temperatures on the anti-icing performance of the HHPs on slippery conditions on the road surface (Mirzanamadi et al. 2018)

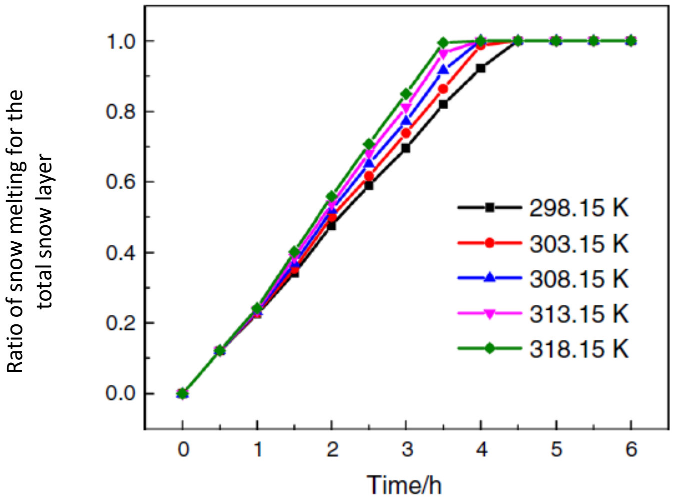

Figure 20. Melting ratio of the snow at different (low) supplied fluid temperatures (Zhao et al. 2020)

It can be concluded that utilizing a low-temperature supply in HHPs for snow melting is more effective. While the supplied water temperature had minimal impact during the initial melting stage, a lower supply temperature can be used to save energy. The energy-saving control strategy can involve maintaining the supplied fluid temperature at 25°C during the first hour of the heating period, gradually increasing it to higher temperatures, and then reducing it back to 25°C from 4–6 hours (Figure 20). This approach effectively balances energy efficiency with snow melting performance (Zhao et al. 2020).

The snow melting performance of HHPs is influenced by both the heating capacity and the duration of preheating, even when operating in the same location. Preheating time, in particular, is a critical factor that cannot be overlooked. For instance, increasing the preheating time from 0 to 3 hours enhances snow melting performance by 21%, while maintaining the same input heat flux. This highlights the importance of activating the system several hours in advance to “pre-heat” the pavement, thereby improving its snow melting efficiency during snowfall events. A comparison of snow melting performance between Harbin and Beijing revealed that climate conditions play a crucial role in determining system effectiveness. As such, it is essential to design systems that are specifically tailored to local climatic conditions to ensure optimal performance (Xu et al. 2018).

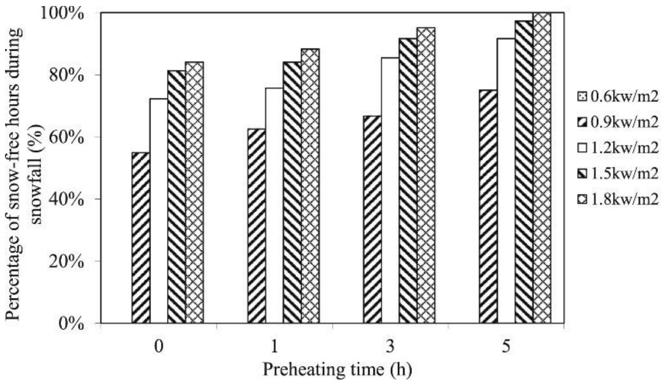

Figure 21. Effect of pre-heating and heating capacity on snow melting performance (Harbin, China) (Xu et al. 2018)

Key environmental parameters, including ambient air temperature, snow density, and snow height, significantly influence the snow melting performance of HHPs. A decrease in ambient temperature from −5.7°C to −14.3°C extended the total snow melting duration by 21% and increased overall energy consumption by 10%, highlighting the strong correlation between temperature and system efficiency.

Similarly, snow density plays a crucial role, as an increase from 50 to 150 kg/m^3 led to an 82% rise in melting duration and a 24% increase in energy consumption. Additionally, snow height has an even more pronounced effect, with the melting period extending by 168% when snow height increased from 14 mm to 90 mm. These findings underscore the necessity of considering site-specific weather conditions when designing and optimizing HHP systems for effective and energy-efficient snow melting (Zhao et al. 2023).

6.4 Mechanical requirements of the surface heating system

The heat exchange layer embedment in HHPs introduces distinct challenges related to structural integrity and performance. A primary issue is the potential for cracking, attributed to the stiffness difference between the asphalt mixture and the pipes within the structure. These cracks emerge not only due to heavy loadings but also due to possible inadequate compaction around the pipes during construction. Such poor compaction around the pipes will lead to stress concentration, thereby inducing the initiation and propagation of cracks in the vicinity of the pipes, leading to the debonding of the pipe from the asphalt, consequently posing a threat to the structural integrity of the system. Besides, with the pipe placement, the structural performance of the pavement is expected to vary due to high stresses developing around the pipes, challenges in the construction stage (i.e., laying and compaction of the heat exchange layer), cracking resistance, differences in the thermal expansion coefficient of asphalt and pipe, improper adhesion between asphalt and pipe, and moisture damage.

Furthermore, the placement of pipes into asphalt pavement, along with considerations of their geometrical configuration—such as pipe spacing and orientation—exerts a substantial impact on the stiffness properties of the asphalt layer. Consequently, this influence extends to the overall structural behaviour of pavements in HHPs (Zhu et al. 2021).

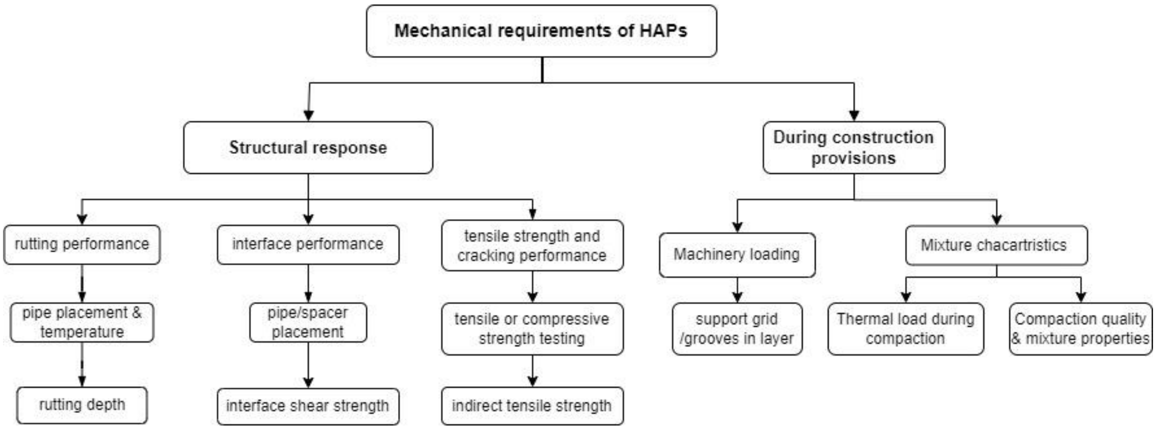

Figure 22. Mechanical response of HHPs during construction and under structural loading

Mechanical provisions during- and post-construction

The construction stage of roads, bike paths, etc can be influences by placement of pipe networks. In the bituminous mixture asphalt pavements, the temperature of the mixture (hot mix asphalt) during paving can rise up to 160 °C. This high temperature can adversely impact on pipes since the melting point of low-density and HDPE pipes is typically in the range 100 to 130 °C, respectively. As a result, either using warm mix asphalt that is produced at temperatures slightly above 100 °C or other alternative techniques such as circulating cold water through pipes during asphalt paving have been used to diminish the thermal loads on pipes.

Furthermore, during the placement of the heat exchanger layer, the heavy machinery applies excessive loads on pipes during the construction stage. As discussed earlier in Section 0 '*6.2 Thermal development of the* heating surfaces', several innovative approaches were implemented in projects for pipe placement. Laying pipes within grooves in previously installed layers or placement of grids (Figure 23) provides a solid layout for precise placement of pipes, enhances confining and arching actions, and takes the paving and compaction machinery loading during construction partially. It should also be noted that small pipe spacings (e.g., less than 10 cm) can result in low-quality compaction of the asphalt between the pipes and grid (if any). Such insufficient compaction in the pipe vicinity region may create an insulation layer of air voids and decrease the heat transfer between pipe and asphalt. Another drawback of inadequate compaction is that the stress concentration will initiate cracks in these regions and consequently service life of the asphalt pavement could shorten due to an increase in rutting.

Although challenges regarding the machinery load may not be present in concrete pavements such as jointed plain concrete pavement, these rigid pavements may impose certain design and construction challenges at construction stage. Since the rigid pavements are constructed in slab blocks connected with dowel bars that are typically used at transverse joints to assist in load transfer and tie bars are typically used at longitudinal joints. As a result, if the pipes are planned to be placed within rigid pavements, geometrical design aspect of HHPs should be considered carefully. Moreover, in case pipes are placed in base layer, considerations regarding snow melting effectiveness needs attention, as the surface course can vary in thickness between 150 mm and 300 mm, for light loading and heavy loads and high traffic, respectively. For other types of rigid pavements, jointed reinforced concrete pavement and continuously reinforced concrete pavement, the primary challenge is associated with placement of pipes in pavement together with reinforcing steel (Figure 24).

Figure 23. The pipe and grid structure in HEAL prototype at University of Antwerp, Belgium during asphalt placement

Figure 24. Pipe installation in concrete with spacer holders (Uponor project) (Uponor 2015)

Structural response of hydronic heating systems incorporated pipe network

The integration of pipes in HHP may impose several structural and thermal challenges that influence long-term performance of pavement. The choice of pipe material affects both compaction quality and heat distribution across the pavement surface. Differences in stiffness between the pipe and surrounding materials can lead to cracking initiation, particularly around the pipe zone. Additionally, pipe placement plays a crucial role in pavement deformation, as it may contribute to rutting during warmer months. Addressing these factors is essential to ensure a balance between effective heat transfer and structural integrity, ultimately enhancing the durability and reliability of HHP systems.

Rutting deformation

The placement of pipes within bituminous asphalt pavement can influence its rutting performance. Rutting refers to the permanent deformation that forms in the wheel tracks of the asphalt surface, which can significantly affect driving comfort and road safety. This deformation contributes to premature pavement deterioration, thereby impacting the overall lifespan of the road. Studies have shown that not all asphalt layers contribute equally to rutting, with the binder layer (intermediate layer) playing the most significant role in total rutting (Wang et al. 2009, Zou et al. 2017, Li et al. 2021). Since the pipes are installed mainly in binder layer, it is important to consider the potential negative impact of pipe placement in geographical locations with higher rutting deformation potential. A recent study demonstrated that when compaction quality is well-maintained, the rutting deformation in HHPs with embedded pipe and grids is negligible compared to that in asphalt pavement without HHP (Ghalandari et al. 2024).

Tensile and compressive strength testing

The impact of pipe placement on the strength of bituminous asphalt samples can be explored by performing an indirect tensile strength (ITS) test on HHP samples containing embedded pipes. ITS is a measure of the tensile strength of bituminous mixtures determined indirectly by subjecting specimens to compression in a Marshall-type testing machine. In this test, a cylindrical specimen is placed between two loading strips, and a compressive force is applied diametrically until failure occurs. The values of ITS test can indicate whether the placement of the pipe influences specimen tensile strength at various temperatures and mixture properties. Such strength testing in concrete pavement samples with HHP is assessed through compressive strength testing.

Although the results of a recent study suggested that the embedment of pipes and grid structure has no major impact on HHP specimens' tensile strength in bituminous mixtures, more laboratory investigations might be necessary for HHPs constructed in colder regions, different placement techniques and local mixture properties. Also, incorporating pipes along with grid support reduces results in a slower crack propagation rate. This phenomenon occurs post-peak load and specimen failure, where the support grid engages in tension due to cracking, thereby increasing the fracture energy of samples containing pipe and grid (Figure 25).

Figure 25. Post-failure resistance behaviour of reference and HHP specimens in ITS test

Interface shear strength

Debonding in asphalt pavements occurs when two adjacent layers lose adhesion, often due to horizontal shear stress exceeding the interface shear strength (ISS). High temperatures reduce ISS values, increasing debonding risks. In HHPs, where pipes and grid structures are integrated, ISS can be affected both by cooling/heating effects from the system and the structural interference of pipes and grids at the interface layer. Notably, pipe and grid (if any) placement in HHPs can significantly lower ISS, primarily due to the their smoother surface compared to the asphalt mixture, which weakens adhesion. Additionally, inadequate tack coat application between the pipe/grid and interface layer can further reduce ISS in HHPs. It is worth noting that the grid placement provides a reinforcing effect and reaching shear failure in large-scale applications in roads would require displacing a significant portion of the grid from its position (e.g., heavy loading trucks in hot summer).

Other mechanical and structural considerations

To enhance compaction quality around the pipe zones in bituminous mixtures used in HHPs, a relatively soft mixture with reduced bitumen viscosity is recommended. This mixture should exhibit strong performance at both low and high temperatures to resist cracking and rutting. Additionally, to improve heat transfer, adhesion between the pipe surface and surrounding asphalt, and accommodate movement due to thermal expansion differences, the pipes and grid can be coated with high-quality, elastomer-modified bitumen before the asphalt paving stage (Van Bijsterveld and De Bondt 2002, Sullivan et al. 2007).

When designing HHPs, the properties of the mixture, including aggregate size, play a crucial role in ensuring high-quality compaction around the pipes. The maximum aggregate size in bituminous mixtures is directly linked to the spacing of the pipes, ensuring that the mixture is adequately compacted between the pipes, particularly in challenging areas like around the pipes and spacers. For concrete mixes, aggregate size and additives should be carefully considered to optimize performance. Additionally, the materials used should have good heat transfer properties—such as appropriate surface emissivity, absorptivity, and thermal conductivity—to enhance the system's efficiency in snow melting. Practical construction considerations also include ensuring a minimum concrete cover to protect pipes from weathering and damage. In bituminous asphalt pavement, the heat exchanger layer cannot be placed on the surface layer due to resurfacing challenges, so a minimum asphalt thickness of 4 cm above the pipes is recommended to prevent pipe damage during surface milling. For compaction reasons, the bituminous mixture should be placed at the bottom of layers for optimal results.

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7. DEVELOPMENT OF SYSTEM COMPONENTS FOR SELECTED APPLICATIONS, SUBTASK 3, DELIVERABLE D3.3: THERMAL VS. STRUCTURAL PERFORMANCE -SUGGESTIONS TO FACILITATE SYSTEM DEVELOPMENT FOR FURTHER APPLICATIONS

Hydronic Heated Pavements (HHPs) have emerged as an innovative solution for improving winter road safety and infrastructure durability by utilizing subsurface heating to prevent snow and ice accumulation. However, their effectiveness depends on a careful balance between thermal performance, which governs heat transfer efficiency, and structural integrity, which ensures long-term durability under various loading conditions.

This document, as part of Subtask 3 within the framework of the Technology Collaboration Programme on Energy Storage (ES TCP) of International Energy Agency (IEA) '*Task 38 - Ground Source De-Icing and Snow Melting Systems for Infrastructure*', explores the interplay between these two critical aspects, analysing how material selection, system configuration, and environmental factors influence the overall performance of HHPs. It also addresses key challenges, such as optimizing energy consumption, minimizing thermal-induced stresses, and enhancing construction feasibility.

Furthermore, this report offers strategic recommendations to enhance HHP development for broader applications, including design improvements, material innovations, and advanced control mechanisms. These suggestions aim to facilitate the wider adoption of HHP technology, making it a viable, sustainable, and efficient solution for diverse infrastructure needs, from roadways and bridges to bicycle lanes and pedestrian walkways.

7.1 Thermal and mechanical response of hydronic heated pavements

Hydronic Heated Pavements Systems (HHPS) prevent snow and ice accumulation by circulating heated fluid through embedded pipes, enhancing road safety and infrastructure durability. They reduce reliance on de-icers, lower maintenance costs, and can integrate renewable energy sources for sustainable operation. Hydronic Heated Pavement (HHP) can also extract thermal energy from asphalt pavement and supply clean energy for domestic or industrial purposes. The efficiency of the HHPs is calculated by determining the ratio between the extracted energy and the thermal energy of the incident solar irradiation. The thermal performance of HHPs has been extensively studied with energy harvesting efficiency—defined as the ratio of extracted heat to incident solar radiation—estimated to range between 20% and 30% in most cases, and reaching up to 50% in some studies (Lund 2000, Zhou et al. 2013, Ceylan et al. 2014, Guldentops et al. 2016, Johnsson and Adl-Zarrabi 2020, Ghalandari et al. 2022). The energy harvesting capacity of large-scale HHPs is influenced by a combination of factors, including their geometric design, geographic location, and operational conditions [9]. Key parameters such as pipe spacing, flow rate, inlet supply temperature, and pipe embedment depth significantly affect the efficiency of these systems (Ghalandari et al. 2022, Ghalandari et al. 2023). It should be noted that an increase of efficiency results in ultra-low fluid temperatures which is insufficient for direct use in district heating purposes, and needs for supplementary heating to integrating HAPs into district heating networks.

The application of HHPs can also reduce the temperature gradient through the depth of the pavement. Recent studies claimed that pavement service life could be extended between 3-5 years by using HHPS (Mallick et al. 2009, Dakessian et al. 2016). This is due to controlling the temperature profile of the asphalt pavement, which could reduce distresses, such as top-down cracking, rutting, and fatigue cracking (Ghalandari et al. 2022). A recent research study showed that stress concentrations are more likely to develop around the pipes, and the higher tensile stress becomes more prominent between adjacent pipes, where its findings indicated that stress concentration could be diminished by increasing pipe spacing and pipe depth (Zhu et al. 2021). Nevertheless, such adjustments are likely to lead to a decline in snow melting effectiveness.

Therefore, during the design phase, the structural performance of HHPs presents a challenge, as proper pipe placement is critical. To ensure that the potential risks of structural damage remain within an acceptable range for the road, the generated tensile stresses must remain minimal, and the interface shear strength shall exceed the shear stress. From this point of view, the pipe depth is a key design parameter to fulfil a balanced trade-off between harvesting maximum heat (pipes closer to the surface) and minimum risk of structural damage (pipes deeper in the asphalt layer). Despite the importance of the structural response of HHPs, there remains a paucity of evidence on the optimum pipe depth and impact of HHPS on damage reduction as a result of reduced asphalt pavement temperature profile.

7.2 Heat extraction and injection, energy collection efficiency

A recent feasibility study conducted on a large-scale HHP project in Utrecht province, Netherlands, evaluated the annual heat gain capacity of the system under various pipe section length configurations. The study estimated the total heat harvesting potential to range between 0.58 and 1.15 GJ/m² per year, depending on the pipe section length (Figure 26). The findings revealed that increasing the pipe section length from 50 to 300 meters resulted in a substantial 49% reduction in heat harvesting capacity, underscoring the significant influence of pipe configuration on the thermal performance of HHPS (Ghalandari et al. 2023).

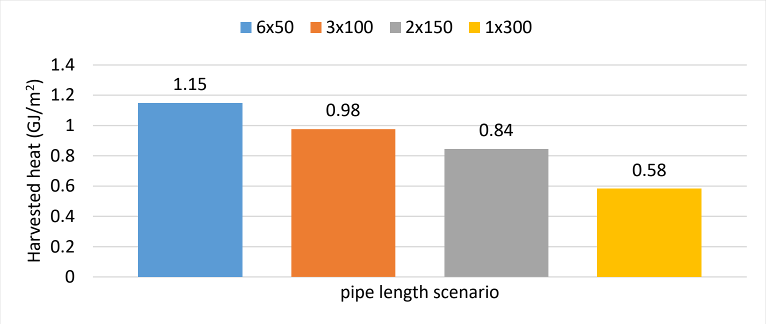

Figure 26. Total yearly heat harvesting capacity for various pipe section length for the following design parameters: flow rate 180 l/hour, pipe depth 7.5 cm, and water inlet temperature 12 °C (April-September 2020)

The response of pipe embedment change on the harvested heat is shown in Figure 27. The results show that an increase in pipe depth decreases the heat gain in HHPs. Figure 27 displays the harvested monthly energy at different embedment depths for pipe lengths. The results of the parametric analysis show that an increase in pipe embedment depth from 75 mm to 150 mm decreases the heat gain capacity by 20% and 10% for the 50 m and 300 m pipe length, respectively.

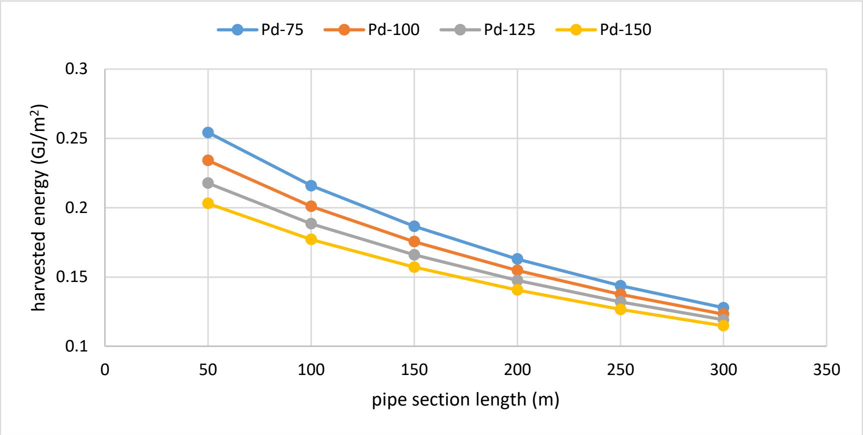

Figure 27. Harvested monthly energy vs. embedment depth for various pipe section lengths for June 2020 with the following design parameters: flow rate 180 l/hour and water inlet temperature 12 °C

In terms of pipe section length, Figure 28 displays the harvested yearly heat energy vs. embedment depth variation in four pipe section length scenarios. According to this figure, with an increase of pipe section length from 50 to 300 m, the yearly energy harvest drops by half, while an increase of pipe section length from 100 to 300 m will result in a 40 % drop in yearly energy harvest. It should be noted that the maximum harvested heat can be found in the 6x50 m scenario and a pipe embedment depth of 7.5 cm (1.14 GJ/m^2/year) (Ghalandari et al. 2023). Such geometric configurations significantly influence both the system's HHC in summer and its snow melting efficiency during winter. These aspects will be explored further in Section 0.

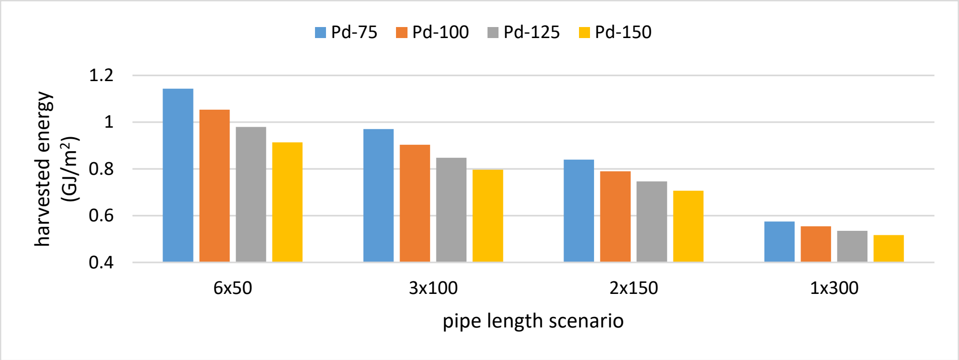

Figure 28. Harvested yearly heat energy vs. embedment depth variation for different pipe section length scenarios for June 2020 with the following design parameters: flow rate 180 l/hour and water inlet temperature 12 °C

A comparison of average hourly heat gain during summer with heat consumption for snow melting and de-icing in winter reveals that utilizing a low-temperature supply in winter can preserve over 80% of the heat harvested in summer, assuming an equal number of operational days. The remaining stored heat can be repurposed for applications such as supplying (preheated) domestic hot water or supporting heating systems in nearby buildings (Baetens et al. 2018, Ghalandari et al. 2022). Nonetheless, the direct use of this low-temperature heat in district heating networks remains a significant challenge.

7.3 Considerations for heat harvesting over time

The solar absorptivity of asphalt and concrete surfaces significantly influences the heat harvesting efficiency of HHPS. Asphalt, with its higher solar absorptivity, captures a larger portion of incoming solar radiation, resulting in higher surface temperatures and greater heat collection potential. Conversely, concrete, with lower absorptivity, reflects more solar radiation, thereby limiting its energy harvesting capability. As asphalt ages, its colour lightens, causing it to reflect a larger portion of incident solar radiation. This change can result in a reduction of up to 50% in the surface's absorptivity over the pavement's lifetime (Guldentops et al. 2016). Consequently, the decrease in HHC throughout the pavement's lifespan must be considered when designing HHP for heat harvesting applications.

(Guldentops et al. 2016) observed that the efficiency of asphalt solar collectors declines linearly over the pavement's lifespan, decreasing from approximately 18% to 13% as the absorptivity of the surface reduces from 0.95 to 0.65. This highlights the direct correlation between surface absorptivity and the collector's thermal performance (Ghalandari et al. 2023).

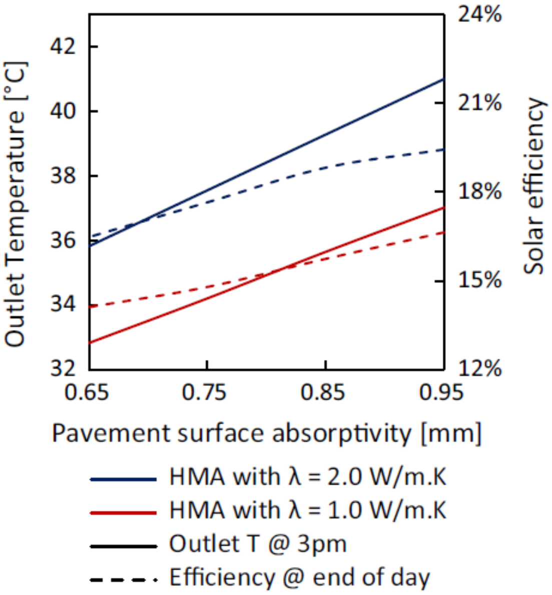

Figure 29. Solar efficiency as a function of pavement surface absorptivity (Ghalandari et al. 2023)

(Johnsson and Adl-Zarrabi 2020) investigated how variations in albedo impact the heat harvesting capacity (HHC) of concrete pavements. Their study calculated the energy absorbed by a concrete surface with albedo values ranging from 0.05 to 0.4 (Figure 30), using consistent weather data and control settings from an experimental setup during the summer of 2018. The findings revealed that reducing the surface albedo from 0.4 to 0.05 increased the harvested energy by approximately 30%, rising from about 240 kWh/m² to 320 kWh/m², demonstrating the significant effect of lower albedo on energy absorption.

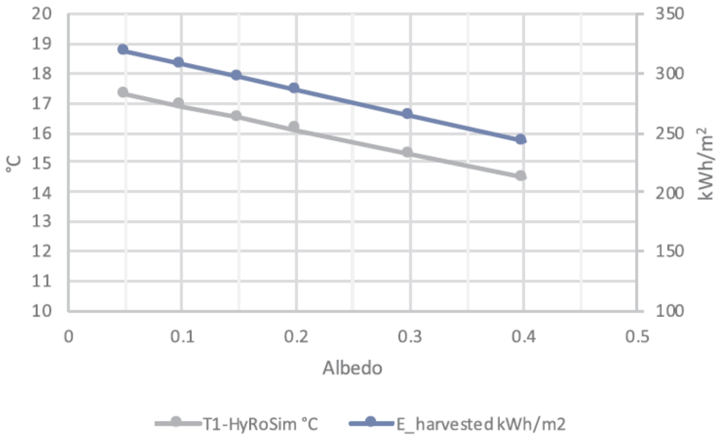

Figure 30. Calculated mean surface temperature (T1-HyRoSim) and accumulated amount of harvested energy corresponding to different values of albedo on pavement surface (Johnsson and Adl-Zarrabi 2020)

7.4 Thermal vs. structural performance trade off

The thermo-mechanical behaviour of HHPS is significantly influenced by various geometrical parameters, with pipe embedment depth being a key factor affecting snow-melting performance. Shallower pipe placement generally enhances efficiency by reducing the thermal resistance between the heat source (flowing fluid through pipes) and the road surface. This allows for quicker and more effective heat transfer, enabling faster snow melting and improved safety during winter conditions. Moreover, snow melting is more uniform with shallow pipes and dense pipe spacings, as heat is distributed more evenly across the surface. In contrast, deeper pipe embedment may lead to heat loss within the pavement layers and uneven heating, leaving some areas prone to ice formation and reducing the system's effectiveness.

Placing pipes closer to the surface increases the risk of pavement damage, especially in areas subjected to high traffic intensity and frequent load cycles. Conversely, in low-traffic zones, such as parking lots or sports fields, the likelihood of such damage is minimal, making shallow pipe placement more feasible. Hence, structural durability and maintenance of the roads equipped with HHPS necessitate a minimum depth for pipe embedment.

When comparing thermal and mechanical considerations, it is crucial to recognize that only geometrical factors such as pipe embedment depth and pipe spacing influence the mechanical response of HHPS. Operational parameters, such as fluid flow rate or inlet temperature, do not directly affect the mechanical performance of the pavement. As a result, the pipe placement depth in HHP requires careful optimization to balance thermal performance with structural durability. By addressing these trade-offs, HHPS can achieve efficient snow melting, contributing to safer and more sustainable winter road management solutions.

7.5 Suggestions to facilitate system development for further applications

HHPs represent a promising technology for improving winter road safety and infrastructure durability by enabling effective snow melting and de-icing. Despite their promising potential, the widespread adoption of HHP technology is limited by various technical, operational, and financial obstacles.

Expanding the use of HHPS to areas such as airport aprons, aircraft parking stands, and tunnel entrances can significantly reduce safety hazards caused by ice accumulation and enhance operational reliability. Airports, where ice buildup can lead to flight delays and safety risks, could greatly benefit from HHPS by minimizing the need for chemical de-icing and mechanical snow removal. Similarly, tunnel entrances, which often experience abrupt temperature fluctuations leading to ice formation, could be kept clear with minimal energy input.

To maximize the benefits of HHPS and expand their applicability, it is crucial to focus on targeted improvements and innovations. Key priorities include optimizing system design for enhanced thermal efficiency, selecting materials that improve performance and durability, and integrating sustainable energy solutions. Additionally, adapting to diverse climate conditions, exploring advanced control strategies, and ensuring cost-effective construction and maintenance practices are essential to making HHP technology more accessible and scalable.

This section presents actionable suggestions to address these challenges and facilitate the development of HHPS for broader applications. By identifying pathways for innovation and overcoming existing barriers, these recommendations aim to support the adoption of HHP technology, ultimately contributing to more resilient and sustainable infrastructure solutions.

7.6 Technological advancements

Advancing the design and configuration of HHPs is essential to enhance their efficiency and broaden their applications. One of the critical aspects in snow and ice melting systems is achieving uniform heat distribution across the pavement surface. Among the various pipe configurations, the serpentine layout is widely used due to its simplicity and ease of installation. However, it has limitations in evenly distributing heat, as significant surface temperature differentials can occur. Alternatively, the reverse-return layout offers a more effective solution for uniform heating. This configuration positions the supply and return tubing parallel to each other, ensuring that the entire snow and ice melting surface heats evenly, making it particularly suitable for applications where uniformity is a priority.

Beyond layout considerations, the depth, spacing, and material of the pipes play pivotal roles in determining the thermal efficiency and snow melting performance of HHPS. Geometric design parameters, operational conditions, and thermophysical properties of materials are the primary factors influencing system performance (for further details, refer to *WP2 - development of system components for selected applications*). However, these factors differ in their sensitivity to snow melting efficiency and feasibility of alteration. Geometrical parameters such as pipe depth and spacing are relatively adjustable during the design and construction phases, enabling tailored optimization for specific applications. In contrast, material properties, such as thermal conductivity and durability, are less flexible due to their significant contribution to system construction and associated logistical challenges. Given the high costs associated with material transportation and procurement, prioritizing locally available, high-performance materials is essential for efficient HHP development.

In road applications, incorporating insulation presents challenges in the base and subbase layers, as it may affect the load transfer mechanism. However, in bike paths and pedestrian walkways, where mechanical loads are minimal, insulation can significantly enhance thermal performance with negligible impact on structural integrity.

To expand the scope of HHPS for broader applications, their adaptability must be ensured to optimize effectiveness across various climatic conditions and infrastructure types. Since climate varies significantly by region, key factors such as ground temperature (especially in geothermally coupled projects), ambient air temperature, and precipitation patterns must be carefully considered during the design and implementation phases. Large-scale HHP installations must be designed to function effectively in high-priority areas where maintaining a snow-free surface is crucial, such as helipads, emergency entrances, and other critical locations. In cases where uninterrupted operation is crucial, integrating a backup heat pump can ensure reliable snow and ice prevention when thermal energy alone is insufficient.

7.7 Material improvements

Advancements in asphalt and concrete materials will enhance the thermal efficiency, durability and overall energy efficiency transfer of HHPs. One promising approach involves modifying asphalt mixtures to increase thermal conductivity. Factors such as binder composition, air void content, and the type of aggregates used significantly influence the thermal properties of the mix. Incorporating conductive materials, such as quartzite or steel slag, as fillers or aggregates has shown potential for enhancing conductivity due to their superior thermal properties. Additionally, asphalt gradation and compaction techniques contribute to improving heat transfer efficiency, ensuring uniform heat distribution across the pavement surface (Abbas and Alhamdo 2023).

Surface coatings and additives also present opportunities for maintaining or enhancing absorptivity over the pavement's lifetime. While colouring asphalt is a cost-effective method to increase HHC, evidence supporting its direct impact on snow-melting performance remains inconclusive. Thus, further research into innovative surface treatments that sustain long-term absorptivity while improving snow-melting efficiency is needed.

Pipe materials are another critical consideration in the overall performance of HHPS. Polyethylene (PE) and cross-linked polyethylene (PEX) are commonly used in large-scale projects due to their low cost, ease of installation, and durability. However, alternative materials like copper or iron, while offering higher thermal conductivity, are more expensive and prone to issues like leakage and corrosion. Balancing cost, thermal efficiency, and long-term reliability is essential when selecting materials for HHPS. These material innovations underscore the importance of adapting solutions to specific project needs and constraints, particularly for improving thermal efficiency and ensuring the durability of HHPs in diverse environmental conditions.

When utilizing high-temperature inlet supplies, such as waste heat, the pipe material, connections, and manifolds must be designed to withstand elevated temperatures. While there are no strict limitations on the lower boundary of the inlet supply temperature, the upper limit is primarily dictated by construction materials rather than the PEX tubing itself. For concrete installations, it is recommended that the maximum supply fluid temperature does not exceed 65.56°C to prevent expansion and cracking .

7.8 Operational strategies and maintenance

Efficient operation of HHPS relies heavily on advanced control strategies designed to optimize energy use while maintaining system effectiveness. Adaptive control mechanisms, such as temperature modulation and real-time monitoring, are important in achieving this balance. For instance, integrating predictive models for surface temperature estimation and implementing automatic on/off controls can significantly improve operational efficiency. Such systems could anticipate weather changes, activating or deactivating the system based on forecasted conditions to ensure the pavement remains ice-free without excessive energy consumption.

Operational strategies for HHPS follow two distinct approaches. The first approach evaluates system performance based on its capacity to melt a predetermined amount of snowfall per hour. However, this method is influenced by several variables, including snowfall prediction accuracy, snow density, wind conditions, and road surface temperature, making precise performance forecasting challenging. The second approach, on the other hand, designs the system according to prevailing outdoor climatic conditions to ensure reliable snow and ice melting performance. This method accounts for environmental factors more comprehensively. Additionally, more effective control parameters, such as dew point temperature, may be used instead of air temperature, offering better predictions of icy conditions and system activation needs (Mirzanamadi et al. 2018).

Another key consideration is the implementation of pre-heating strategies, which involve maintaining the pavement surface just above freezing for a few hours before snowfall (idling time). This approach has been shown to reduce overall heat demand for snow melting while also preventing potential expansion and fracturing of concrete slabs caused by rapid temperature fluctuations. By pre-heating the pavement, energy consumption is minimized, and the system responds more efficiently to snow and ice conditions. Additionally, for any intermittent control strategy or shifting between an idle setpoint and an active snow-melting temperature, it is essential to monitor the temperature differential between the supply and return fluid within the slab.

Regular maintenance of HHPS ensures their long-term performance and minimizes operational disruptions. Key components requiring attention include valves, connections, manifolds and the Heat Exchanger (HEX) sections. To address potential issues like leakage, the system should be designed with segmental HEX sections that can be connected in series or parallel depending on the project requirements. This segmentation not only simplifies repairs but also ensures that the system remains operational by redirecting the flow to unaffected segments (Figure 31). Pressure and temperature monitoring systems are another aspect of maintenance. By integrating alarms for pressure drops or unusual temperature variations, potential issues such as leaks or blockages can be identified and resolved promptly. This proactive approach reduces downtime and prevents more extensive damage to the system. By implementing these advanced operational strategies and robust maintenance practices, HHPS can achieve higher energy efficiency, extended service life, and improved performance, even under challenging winter conditions.

Figure 31. Manifolds of a RES project, source De Peyler (www.restreets.org/case-studies/solar-roadway)

7.9 Economic and feasibility considerations

Minimizing the cost of HHPS is essential for their broader implementation. One effective strategy is optimizing design techniques for both flexible and rigid pavements. In rigid pavement applications, instead of embedding pipes during on-site construction, they can be pre-installed in prefabricated pavement sections. This modular approach significantly shortens construction time and reduces road closures, leading to lower labour costs and minimal traffic disruptions.

Another way to enhance cost efficiency is by standardizing HHP designs for different applications and material types, creating a catalogue of pre-designed solutions (Uponor 2015). Developing adaptable, location-specific designs allows for easier integration into various infrastructure projects, reducing the need for extensive customization. This method is particularly advantageous for public-private partnerships, government-funded projects, and municipal planning, as it simplifies the design process and ensures cost-effective, scalable implementation. A standardized design framework enables engineers to implement HHPS across diverse climatic conditions efficiently.

Although the initial investment for HHPS may be high, their long-term financial and environmental benefits make them a viable economic solution. One of the most significant advantages is the improvement in pedestrian and vehicle safety. As outlined in *IEA ES Task 38 "Ground Source De-Icing and Snow Melting Systems for Infrastructure – WP1*, HHPS reduce winter-related accidents on sidewalks and roadways, decreasing government expenditures on medical care, insurance claims, and compensation for injury-related social benefits (Amin et al. 2024). This is particularly relevant in urban areas, where pedestrian safety is a priority.

For suburban and highway applications, Life Cycle Cost Analysis (LCCA) should account for advantages such as reduced traffic delays, improved roadway efficiency, and extended pavement lifespan. By preventing ice accumulation and mitigating freeze-thaw damage, HHPS lower maintenance costs and prolong pavement durability, leading to reduced long-term infrastructure costs. Additionally, these systems contribute to environmental sustainability by decreasing road salt usage and lowering greenhouse gas emissions associated with conventional de-icing methods. Moreover, when HHPS are integrated with renewable energy harvesting, their economic feasibility is further enhanced. These systems can collect and store heat during warmer months, which can then be used for snow and ice melting in winter, increasing energy efficiency (Section 0). The potential for integrating HHPS into district heating networks makes them even more cost-effective and sustainable, providing a solid return on investment over time.

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SUMMARY OF ACTIVITIES FOR SUBTASK 3

The Subtask 3 of Task 38 aimed to advance the development of system components for ground source de-icing and snow melting hydronic heated pavement (HHP) systems for specific applications. The focus was on optimizing the thermal design of heating surfaces, defining the mechanical requirements for surface heating systems where necessary, and selecting appropriate materials for HHPs across different infrastructure types.

In mid-2021, the Sustainable Pavements and Asphalt Research (SuPAR) team at the University of Antwerp was invited to lead Subtask 3. The team successfully achieved the objectives outlined in the initial work plan. During the first meeting in October 2021, the draft content was reviewed, and key areas were refined to enhance project alignment. Initially, Subtask 3 covered the thermal design of heating surfaces, mechanical requirements for the surface heating system, materials for geothermal heating systems, and adapted drilling methods.

Following discussions with subtask leaders and Task Manager Bijan Adl-Zarrabi, the scope of Subtask3 was revised and structured into the following sections:

- State-of-the-art review of system component developments for selected applications
- Evaluation of thermal design for heating surfaces
- Analysis of factors influencing the thermal performance of HHPs
- Studying on the mechanical requirements of surface heating systems
- Addresses the thermal and mechanical balance response of HHPs and proposes strategies to support further system development for expanded applications.

This structured approach not only consolidates current knowledge and advancements but also sets the foundation for future innovations, ensuring the development of efficient, resilient, and adaptable HHP systems for diverse infrastructure needs.

Meetings and collaborative activities

Throughout the execution of Task 38 - Subtask 3, active participation in international meetings facilitated collaboration between research groups from different countries and institutions. Key milestones included:

- **April 2022** – Attended an online meeting to define the objectives of Subtask 3 and welcome new members to Task 38, coordinated by UAntwerpen.
- **November 2022** – Participated in an online meeting in Istanbul, where the Subtask 3 outline was presented and approved by experts and subtask leaders.
- **May 2023** – Organized and hosted an expert meeting in Antwerp, Belgium, where findings from experimental and laboratory testing on a large-scale prototype were reviewed and discussed.
- **March 2024** – Took part in the expert panel meeting (online) in Perugia, presenting the draft of Deliverable 1 for Subtask 3 and refining the study outline for selected applications, and discussions focused on the state of the art (SOTA) for Belgium (contribution to Subtask 1).

- **November 2024** – Final participation in the Gothenburg meeting, where Deliverables 1 & 2 were presented alongside a draft of Deliverable 3, with discussions on the overlapping objectives of WP2 & WP4 among expert partners.

Summary of activities - Deliverable 3.1&2

During the November 2024 expert meeting, it was decided that Deliverable 1 (HHP system components & sensitivity analysis of HHPs) and Deliverable 2 (Mechanical requirements of HHPs) would be combined into a single deliverable due to their closely related content.

The resulting report, D3.1-2: "Development of System Components for Selected Applications," provides a comprehensive review of the SOTA in HHP system components across various applications, including roads, bicycle lanes, ramps, and stairs. Key activities covered in this deliverable include:

- Categorization of case studies from literature, encompassing both small- and large-scale projects, classified into heavy-loaded, light- or no-load applications, and other specialized uses (e.g., railway switches).
- Definition of HHP components and sub-components, outlining their characteristics and material specifications.
- Sensitivity analysis of key parameters affecting thermal performance, focusing on geometrical specifications, thermophysical properties, and operational conditions. *(This section was discussed and finalized during the November 2024 Gothenburg meeting, leading to a restructuring of the deliverables.)*
- Evaluation of the mechanical response of HHPs, addressing provisions for the construction phase and necessary post-construction measures.
- Assessment of structural response, including deformation risks at high temperatures (rutting), tensile/compressive strength, and other practical considerations.

This deliverable establishes a solid foundation for further exploration of the thermal development and mechanical performance of HHPs.

Summary of activities - Deliverable 3.3

The report D3.3: '*Thermal vs. structural performance - Suggestions to facilitate system development for further applications*' explores the interplay between thermal and structural aspects, analysing how material selection, system configuration, and environmental factors influence the overall performance of HHPs. Moreover, this report offers strategic recommendations to enhance HHP development for broader applications, including design improvements, material innovations, and advanced control mechanisms. The key activities include:

- Evaluated the heat harvesting capacity of HHP systems under various pipe configurations (e.g., reverse-return vs. serpentine), demonstrating that optimal pipe spacing and shallower embedment significantly reduce melting time.
- Proposed using advanced control mechanisms, including adaptive temperature modulation and real-time monitoring, to optimize energy use. Recommended pre-heating strategies to

keep pavement surfaces above freezing before snow events, thereby reducing overall energy demand.

- Highlighted technological advancement and materials improvement for adaptability and optimising performance
- Outlined cost reduction strategies such as employing modular designs, prefabricated components, and standardized design catalogues to streamline construction and reduce installation time.
- Highlighted long-term benefits, including reduced maintenance costs, extended pavement lifespan, improved safety outcomes, and lower environmental impact through renewable energy integration.
- Recommended collaborative research initiatives to address technical, economic, and operational challenges, paving the way for scalable and sustainable HHP solutions.

8. PLANNING, CONSTRUCTION, AND MONITORING SUBTASK 4, DELIVERABLE 4.1: MAPPING OF DEMONSTRATION AND EXISTING PLANTS

This report is part of the work conducted within the framework of IEA ECES Task 38, "Ground Source De-Icing and Snow Melting Systems for Infrastructure," covering 2021 to 2024. The main objective of this task is to promote the use of ground source de-icing and snow-melting applications. This document focuses on the objectives of Subtask 4.1, which aims to gather and analyze information from demonstration plants and national reports, presented in subtask 1, to provide recommendations for the future development and integration of renewable energy-based de-icing and snow-melting systems.

Based on the input from Subtask 1, this report highlights the key findings related to utilization of ground source energy, underground thermal energy storages included, control systems, and the types of applications where these technologies are implemented. The findings provide a comprehensive overview of current technologies while identifying potential innovations and market opportunities for ground source de-icing and snow-melting systems.

The authors gratefully acknowledge the financial support from the Swedish Energy Agency, Grant 51491-1.

Chapter 1 outlines the background and objectives of the work, emphasizing the role of ground source thermal energy in de-icing and snow-melting. **Chapter 2** maps de-icing and snow-melting systems across participating countries, including Sweden, Germany, France, Belgium, Italy, Türkiye, and Japan. **Chapter 3** details the demonstration plants using ground source systems, highlighting technological advancements, performance, and challenges. **Chapter 4** summarizes key insights and outlines future development needs for ground source energy-based de-icing and snow-melting technologies.

8.1 Introduction

Winter maintenance is crucial for ensuring safety and accessibility of infrastructures. De-icing and snow-melting systems are widely used across various applications, including roads, bridges, parking lots, runways, railway switches, and public spaces such as stadiums and football fields. In cold climates, these systems not only improve mobility but also reduce fall-related accidents and injuries of pedestrians. For example, in Sweden, pedestrian falls due to icy conditions are a significant societal cost, leading to thousands of injuries and substantial healthcare expenses per year. The use of hydronic heated pavement systems (HHPSs) has shown to drastically reduce the number of falls-related accidents in urban areas.

Despite their widespread adoption, many existing de-icing systems rely on conventional electrical heating or district heating, both of which have environmental and economic limitations. Electric heating systems (EHPSs) consume large amounts of energy, and district heating, though more sustainable, is often unavailable in rural or remote locations. As a result, there is a growing interest in integrating renewable and energy-efficient technologies, such as geothermal energy and ground source heat pumps (GSHPs), to reduce the environmental impact and operational costs of winter maintenance systems.

This report is part of the IEA ECES Task 38 "Ground Source De-Icing and Snow Melting Systems for Infrastructure" (2021–2024). The overall goal of Task 38 is to promote the use of renewable energy sources in de-icing and snow-melting systems, with a particular focus on ground source thermal energy. By replacing conventional electrical resistance heating with systems powered by ground sources, Task 38 aims to improve energy efficiency, reduce greenhouse gas emissions, and enhance the resilience of infrastructure during winter season.

The specific objective of this report, developed under Subtask 4, is to map and analyze de-icing and snow-melting systems in participating countries. The mapping focuses primarily on technologies with a Technology Readiness Level (TRL) of 8 or higher, ensuring that the analysis reflects well-developed and commercially viable systems. Information was gathered from national reports and demonstration plants (subtask 1), to provide recommendations for future development and integration of renewable energy-based de-icing systems.

This report includes a general mapping of de-icing and snow-melting systems across seven countries: Sweden, Germany, France, Belgium, Italy, Türkiye, and Japan. Moreover, a specific mapping of demonstration plants utilizing ground source energy is presented. Through this analysis, the report provides a comprehensive overview of current technologies and highlights opportunities for future innovation, to foster more sustainable and resilient infrastructure solutions.

8.2 General mapping of de-icing and snow-melting applications in the participating countries

This chapter provides a comprehensive review of the de-icing and snow-melting applications implemented across the participating countries. The content is derived from the national reports of Subtask 1 of the project. The general mapping aims to categorize the various systems used, their heat sources, and the corresponding applications. A detailed account of the power demand, energy consumption, and control mechanisms is also provided in case of available data. For further details on specific cases, the reader is referred to Appendix D4.1.

Sweden

Sweden's cold climate necessitates effective snow and ice management systems across a range of infrastructure, particularly during the winter months. Various de-icing and snow-melting systems have been implemented nationwide, utilizing different heat sources. Figure 1 presents a general categorization of these applications, techniques, and heat sources, and Table 1 summarizes power and energy demands.

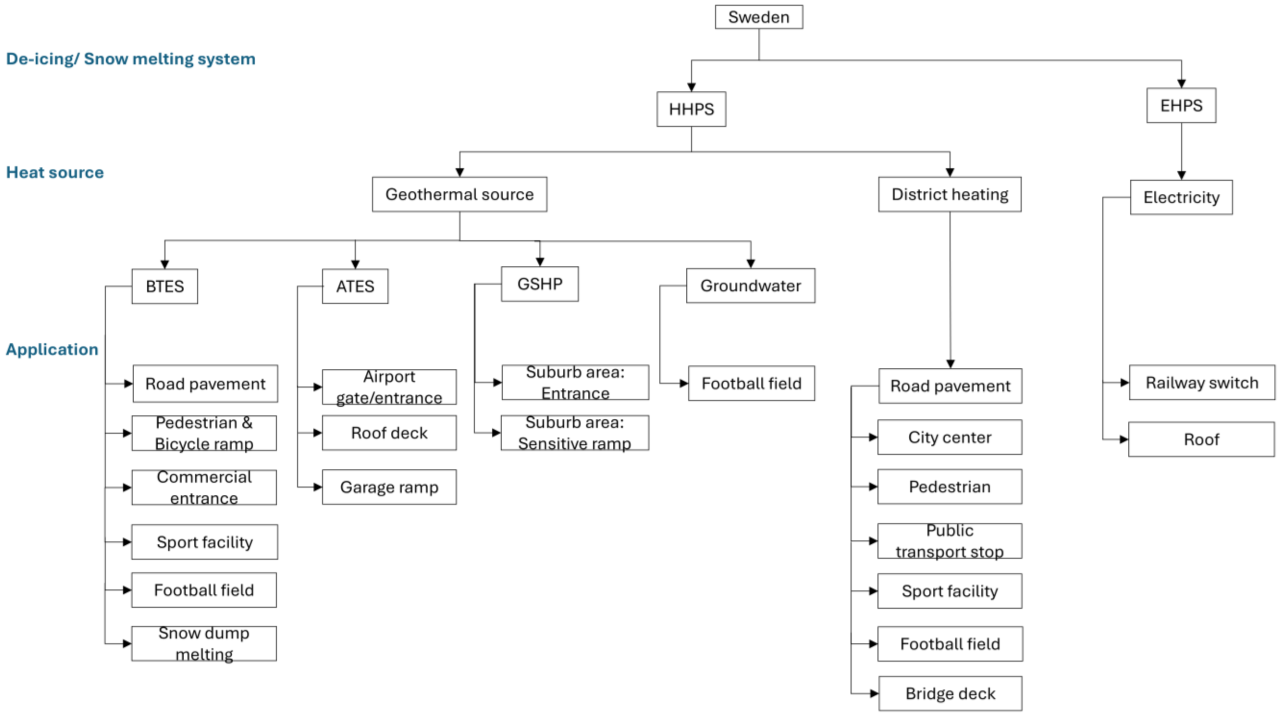

Figure 32. General mapping of de-icing and snow-melting applications in Sweden, describing the utilized techniques and the corresponding heat sources.

Table 1. Examples of the de-icing applications in Sweden, the corresponding system and typical power and energy demand.

Application	De-icing/ Snow-melting system	Required power, (Energy)
Railway switch	EHPS	100 W/plate, (100-130 GWh/year)
Pavement road	HHPS	250-350 W/m^2, (300-350 kWh/m^2/year)
Football field	HHPS	N/A, (800-900 MWh/field/year)

De-icing and snow-melting systems

The predominant de-icing systems in Sweden are hydronic heated pavement systems (HHPSs) and electrical heated pavement systems (EHPSs), each applied depending on the infrastructure and local energy sources.

- (HHPS: Extensively used in pedestrian areas, roads, bridges, sports fields, and airports, HHPS systems rely on heated fluids circulated through pipes to melt snow and ice. The most common heat source for HHPS in Sweden is district heating (DH).
- EHPS: These systems, typically involving cables or mats, are mainly used in smaller or more localized applications, such as railway switches, building entrances and roofs.

Key applications and heat sources

1. City centers: HHPS systems are commonly used to ensure pedestrian safety in busy areas such as sidewalks, public transport stops, and squares. These systems cover around 600,000 m^2 across Swedish cities, with power demands ranging from 250 to 350 W/m^2 and annual energy consumption of 300-350 kWh/m^2. District heating is the

primary energy source, and most systems are automated based on surface temperature or weather forecasts.

2. Sports facilities: Football fields with artificial turf are a key application of HHPS. Approximately 8% of these fields are equipped with heating systems covering a surface area of around 580,000 m². These systems typically consume 800-900 MWh per field annually, primarily powered by district heating. Automatic controls optimize the system's efficiency based on weather conditions and precipitation levels.
3. Airports: Stockholm Arlanda Airport utilizes HHPS systems powered by Aquifer Thermal Energy Storage (ATES), which stores heat from cooling systems and solar energy collected during the summer. Covering an area of 100,000 m², these systems are fully automated and consume around 10 GWh annually for both de-icing and cooling.
4. Roads and bridges: HHPS systems are also deployed to ensure safe driving conditions on roads and bridges, particularly in areas prone to ice buildup. For instance, Göteborgsbacken has 30 km of heating pipes installed to prevent icing on a steep ramp, with a power demand of around 350 W/m².
5. Railway switches: EHPSs are widely used for railway switches, with total energy consumption ranging between 100 and 130 GWh per year. Control systems activate the heaters when outdoor temperatures drop to between 6-8°C, with plans to install more efficient point heaters that activate at 0°C.

Ground source energy in de-icing and snow-melting systems

While district heating is the dominant energy source for HHPS systems in Sweden, ground source heat such as Borehole Thermal Energy Storage (BTES) and ATES are emerging as a more common alternative. These systems, used in locations like football fields and airports, offer CO_2 reductions (up to 85-95%) compared to district heating systems. They store excess heat during the summer, which can then be used for de-icing during the winter months, offering both environmental and cost-saving benefits.

Germany

Germany’s varied climate, from temperate lowlands to snow-prone mountainous regions, requires robust snow and ice management systems to maintain the safety and functionality of infrastructure. To address this need, Germany has implemented a wide array of de-icing and snow-melting technologies, customized to fit the country’s geographic and climatic diversity. Figure 33 and Figure 34 illustrate the general categorization of de-icing applications in Germany, based on the heat sources and technologies used. Table 2 highlights the energy and power demands of the key systems in a selection of applications. The following overview explores the primary systems, heat sources, and major applications in Germany.

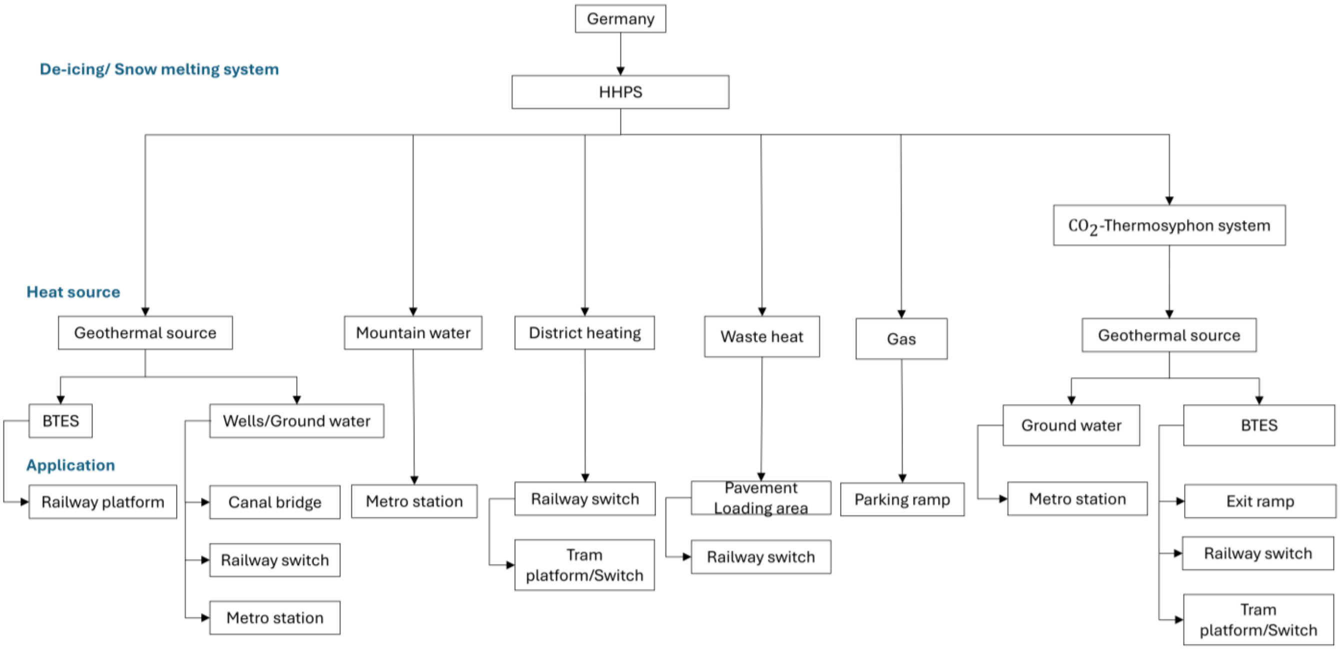

Figure 33. General mapping of de-icing and snow-melting applications in Germany utilizing hydronic heated pavement system, and the corresponding heat sources.

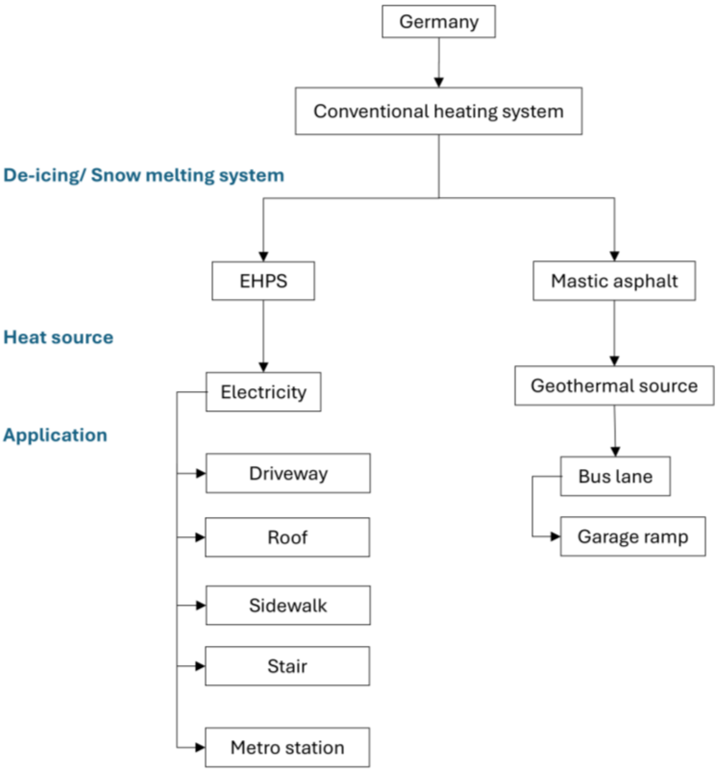

Figure 34. General mapping of de-icing and snow-melting applications in Germany utilizing non-hydronic heated pavement system, and the corresponding heat sources.

Table 2. Examples of the de-icing applications in Germany, the corresponding system and typical power and energy demand.

Application	De-icing/Snow-melting system	Required power, (Energy)
Parking ramp	HHPS	280 W/m^2, (N/A)
Pavement road	EHPS	200-500 W/m^2, (N/A)
Metro station	CO_2 thermosyphon	250 W/m^2, (N/A)

Railway switch	CO_2 thermosyphon/HHPS	Up to 1000 W/m², (N/A)

De-icing and snow-melting systems

The de-icing and snow-melting systems used in Germany include HHPSs, EHPSs, and other specialized solutions such as CO_2-thermosyphon systems and mastic asphalt systems. These systems are applied across a wide range of infrastructure, from urban roads and bridges to specialized industrial and transport applications.

- HHPS: These are widely used de-icing systems in Germany. A range of heat sources is used for HHPS, including district heating, geothermal wells, gas condensing boilers, and process waste heat. HHPS is frequently applied to large-scale outdoor areas, such as loading zones, parking ramps, bridges, and railway switches.

  EHPS: EHPS systems, which include cables or mats, are primarily used for residential and commercial settings. Applications include de-icing of driveways, sidewalks, stairs, and roofs. These systems operate during the winter months, typically controlled by temperature and humidity sensors, to maintain accessibility and safety.
- CO_2-thermosyphon systems: This system uses shallow geothermal energy to circulate CO_2 in a closed loop, utilizing phase changes (evaporation and condensation) to transfer heat. CO_2-Thermosyphon systems have been particularly used in railway switches, metro stations and ramps, where they help maintain functionality during freezing temperatures.
- Mastic asphalt systems: These systems use mastic asphalt in combination with ground source heat pumps or other heat sources to de-ice large surfaces such as bus lanes and parking ramps. Mastic asphalt is known for its durability and energy efficiency, making it suitable for industrial applications.

Key applications and heat sources

1. Loading Areas and Parking Ramps: HHPS systems are frequently used in loading zones and parking ramps, ensuring snow and ice are cleared from critical areas. For instance, the loading area at Roth Plastic Technology uses waste heat from injection molding production to de-ice a 750 m² area. Similarly, parking ramps in Unterföhring use gas condensing boilers to maintain a 180 m² surface, with a power demand of around 278 W/m².
2. Railway Switches and Platforms: Germany's extensive rail network requires advanced de-icing systems to ensure smooth operations during the winter. HHPS and CO_2-thermosyphon systems are used for this purpose. For example, the Triple S-System switch point heating system employs geothermal heat and waste heat in conjunction with automated controls to regulate the temperature of railway switches based on air and rail temperature, pressure, humidity, and snow drifts. These systems consume up to 1000 W/m², ensuring that critical rail components remain functional in extreme conditions.
3. Bridges and Roads: HHPSs are deployed to maintain safety on bridges and road surfaces, particularly in areas prone to snow accumulation and freezing temperatures. The canal bridge Berkenthin employs geothermal wells and a two-stage heat pump to maintain its bridge deck free from snow, using 110 W/m² in the first stage and 225 W/m² in the second stage. Additionally, the Füssen Border Tunnel test site uses HHPSs

powered by geothermal heat and mountain water to keep road surfaces clear of snow and ice, delivering a heating output of 400 W/m².

4. Public transport: Metro stations and tram switches also rely on advanced de-icing technologies. The Metro Station Therese-GiEHPSe-Allee in Munich, for example, utilizes a combination of systems: pumped systems, CO_2-thermosyphon systems, and electric resistance heating to maintain a snow- and ice-free surface. The system operates over a 200 m² area with a power requirement of 250 W/m², controlled via temperature and humidity sensors.
5. Industrial applications: Industrial sites, such as the Audi garage ramps in Ingolstadt, have implemented de-icing systems using geothermal energy combined with mastic asphalt. These ramps cover an area of 2200 m², demonstrating the scalability of mastic asphalt systems in large industrial applications.

Ground source energy in de-Icing systems

Germany has been one of the leaders in integrating ground source energy into de-icing systems. BTES and ground source energy via CO_2-thermosyphon systems are becoming increasingly popular, offering significant energy savings and environmental benefits. For example, railway switches and platforms in Bad Lauterberg and Barbis (Harz) use BTES to store and provide heat for de-icing. Similarly, CO_2-thermosyphon systems are employed in several pilot plants, including the Pintch Aben Geotherm switch point heating system, to ensure sustainable and energy-efficient winter maintenance.

France

France experiences a diverse winter climate due to its varied geography, which includes oceanic, continental, Mediterranean, and mountainous influences. This diversity necessitates a range of snow and ice management strategies across the country. Figure 35 presents the general mapping of de-icing and snow-melting applications in France, categorized by heat sources and techniques. Table 3 summarizes the power and energy demands for various applications.

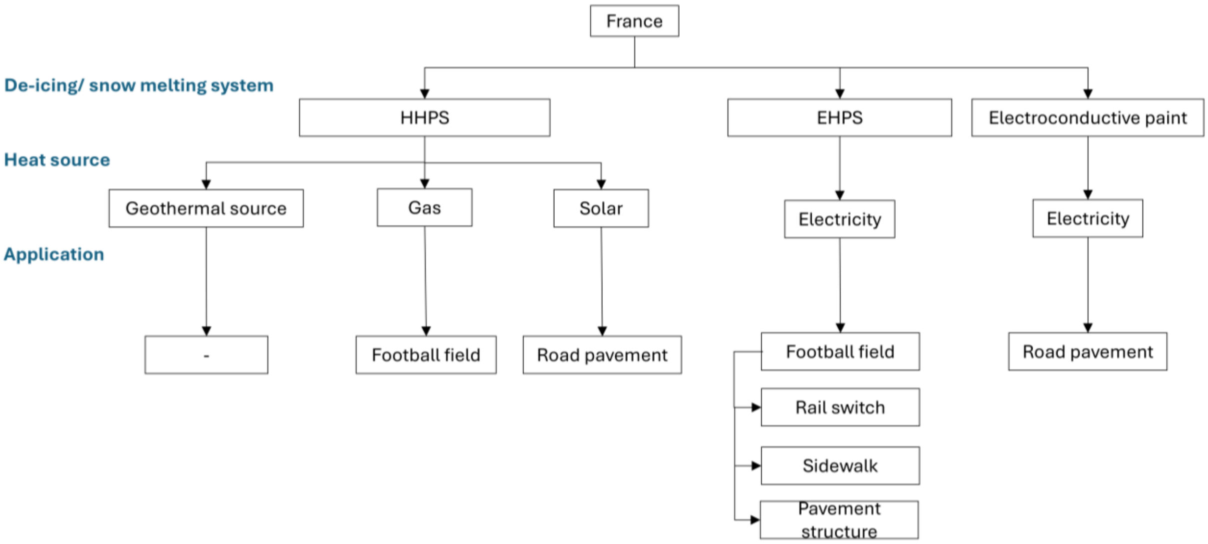

Figure 35. General mapping of de-icing and snow-melting applications in France, describing the utilized de-icing systems and the corresponding heat sources.

Table 3. Examples of the de-icing applications in France, the corresponding system and typical power and energy demand.

Application	De-icing/ Snow-melting system	Required power, (Energy)
Pavement road, Railway switch	EHPS	300 W/m^2, (N/A)

De-icing and snow-melting systems

In France, de-icing and snow-melting systems are typically divided between EHPSs and HHPSs, depending on the application and available energy sources. These systems are widely used across a variety of infrastructure, particularly in urban areas, transportation networks, and sports facilities.

- EHPS: These systems, usually in the form of electric cables or mats, are widely employed for railway switches, sidewalks, and pavement de-icing. They rely on electricity as a heat source and often come with automated control systems to ensure energy efficiency. The installation cost for these systems can range between €50-100 per m^2 in France, with typical energy consumption around 300 W/m^2.
- HHPS: These systems are most commonly applied in sports facilities such as football fields. The energy source for HHPSs in France is typically gas, with control mechanisms aimed at reducing consumption by regulating working times and temperatures.

Key applications and heat sources

1. Railway switches and pavement structures: EHPSs are widely applied in France for de-icing purposes in critical infrastructure such as railway switches and sidewalks. These systems are automated to ensure efficiency and are primarily powered by electricity. The energy consumption for these applications is typically around 300 W/m^2.

2. Football fields: Approximately 90% of football fields in France are equipped with either electric cables or HHPS to prevent snow and ice buildup, which is crucial for maintaining playability during winter months. The construction cost of these systems ranges from €250,000 to €1,000,000, with annual energy costs ranging from €25,000 to €140,000. In cases where games are canceled due to weather, the financial loss can reach up to €250,000, particularly when broadcasting is involved.
3. Road de-icing and building heating: A notable example of innovative technology in France is the Power Road® project on the Autoroute A10 in Saint-Arnoult-en-Yvelines. This system integrates ground source energy (via vertical probes) and a heat pump with energy-positive asphalt to provide roadway de-icing and building heating. The system is closely monitored with remote maintenance to track energy exchanges between the devices and geothermal production. Covering an area of 500 m², this system not only ensures road safety during winter but also stores energy for heating buildings during other seasons.
4. Solar-assisted systems: France has seen several innovative projects focused on utilizing solar energy and new asphalt solutions for de-icing and snow-melting. The Power Road project in Egletons and the Dromotherm project in Chambéry are two examples that harness solar radiation. These projects feature asphalt solar collectors designed to capture solar energy during the summer, which is then stored and used in winter to maintain ice-free surfaces.
5. Research and Development Projects: France is actively engaged in research to further optimize snow-melting and de-icing technologies. A notable project in Lyon, the ICCAR project, is experimenting with electroconductive paint applied to road pavements, powered by electricity. The project aims to optimize the thermal properties of these materials and develop advanced control systems to improve efficiency.

Ground source energy in de-icing and snow-melting systems

France has made progress in integrating ground source energy into de-icing and snow-melting systems. This is most evident in projects such as Power Road and the Autoroute A10, which use BTES to store heat inter-seasonally. These systems combine renewable energy with innovative design, offering sustainable solutions for winter maintenance that reduce reliance on conventional electricity and gas-powered systems.

Belgium

Belgium experiences a temperate maritime climate, which is characterized by relatively mild winters. While snowfalls are typically light and sporadic, frost and icy conditions often occur, making de-icing systems relevant for maintaining safe and accessible infrastructure during the winter months. Belgium has implemented a mix of conventional and innovative snow-melting and de-icing systems across its infrastructure, particularly in urban areas. Figure 36 presents a general mapping of these systems, while the table in the appendix D4.1 provides details on various projects and technologies.

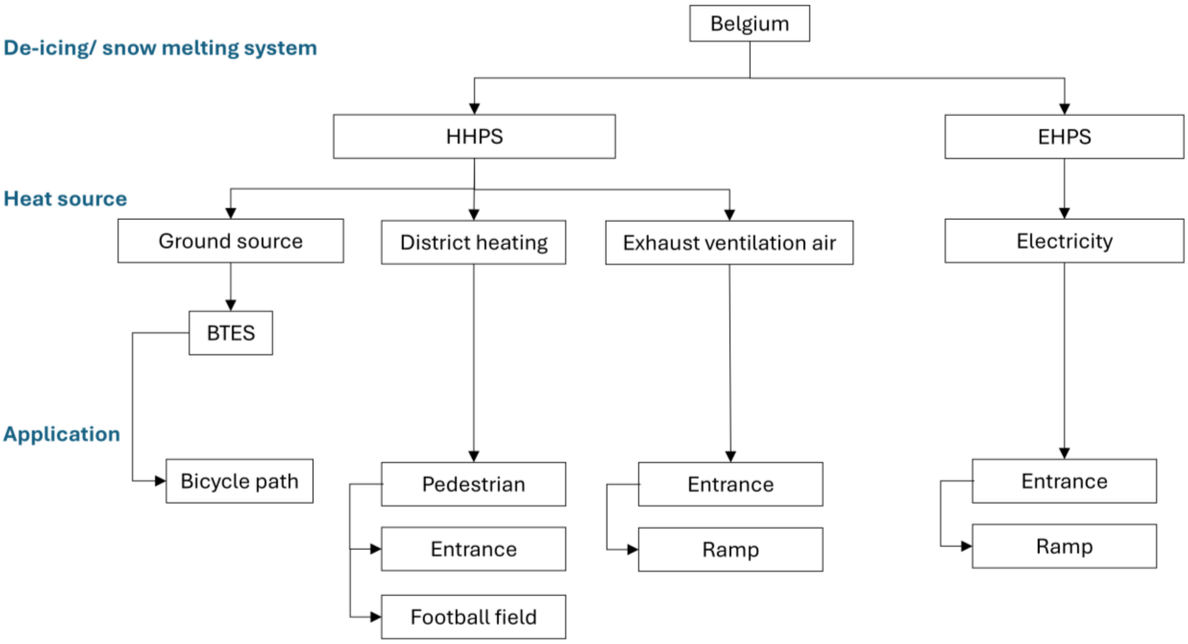

Figure 36. General mapping of de-icing and snow-melting applications in Belgium, describing the utilized de-icing systems and the corresponding heat sources.

De-icing and snow-melting systems

In Belgium, conventional de-icing and snow-melting systems based on EHPSs are typically used. Most EHPSs in Belgium are employed to de-ice pedestrian streets, building entrances, ramps, and football fields. These systems generally rely on district heating return or ventilation air volumes from buildings as their primary heat sources.

Research and innovative solutions

A number of demonstration projects have been developed in Belgium focusing on advanced de-icing systems moving from the conventional EHPSs. The Heat Exchange Asphalt Layer (HEAL) system, located at the University of Antwerp, is a prime example of such. The HEAL system uses a combination of solar radiation, harvested via an asphalt solar collector, and BTES to provide snow-melting and de-icing capabilities. The system covers 65 m² and includes two 100-meter-deep boreholes. In winter, the heat pump transfers stored heat from the BTES to the asphalt surface, supplying temperatures of up to 35°C. The HEAL system can be configured in various operational modes, including parallel or series pipe configurations, to optimize its performance in different weather conditions.

In addition to the HEAL system, the Zonnige Kempen Social Housing Complex incorporates an asphalt solar collector along with ground storage systems to provide heat for underfloor heating and domestic hot water (DHW) production. This system uses a smart control mechanism that prioritizes the production of DHW over underfloor heating. If the solar collectors provide sufficient heat, it can be transferred directly to the heating system; otherwise, stored heat from the ground storage system is used. The project is notable for its energy efficiency, with a 32% reduction in primary energy consumption during the first measurement period.

Hybrid ground source systems

Belgium is also exploring geothermal energy as part of its broader efforts to integrate renewable energy into de-icing solutions. Hybrid systems, which combine ground-source heat pumps with additional heat sources like solar or district heating, offer promising opportunities for large-scale snow-melting applications. Although not yet widespread, hybrid ground source systems in Belgium could mirror the successes of other international projects where geothermal energy has been effectively used for de-icing airport aprons and bicycle paths.

Italy

Italy's winter climate is highly diverse, due to the country's geographical range stretching from the Alps in the north to the Mediterranean Sea in the south. This diversity necessitates different snow and ice management approaches depending on the region. Italy can be divided into several climate zones that experience varying winter conditions, which influence the need for de-icing and snow-melting technologies.

De-icing and snow-melting applications in Italy

Although Italy's winters are generally mild in most regions, some areas like the Alps and Po Valley still require effective snow and ice management. However, the adoption of de-icing and snow-melting technologies is limited and primarily focused on small-scale applications. Figure 37 presents a general overview of the snow-melting and de-icing systems used in Italy. The main de-icing systems in Italy are EHPSs particularly electrical cables and mats. These systems are predominantly used for localized applications such as residential ramps, stairways, and helicopter landing areas.

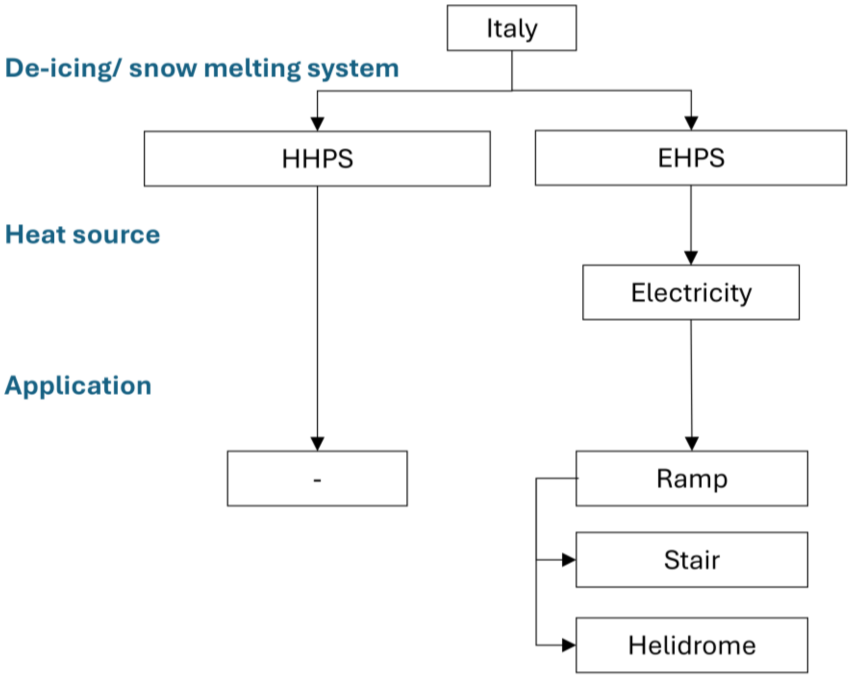

Figure 37. General mapping of de-icing and snow-melting applications in Italy, describing the utilized de-icing systems and the corresponding heat sources.

Residential and commercial settings: EHPSs are commonly employed to de-ice residential and commercial areas like residential ramp tracking, exterior stairs, and helicopter landing zones. These systems use electrical resistance heaters embedded in the surfaces that require de-icing, effectively melting snow and ice in these specific, targeted applications. The systems are powered by electricity, with continuous power supply being the primary operational scheme. While this ensures that snow and ice are efficiently removed, the high energy demand of electrical resistance heating limits operational use to about 100-300 hours per year. Unlike more advanced systems, the de-icing systems in Italy typically lack automated or advanced control mechanisms. The systems are straightforward, relying on continuous power supply during operational periods.

The predominant challenge in Italy's approach to de-icing is the high-power demand associated with electric resistance heaters. A move towards HHPSs or hybrid solutions could potentially enhance energy efficiency, reduce operational costs, and align Italy with broader sustainability goals.

Türkiye

Türkiye's diverse winter climate across its regions necessitates various de-icing and snow-melting systems, particularly in areas experiencing severe winters. A wide range of systems has been implemented nationwide, utilizing both electrical and hydronic heating technologies. Figure 38 presents a general mapping of these systems and their associated heat sources, while Table 4 summarizes typical power and energy demands.

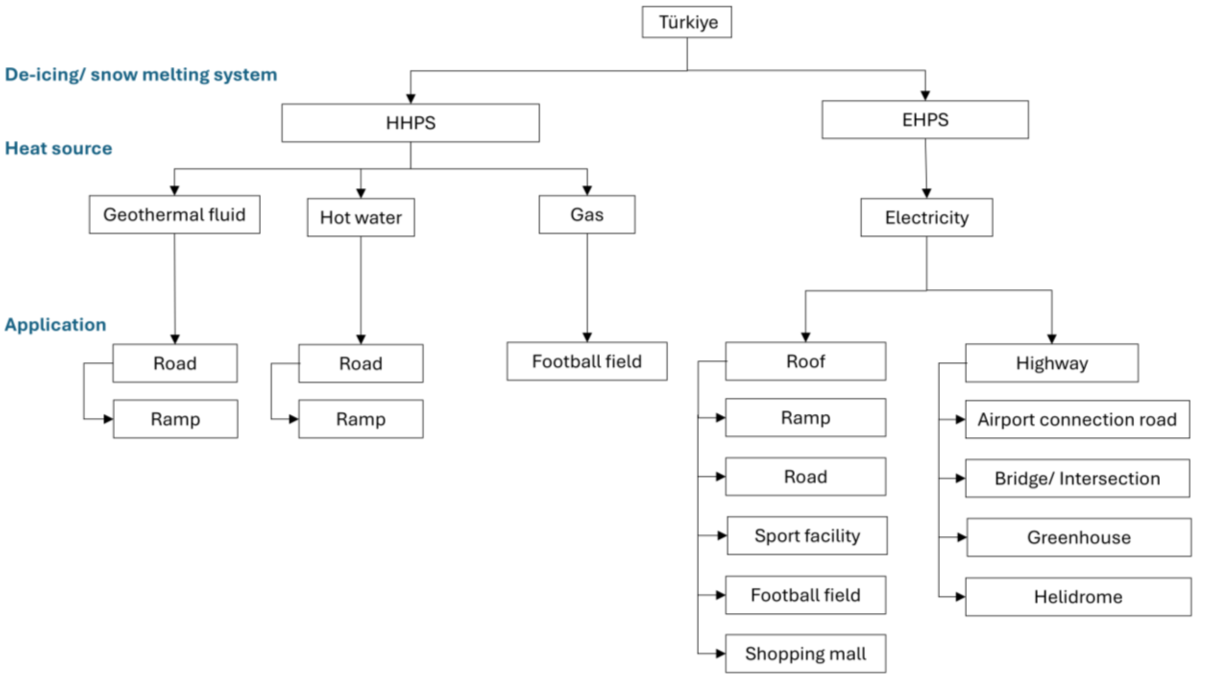

Figure 38. General mapping of de-icing and snow-melting applications in Türkiye, describing the utilized de-icing systems and the corresponding heat sources.

Table 4. Examples of the de-icing applications in Türkiye, the corresponding system and typical power and energy demand.

Application	De-icing/ Snow-melting system	Required power, (Energy)
Ramp and road	EHPS, HHPS	85 W/m^2 [300-500 W/m^2 cold regions], (N/A)
Stadiums and public space	EHPS	300-375 W/m^2, or 18-30 W/m, (N/A)
Roof	EHPS	30 W/m

De-icing and snow-melting systems

The de-icing systems in Türkiye are either EHPSs or HHPSs, each utilized based on the specific infrastructure and the region's climate conditions.

- HHPS: These systems are used for large areas such as ramps, roads, and football fields. HHPS systems often use gas or geothermal fluid as the primary energy source.
- EHPS: Typically found in smaller, more localized applications like pedestrian pathways, stairways, and roofs. These systems are widely used in airports, bridges, and rooftops to prevent snow accumulation and ensure safety.

Key applications and heat sources

1. Ramps and roads: HHPS and EHPS systems are used to maintain snow-free ramps and roads, especially in urban areas like Istanbul, Ankara, and Erzurum. The systems are often controlled by air and humidity sensors to ensure efficient energy use. In Istanbul,

power demands are typically around 85 W/m², whereas colder regions can require up to 300-500 W/m². These systems use electricity, gas, or geothermal fluids as the primary heat sources.

2. Football fields: Türkiye utilizes HHPS and EHPS systems for snow-melting on football fields, with a significant area heated by these systems: 157,080 m² by HHPS and 71,400 m² by EHPS. The design parameters assume an outdoor temperature of -10°C, with HHPS systems operating at a supply temperature of 50°C and a return temperature of 34°C. This setup ensures that playing surfaces remain free from snow and suitable for use during the winter season.
3. Public and commercial spaces: EHPS systems are prevalent in public areas such as stadiums, shopping malls, parking areas, and airports. The electrical cables used in these systems provide heat output ranging from 18-30 W/m or up to 300-375 W/m² in colder regions like Ankara, Istanbul, and Erzurum.
4. Roofs: EHPS systems are also applied to roofs, preventing the formation of ice dams and snow accumulation. These systems ensure building safety by maintaining a minimum heat output of 30 W/m at temperatures as low as -10°C.

Ground source energy in de-icing and snow-melting systems

Türkiye's rich in deep geothermal resources provide an opportunity for more sustainable snow-melting and de-icing solutions. HHPSs powered by high temperature geothermal fluids are promising and environmentally friendly alternatives to EHPSs especially in regions close to geothermal sites. These systems can for instance repurpose geothermal waste heat from electricity generation and residential heating for de-icing applications, aligning with Türkiye's broader goals of sustainability and reducing reliance on salt-based de-icing methods.

Japan

Japan's diverse climate, particularly the heavy snowfall in its northern and mountainous regions, necessitates effective snow and ice management systems to ensure the safety and functionality of critical infrastructure during the winter months. A variety of systems has been implemented across the country. Figure 8 presents a general mapping of these applications.

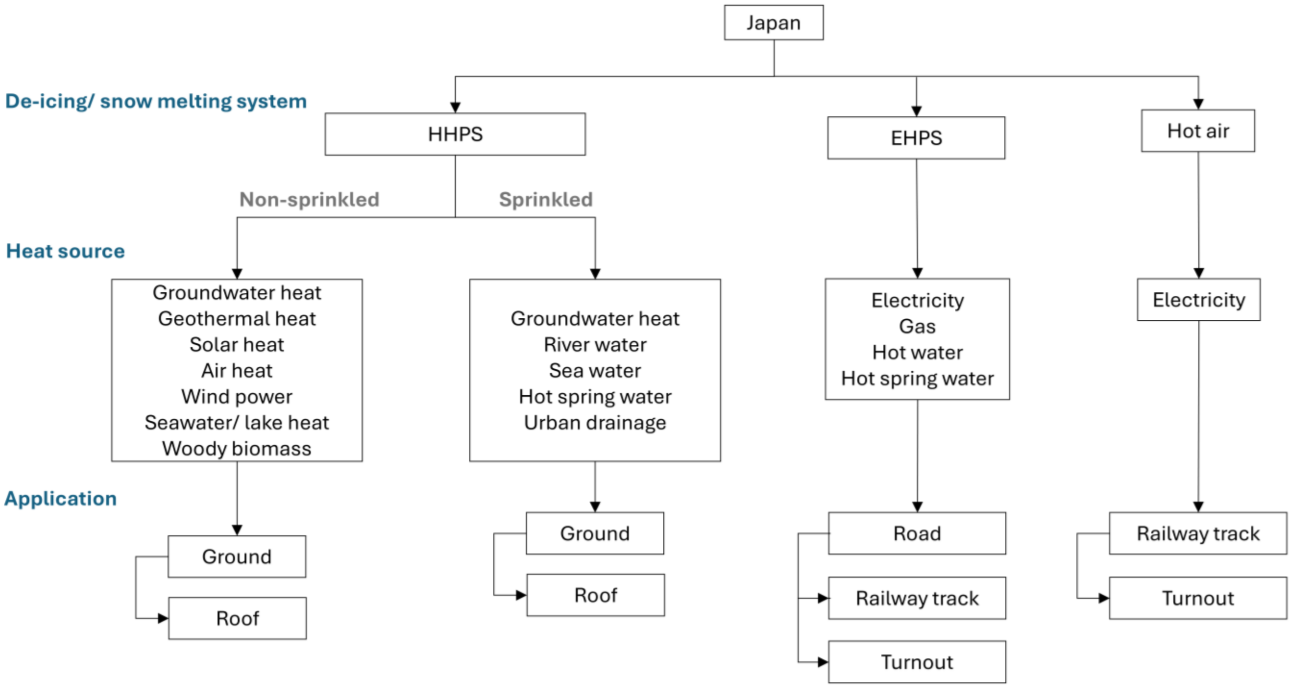

Figure 39. General mapping of de-icing and snow-melting applications in Japan, describing the utilized de-icing systems and the corresponding heat sources.

De-icing and snow-melting systems

Japan's approach to snow and ice management is a mix of traditional and innovative technologies. These systems are critical for maintaining operational infrastructure, particularly in areas with severe snowfall, such as Hokkaido and the Sea of Japan coast.

- EHPSs and hot air snow-melting (railways): These systems are primarily used for removing snow and ice from railway tracks and turnouts. They are often powered by electric heaters.
- Sprinkled snow-melting (ground and roof): This method involves the use of pipe-buried systems that spray water from sources such as groundwater, rivers, sea water, hot springs, or urban drainage onto snow-covered surfaces to melt snow. This system is particularly suitable for warmer snowy regions, where temperatures remain above 0°C in January.
- Non-sprinkled snow-melting (ground and roof): In contrast to the sprinkled system, this method utilizes buried pipes that circulate heated fluids, relying on renewable energy sources such as groundwater heat, geothermal heat, solar energy, or woody biomass. This system is versatile and can be adapted for various types of infrastructure, including residential roofs and public spaces, without the need for spraying water.
- Road heating in Sapporo city: Sapporo, one of Japan's snowiest cities, employs an extensive road heating system that uses both EHPSs and HHPSs to keep streets free of ice and snow. The system is driven by a combination of electric heating (84%), gas hot

water systems (11%), and hot spring water (5%). The road heating system covers 52 km of roads, equivalent to 221,000 m². The control system relies on a multi-sensor network that monitors weather conditions, including snowfall, temperature, and wind speed, to efficiently manage the application of heat.

Geothermal energy in de-icing and snow-melting systems

Japan has also integrated geothermal heat into some snow-melting applications, particularly in areas with access to natural deep geothermal resources. Groundwater heat and geothermal heat are key energy sources for non-sprinkled snow-melting systems. By utilizing these sustainable heat sources, Japan reduces its reliance on electricity and fossil fuels, aligning with broader environmental goals.

8.3 Specific mapping of demonstration plants with ground source de-icing and snow-melting systems

The main and second stage of the mapping process focused on specific case studies of pilot and demonstration plants from various countries participating in the project. These case studies were documented based on detailed national reports in Subtask 1. A review of all cases around the world is presented in (Ghalandari et al., 2021). Each plant was evaluated in terms of its design, energy performance, operational challenges, and success factors. The aim was to assess the effectiveness of these systems in addressing de-icing and snow-melting challenges and identify areas where further research and development are required. This mapping was structured around key areas of focus:

- **Design and Construction**: The technical setup, including the type of system used, scale, heat source, and construction challenges.
- **Control Systems**: The control mechanisms used, including automated systems and weather-responsive technologies.
- **Performance and Challenges**: Key performance data, challenges faced during operation, and how external factors such as weather conditions impacted system efficiency.

Demonstration Plants

This section provides an overview of the identified demonstration plants. A total of eight demonstration plants have been included in the specific mapping, representing different countries and varied applications of de-icing and snow-melting systems. Table 5 presents a summary of the key details for each plant, including the type of de-icing system, the heat source used, the control mechanism applied, and the specific application. In the following, the details of each demonstration plant are presented separately.

Table 5. Compiled list and key details of the identified de-icing/snow-melting demonstration plants.

	Demonstration Plant	Country	Application Type	De-Icing System Type	Heat Source	Control Mechanism
1	**Stockholm Arlanda Airport**	Sweden	Airport gates	HHPS	Solar energy Waste heat ATES system	Flow rate control, Wind speed-adjusted
2	**HERO* Experimental Site, Östersund**	Sweden	Road	HHPS	Solar energy, BTES system	Weather station
3	**Snow Dump melting, Arlanda Airport**	Sweden	Snow dump	HHPS	Solar energy BTES system	Supply temperature control
4	**Metro Station Therese-GiEHPSe-Allee, Munich**	Germany	Subway station	Pumped System, Two-phase CO_2 Thermosyphon, EHPS	Groundwater, CO_2 Thermosyphon, Electricity	Temperature and humidity sensors
5	**Canal Bridge Berkenthin**	Germany	Bridge deck	HHPS	Groundwater Heat pump	Automated measurement, control, and regulation, Weather-responsive
6	**Füssen Border Tunnel**	Germany	Road surface	HHPS	Mountain water	Water flow regulation, Preheating (9 hours in advance)
7	**Dromotherm System, Egletons**	France	Pavement and road surface	Porous Asphalt Solar Collector	Solar radiation	Gravitational water flow with pump
8	**HEAL**, University of Antwerp**	Belgium	Bicycle path	HHPS	Solar energy BTES system	Programmable Logic Controller (PLC), Configurable pipe network

1, 2, 3: (Andersson et al., 2025), 4, 5, 6: (Staudacher et al., 2025), 7: (Gennesseaux et al., 2025), 8: (Ghalandari & Van den bergh, 2025)

*: Heating Road with Stored Solar Energy

**: Heat Exchanging Asphalt Layer

Gates at Stockholm Arlanda Airport, Sweden

This system at Stockholm Arlanda Airport focused on using an Aquifer Thermal Energy Storage (ATES) system to maintain the surface temperature of airport gates at +3°C during winter. The deicing and snow melting system covers 36 000 m^2 that earlier was using district heating as the heat source. From 2010 the system utilizes groundwater at +20°C to heat the gates, with a particular emphasis on managing power demand in response to external factors such as wind speed.

- **Design and Construction**: The ATES system, that provides both heat and cold to the airport utilizes groundwater from the warm wells at +20°C to maintain the surface temperature of the gates at +3°C. In the summer waste heat from the cooling system combined with solar heat from gates is the heat sources that are stored. The study also investigated the influence of varying flow rates on maintaining the desired temperature as well as different factors affecting the load demand.
- **Operation and Control**: Variable flow rates were used to optimize the heat distribution under different power demands. The system's power demand was highly influenced by external factors such as wind speed and snowfall intensity. As wind speed and snow intensity increased, so did the required power to maintain the surface temperature.

- **Performance and Challenges**: The experiment found that only 6% of the energy consumed was used to melt snow, with the majority being used to maintain surface temperature. The system also showed potential for using the gates as solar collectors during summer, with solar energy contributing up to 50% of the energy required for winter heating. However, high wind speeds and snowfall intensity were identified as significant design challenges that increased power supply. Further optimization is needed for controlling the needed power under variable weather conditions.

HERO Experimental Site Outside Östersund, Sweden

This experimental site focused on storing solar energy in a Borehole Thermal Energy Storage (BTES) system and using it to heat a road during winter. The project successfully demonstrated that more solar energy could be harvested in the summer than needed for winter de-icing.

- **Design and Construction**: A 20 m long and 3.5 m wide section of road was heated by solar energy stored in a BTES with four 210 m deep boreholes. The system was intended to collect solar energy during summer and store it for use during the winter.
- **Operation and Control**: The road heating system performed in line with simulation models. However, only half of the energy supplied was from the BTES because the temperature from the boreholes was lower than expected. The system's performance demonstrated that effective control of the solar energy harvesting process was crucial to optimizing winter heat usage.
- **Performance and Challenges**: The system successfully harvested more energy during the summer than was needed in the winter, indicating its viability. However, further optimization in the control system could increase the percentage of stored energy used during winter.

Snow Dump Melting at Arlanda Airport, Sweden

This case explored using a BTES system to melt large quantities of snow in snow dump at Stockholm Arlanda Airport. The snow dump floor acted as a solar collector during the summer, storing heat for snow melting use during winter.

- **Design and Construction**: A snow dump floor with heating tubes connected to a BTES system was considered to melt snow during winter for three months. A thermally charged BTES was simulated by using an electrical heater to increase the temperature delivered by the BTES by +3°C. The floor also functioned as a solar collector during summer to recharge the BTES.
- **Operation and Control**: The system was operated during winter using a heated BTES to maintain the supply and return temperatures between 7-8 °C and 2-3 °C, respectively. During the operation the impact of different parameters such as varying circulation flows, higher water level in the snow dump and using the uncharged BTES (ten 200 m deep boreholes) as the only heat source were investigated. In total, 55 MWh of heat was supplied, corresponding to melting approximately 600 tons of snow. During the summer, the system was recharged with 90 MWh of heat using solar collectors.
- **Performance and Challenges**: While the system could successfully melt significant amounts of snow, improvements in the control system could enhance its efficiency, particularly in managing energy use between summer recharging and winter operation.

Metro Station Therese-GiEHPSe-Allee, Munich, Germany

The pilot project at the Therese-GiEHPSe-Allee subway station in Munich, Germany, aimed to evaluate the effectiveness of different de-icing systems in an urban public transport setting, covering a total area of 200 m². The considered surface material was gratinor or paving slabs. The goal was to test the performance of three different de-icing systems: a pumped system using groundwater, a two-phase CO_2 thermosyphon system, and a conventional electric resistance heating system.

- **Design and Construction**: Three different de-icing systems were tested with a specific heating capacity of 200 W/m^2:
    1. Pumped system: Utilizes groundwater as a heat source in the primary loop, transferring heat to the surface via a water-glycol mixture in the secondary loop, separated by a heat exchanger. The system also includes an electric heater for peak loads.
    2. CO_2 Thermosyphon system: A two-phase system where heat from groundwater is transferred to the surface by natural convection, driven by evaporation and condensation cycles within a closed loop of pipes.
    3. Conventional electric resistance heating: A common system in Munich, used as a control comparison.
- **Operation and Control**: The systems were managed using a control setup that measured temperature and humidity to regulate the heating processes. For the CO_2 thermosyphon system, no active control devices were needed, as it is purely temperature-driven and relies on the natural phase change of CO_2. The electric resistance heating system was considered the baseline technology, but the objective was to minimize its use by optimizing other design parameters such as floor structure with thermally conductive mortar with a conductivity of 4.0 W/mK, optimized pipe spacing, turbulent flow in the heating pipes, a large-area heat exchanger with a minimal temperature difference of 1 K between circuits for better performance.
- **Performance and Challenges**: Both the pumped system and the CO_2 thermosyphon system functioned well during the first cold period of operation. However, detailed long-term performance data was not available.
    1. Pumped system: The separating heat exchanger and use of a water-glycol mixture in the secondary loop helped achieve an efficient heat transfer. Optimizing parameters like turbulent flow in the pipes, minimal temperature difference in the heat exchanger, and strategic pipe placement further enhanced the system's performance.
    2. CO_2 Thermosyphon system: The main advantage of this system was that it required no additional operational energy beyond the natural phase change of CO_2. However, its installation required special planning due to the inclination needed for the thermosyphon effect to function properly.
    3. The electric resistance heating system served as a fallback solution for peak loads but was avoided as much as possible to reduce energy consumption.

Canal Bridge Berkenthin, Germany

The Canal Bridge Berkenthin, part of the federal highway B208 in northern Germany, underwent a major renovation in 2010, incorporating an innovative de-icing system as part of a research project. The Canal Bridge Berkenthin project use groundwater at a constant temperature for the bridge deck, capable of both heating and cooling. This dual-purpose system was designed to prevent ice formation in winter and rutting in summer. The primary goal was to evaluate the effectiveness of temperature-controlled road surfaces.

- **Design and Construction**: The bridge is a steel composite tied arch structure with a span of 59 meters and a width of approximately 14 meters between the railings. The innovative aspect of this project was the integration of pipe registers "floating" in the middle of the asphalt layer. This positioning allows for both efficient heat transfer and the ability to replace the top asphalt layer without damaging the heating system. Approximately 6,000 meters of pipes were laid in the direction of traffic, divided into 46 register lines and four controllable main circulation circuits. The geothermal system was complemented by a heat pump to increase heating efficiency and response time.
- **Operation and Control**: The system is operated using a measurement, control, and regulation system, which activates heating or cooling only when necessary. This automated control scheme helps to conserve energy while maintaining a safe road surface. The ground source energy system pumps groundwater from an 86-meter-deep well, with the groundwater maintained at approximately 11°C throughout the year. A multi-stage heat pump boosts the temperature to 55°C if needed, ensuring that the road surface reaches the desired temperature to prevent ice formation. The first stage provides a heating output of approximately 65 kW (110 W/m²), while the second stage delivers 135 kW (225 W/m²), covering a heated area of about 600 m².
- **Performance and Challenges**: The system performed well in controlling surface temperatures, but it was noted that the long pipe registers and local groundwater temperature led to a slow response time. The installation of a heat pump helped mitigate this issue by rapidly increasing the temperature of the heating fluid. A key finding from the research was that uniform surface heating requires pipe spacing no greater than 10 cm to ensure consistent temperatures. Additionally, the positioning of the pipe register in the middle of the asphalt layer proved optimal for both heat transfer and protecting the system from traffic-related wear and tear. Another challenge identified was that maintaining a snow- and ice-free bridge during the entire winter season would be energy-intensive. At temperatures below -3°C, heating the bridge deck was deemed unnecessary as conditions on the surrounding roads were equally critical. The system also had the capability to cool the bridge deck in summer to prevent ruts caused by high temperatures, making it a dual-function system.

Füssen Border Tunnel, Germany

The Füssen Border Tunnel service yard implemented a geothermal, passive open-space heating system in 2019/2020. This pilot project aimed to utilize mountain water from the adjacent tunnel to heat the road surface in winter and cool it in summer, without the use of heat exchangers or pumps. The system was designed to keep the surface snow- and ice-free in winter and prevent rutting in summer.

Design and Construction: The mountain water, collected from the Füssen tunnel, is pumped directly through bifilar pipe registers without using heat exchangers or heat pumps. The simplicity of this passive system is a key innovation, relying solely on adjusting water flow rates to control heat transfer. An output of 400 W/m² was assumed for the system, with design calculations supported by numerical simulations.

The system covers nine test areas with varying setups. Six areas used asphalt as the road surface, while three used concrete. Different configurations were tested, including variations in pipe depth (6.75 cm to 9.5 cm), pipe spacing (10 cm, 15 cm, 20 cm), and pipe material (plastic and copper).

- **Operation and Control**: The system operates passively, with water pumped through the pipes at variable speeds to adjust the heat transfer rate. Faster water flow results in increased heat transfer and a higher return temperature, as the water has less time to cool down. Temperature sensors were installed in each test area to monitor flow rates, inlet and outlet temperatures, and surface temperatures at various points. To ensure timely activation before weather events like icy conditions, it was determined that the system should be activated approximately 9 hours in advance. This preheating phase ensures that the surface reaches the necessary temperature to remain ice-free.
- **Performance and Challenges**: Test results indicated that copper pipes in combination with concrete surfaces were more effective at heating the road than plastic pipes in asphalt. Concrete's higher thermal mass allowed for better heat retention and transfer, which contributed to more efficient snow and ice melting. The system proved capable of keeping surfaces free of ice throughout the winter of 2021/22, though immediate snow-melting proved more energy intensive. In cases of heavy snowfall, additional clearing measures were necessary, but the system ensured that salt was not required for de-icing, significantly reducing environmental impact. A control system programmed with a Python script was used for remote operation, and the system was fine-tuned based on both real-time climatic data and weather forecasts, since forecasted and actual conditions did not always align.

Dromotherm System, France

The Dromotherm system was developed as a de-icing and energy-harvesting solution using a porous asphalt layer. The main objective of this research project was to develop and evaluate a pavement structure that could capture solar energy to de-ice roads and pavements in winter, while also providing an efficient way to harvest solar energy for other purposes during summer.

- **Design and Construction**: The Dromotherm system is composed of a porous asphalt layer supplied with water via road gutters. Unlike conventional asphalt solar collectors that rely on pipes embedded in the pavement, this system utilizes the inherent porosity of the asphalt to capture and circulate water. Two types of porous layers were tested in the lab: one using conventional porous asphalt with 22.5% porosity, and another with an asphalt layer using a polyurethane binder and 30% porosity. The latter demonstrated superior mechanical performance, making it a more effective option for the Dromotherm system. The system was initially modeled in 2D by researchers from Eiffel University and Cerema, simulating the heat exchanges between the fluid circulating in the porous layer and the pavement surface. The sensitivity analysis showed that the surface temperature was significantly influenced by the hydraulic conductivity, fluid temperature, and calorific capacity of the fluid.

- **Operation and Control**: A first outdoor demonstrator of the Dromotherm solar collector was built in Egletons in 2014. This 16 m² prototype used road gutters to circulate fluid through the porous layer. The system was operated on a closed circuit, using a pump to return the water from the downstream gutter to the upstream gutter. The system's design proved highly efficient, capturing 80-90% of incident solar energy. This is significantly higher than traditional pipe-embedded systems, which capture only 30%. This demonstrated the viability of using a porous asphalt layer for both solar energy capture and snow-melting. Results demonstrated that the hydraulic conductivity of the porous asphalt layer plays a critical role in maintaining efficient heat transfer, and the use of polyurethane-bonded asphalt layers showed better performance compared to conventional materials.
- **Performance and Challenges**: The system was found to be very effective in harvesting solar energy during the summer, while also capable of transferring enough heat to remove snow during the winter months. However, the demonstrator built in Egletons was not connected to a heat storage system or an infrastructure that could consume the harvested energy. A new phase of the Dromotherm project (2020-2024) aims to further develop the system. In 2022, a new demonstrator was constructed in Chambéry, featuring a more advanced design. This new system includes a 35 m² pavement collector, a thermal storage tank filled with 40 m³ of wet sand, and a heat pump. The energy harvested by the system is used to heat and supply hot water to a 120 m² model building. The system is reversible, allowing the energy gathered during summer to be stored and later used for snow-melting during winter, increasing the system's year-round efficiency.

Heat Exchanging Asphalt Layer (HEAL) – University of Antwerp, Belgium

The HEAL (Heat Exchanging Asphalt Layer) system was part of the CyPaTs (Cycle Pavement Technologies) project aimed at exploring innovative technologies for snow-melting and energy harvesting for cycling infrastructure. The main goal was to evaluate the system's thermal performance and its capacity to store and utilize solar energy for winter de-icing through a Borehole Thermal Energy Storage (BTES) system.

- **Design and Construction**: The HEAL system was installed on a 65 m² bicycle path at the University of Antwerp. The pavement structure consists of four heat exchange sections (8.5 m x 1 m each) and two reference sections (30 m²) without heat exchange capabilities. The asphalt pavement has a thickness of 12 cm: the top layer is 3 cm thick, and the collector layer (where heat exchange occurs) is 4 cm thick, made from dense asphalt mixtures. Polyethylene pipes were embedded in the collector layer, supported by a reinforcing grid, ensuring proper positioning and protection during construction. The system includes a BTES system with two 100-meter-deep boreholes filled with U-shaped pipes. These boreholes store thermal energy collected during the summer and supply heat during the winter. A technical unit houses a reversible heat pump (HP), buffer storage (1000 liters), water pumps, and control systems, enabling the transfer of stored energy to the heat exchanger sections during winter. If the stored heat is insufficient, the HP can increase the temperature through compression and expansion. Temperature sensors, flow transmitters, pressure manometers, and control valves are connected to a programmable logic controller (PLC) for real-time monitoring and system control. The system can deliver up to 35°C during winter to keep the bicycle path ice-free.

- **Operation and Control**: The pipe network can be configured in multiple ways, either as parallel or series connections, depending on the desired thermal performance and weather conditions. The system can switch between different pipe configurations (e.g., 50 m, 100 m, or 200 m pipe lengths) based on snow severity or freezing temperatures. The BTES system serves as a seasonal thermal energy storage, absorbing excess solar energy during summer and supplying heat during winter. The heat pump can further boost the temperature when needed. The system is monitored via 96 thermocouples placed at different depths within the pavement, measuring temperature variations in both the heat exchange and reference sections. A weather station installed at the site collects air temperature, humidity, wind speed, and solar radiation data to optimize the system's control strategy.
- **Performance and Challenges**: The HEAL system has demonstrated that it can capture 80-90% of incident solar energy, which is significantly higher than traditional pipe-embedded systems that capture around 30%. This efficiency makes the HEAL system a promising technology for both de-icing and renewable energy harvesting. One challenge identified was balancing the injected and depleted heat in the BTES to maintain long-term thermal equilibrium in the soil. If the system extracts more heat than injected, the performance could diminish over time. In cases of extended snow periods or harsh snowstorms, the stored energy may not be enough to maintain the surface temperature above 5°C. In such cases, the heat pump is used to provide additional heating, increasing the system's flexibility and ensuring safe cycling conditions. The environmental concern of contaminating groundwater was addressed by avoiding the use of glycol mixtures in the heat exchanger section, though the BTES boreholes are filled with water and anti-freeze mixture to prevent freezing in the pipes.

Summary and Recommendations

The mapping of demonstration plants provided insights into the potential for ground source de-icing and snow-melting systems, focusing on innovations, challenges, and areas for future development. Several key themes and recommendations emerged from the analysis:

Heat source optimization

Renewable energy sources such as ground source heat, solar energy, and waste heat are central to de-icing systems in the demonstration plants. Projects like HERO in Sweden and HEAL in Belgium have employed BTES systems to store solar energy collected in summer for winter use, demonstrating substantial potential for reducing environmental impact and energy costs.

Also, ATES systems using groundwater as heat source has demonstrated a considerable potential. However, aquifers cannot always be found at specific sites and country specific regulations may be an obstacle for usage.

Climatic variability, as observed in projects like Snow dump melting at Arlanda airport, presents challenges in maintaining consistent heat availability. Optimizing heat storage systems, especially balancing injected and depleted heat (as in the Canal Bridge Berkenthin case), remains crucial for sufficient operation. Further advancements in integrating renewable heat sources are needed, particularly in areas with fluctuating seasonal temperatures.

Control systems

Control systems play a vital role in ensuring efficiency and operational effectiveness. Demonstration plants such as Füssen Border Tunnel and Metro Station Therese-GiEHPSe-Allee have implemented advanced control systems utilizing real-time weather data to optimize system performance. HEAL employs a programmable logic controller (PLC) to adjust pipe configurations based on weather conditions.

Nevertheless, optimizing control systems to respond dynamically to rapid climatic changes remains a challenge, as seen in the Arlanda ATES project, where maintaining consistent surface temperatures in windy conditions increases energy consumption. More adaptable control systems will be essential for minimizing energy use in diverse weather conditions.

Energy efficiency and environmental impact

Reducing reliance on environmentally harmful chemicals such as salt and lowering energy consumption are key objectives in the mapped projects. Systems like Füssen Border Tunnel and Dromotherm demonstrate that geothermal and solar-based technologies can effectively replace traditional salt-based methods, leading to fewer environmental impacts and reduced operational costs. While smaller applications like Dromotherm show great promise, testing scalability for broader infrastructure such as airports, highways, and bridges is still required to ensure their viability on a larger scale.

Challenges and areas for future testing

Despite the success of the mapped pilot projects, key challenges include improving response times, optimizing heat storage, and scaling systems for large infrastructure. Faster-reacting systems, particularly in colder climates, need better heat transfer mechanisms, as seen in the Canal Bridge Berkenthin and Füssen Border Tunnel cases. Additionally, more research is needed to control the depletion rate in BTES and ATES systems, as demonstrated by HERO and Snow Dump Melting.

Scalability and integration remain areas of concern. Small-scale projects like HEAL and Dromotherm have shown potential, but large infrastructures such as airports and bridges will require further testing. The development of hybrid energy solutions combining ground source systems with, solar, and waste heat sources potentially can enhance energy efficiency year-round, offering a more flexible approach to de-icing.

Recommendations for future work

From the mapping exercise, several key areas for future research and development emerged:

- **Optimization of heat storage systems:** Continued research into thermal energy storage systems will be essential to improving their long-term energy storage capacity and maintaining thermal balance.
- **Advanced control systems:** Further refinement of control systems that dynamically adapt to real-time weather changes will be essential for optimizing system efficiency and reducing energy consumption.

- **Hybrid energy solutions:** Investigating how hybrid systems that combine ground source systems with, solar, and waste heat sources can provide efficient, cost-effective de-icing solutions.
- **Scaling for large infrastructure:** More research is needed to scale the technology for larger infrastructures such as airports, highways, and bridges while maintaining energy efficiency and minimizing environmental impacts.

8.4 Conclusions

The implementation of ground source de-icing and snow-melting systems has been mapped and analyzed based on findings from the national reports in Subtask 1. By reviewing the systems across participating countries, this report highlights key trends, challenges, innovations, and market potential in utilization of various heat sources and control technologies in de-icing and snow-melting applications.

The general mapping reveals that most existing de-icing and snow-melting systems are either electric heated pavement systems or hydronic heated pavement systems, with many relying on district heating as their primary energy source. However, there is a significant potential for a shift toward using other renewable sources such as ground source and solar energy, reflecting a growing commitment to reducing environmental impact and improving energy efficiency. Expanding the use of these renewable energies, however, requires reliable thermal storage systems to ensure energy availability during winter months. This makes the integration of ground-source thermal storage systems, such as borehole thermal energy storage and aquifer thermal energy storage, increasingly necessary for the future development of renewable-based de-icing and snow-melting technologies. Key challenges remain, particularly regarding climatic variability, the efficiency of energy storage, and the scalability of these technologies for larger infrastructures such as highways.

The specific mapping of demonstration plants shows the potential of hydronic heated pavement systems to reduce dependence on conventional technologies and energy sources. These projects demonstrate that integrating ground source and solar energy into de-icing systems can lower operational costs while reducing environmental impacts. Despite the successes in these test projects, optimizing heat storage (particularly in borehole and aquifer thermal energy storages), improving system response times, and refining control mechanisms to better adapt to extreme weather conditions remain crucial areas for improvement.

New market opportunities have also emerged, particularly in areas where district heating is not available or where renewable systems offer a more cost-effective solution. Ground source systems have the potential for use in settings such as railway switches, sports facilities, and remote or off-grid infrastructure, where low operational costs and high energy efficiency are essential. Additionally, hybrid systems that combine ground source, solar, and waste heat sources could offer greater flexibility and resilience, making them ideal for diverse applications in the future.

Further research is necessary to address challenges related to scalability and dynamic control systems that can adapt in real-time to changing weather conditions. As these technologies continue to develop, their role in improving the sustainability and resilience of infrastructure in the face of climate change will likely continue to grow, opening new market segments and supporting the broader adoption of ground source de-icing and snow-melting systems.

Summary

This report presents the findings of subtask 4.1 from the IEA ECES Task 38, "Ground Source De-Icing and Snow Melting Systems for Infrastructure," with focus on mapping current applications and analyzing demonstration plants utilizing ground source thermal energy The study spans from 2021 to 2024, intending to promote ground source heat as sustainable alternatives to traditional de-icing and snow-melting systems based on electrical heating and fossil fuel. The report employs the national reports and the information about existing demonstration projects in Subtask 1, to provide a comprehensive overview of existing technologies and to identify future development needs.

The general mapping covers de-icing and snow-melting systems in seven participating countries: Sweden, Germany, France, Belgium, Italy, Turkey, and Japan. It reveals that the majority of systems currently rely on conventional electrical heating methods, primarily using cables and mats. While hydronic heated pavement systems are also present, they are less common and mainly used in selective applications. Among those using hydronic heated pavement systems, only a limited number are powered by ground sources, with most still relying on district heating or other conventional energy sources such as natural gas boilers. Increasingly, there is a shift toward integrating more renewable energy sources in these technologies, aiming to reduce environmental impact and improve energy efficiency. To expand the use of these renewable sources, the implementation of temporary and seasonal thermal storage solutions, such as borehole thermal energy storage, is identified as crucial for ensuring energy availability during winter season and peak demand periods.

The specific mapping of demonstration plants highlights various innovative systems that incorporate ground source energy. Projects like HERO in Sweden and HEAL in Belgium demonstrate the potential of ground source hydronic heated pavement systems for de-icing and snow-melting, rather than electrical heating to reduce environmental impact and operational costs. Despite the success of these pilots, challenges remain in optimizing heat storage, improving response times, and scaling these systems for large infrastructure applications such as highways, airports, and railway systems.

The report concludes that while significant progress has been made, further research and development are required to enhance the scalability, efficiency, and real-time control of these systems. Expanding the use of ground source energy in de-icing and snow-melting applications offers considerable potential for reducing energy consumption and environmental impact. Additionally, new market opportunities are emerging in areas such as sports facilities, railway switches, and off-grid infrastructure, where ground source systems can provide a cost-effective and sustainable solution.

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9. PLANNING, CONSTRUCTION, AND MONITORING, SUBTASK 4, DELIVERABLE 4.2: RECOMMENDATION RELATED TO BEST PRACTICE OF DESIGN, CONSTRUCTION, OPERATION, AND MAINTENANCE OF A HYDRONIC DE-ICING AND SNOW MELTING SYSTEM

The International Energy Agency (IEA), a technology collaboration program related to thermal storage, initiated a project to utilize geothermal/renewable energy sources in pavement for de-icing of transport infrastructures. The project goal is to expand the utilization of direct geothermal heating systems or ground source heat pumps in de-icing and snow-melting systems for infrastructure. From the experience gained from the construction and operation of the demonstration plants in various climatic conditions, as well as from the experience of existing plants, recommendations are to be drawn up which summarize the essential aspects regarding the planning, construction, operation, and maintenance of geothermal snow melting and de-icing systems.

The main barrier against using ground source thermal energy for de-icing of infrastructure is the perceived uncertainty on how to design, construct, and operate such systems. However, it is known that there is a widespread experience that can be tapped into, and this information can be systemized to become useful for designers and decision-makers. This report will gather this information and transform it into specific knowledge.

Hydronic heating pavements (HHP) effectively keep walkways, driveways, and other critical surfaces free of snow and ice during winter. These systems use heated fluid, typically a mixture of water and antifreeze, circulated through a network of tubing embedded in the surface to melt snow and ice. The effectiveness and longevity of such systems depend on several factors, including proper design, construction, operation, and maintenance. The hydronic de-icing and snow melting systems can be divided into three subsystems: energy, pavement, and controlling. An essential parameter in the design of a hydronic system is the energy source. The energy source can be electric boilers or boilers with oil, diesel, or more common natural gas and district heating. Only a few systems are so far heated by deep geothermal heat and even fewer with shallow geothermal systems.

An environmentally friendly and economically feasible hydronic heating system is to take advantage of collecting solar energy, by pavement as a solar collector, mainly during summertime and seasonal storage of thermal energy by underground thermal energy storage (UTES). This will enable saving in the primary power of the system. This report recommends best practices in each area to ensure optimal performance and durability of hydronic de-icing and snow melting systems using the pavement as a solar collector combined with UTES.

9.1 Design Practices

System layout and planning in the design phase are crucial in determining the effectiveness of a hydronic de-icing system. Key considerations include site climate conditions, thermal load, and annual energy demand calculations, supply and return temperature levels, and zoning.

Climate conditions involve understanding the specific environmental conditions, such as typical snowfall, temperature ranges, and wind patterns, to design a system tailored to the site. In the planning phase, the desired climate data can be obtained from the closest national climate station, however, if the site is in a specific geographical e.g. in a valley or forest, this condition should be considered.

Thermal load should accurately be calculated. The thermal load is required to maintain surfaces free of snow and ice, which depends on factors like surface area, pavement structure and thermal properties, desired melt rate, and insulation properties. The thermal load can be calculated using commercial software or the system supplier's homemade software. Some examples of exiting software were presented in the report of work package 2 of this Annex.

The annual energy demand depends on climatic conditions, such as accumulated snowfall, and the number of days with temperatures at or below zero. Another important factor is the wind speed at the site.

The supply temperature depends mainly on the outdoor temperature and the wind speed when it comes to keeping the surface above the freezing point, and the desired melting rate when it comes to intensity of snowfall.

Zoning involves dividing the system into zones for flexible operation, especially in areas with varying exposure and snow loads. This aids in more efficient energy use.

HHP system design

A hydronic de-icing and snow melting system can be divided into three subsystems: hydronic pavement, heat source, and controlling. This chapter provides a detailed explanation of each subsystem.

Hydronic Pavement

The design of the piping network directly impacts the system's performance. Several parameters are essential. The main parameters are the distance between pipes (d), the distance between the pipe center and the surface (t), the material properties of the pavement, the radius of the pipes, and the orientation of the pipes.

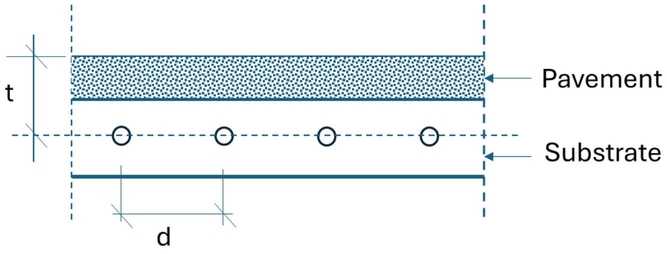
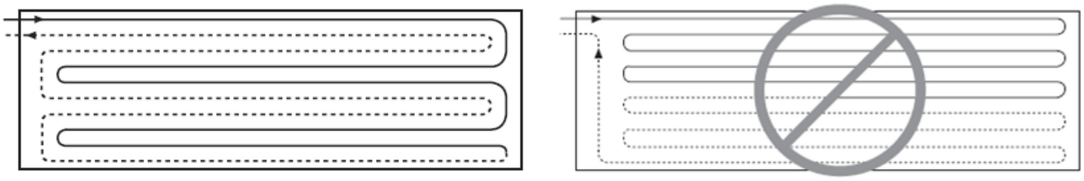


Figure 1: A sketch of embedded pipe in a pavement

Furthermore, achieving the best performance demands optimization of the centrum distance between pipes (d) and the pipe embedment depth (t) with the supply temperature level and flow velocity.

Generally, the pipe diameter is 18-25 mm, the distance between pipes is 100-300 mm, and the embedment depth is 50-100 mm. In the wintertime, closer spacing between pipes significantly enhances the system's effectiveness, reducing slippery pavement conditions by nearly 50% when distances decrease by 2 times. Additionally, shallower embedment depths of pipes proved beneficial, correlating with a 25% reduction in slippery conditions when varied from 150 mm to 60 mm, with the same temperature supply and flow velocity. Moreover, employing larger pipe diameters effectively decreased the risk of slippery road surfaces, a diameter increase of 2 times gives about 20% reduction in such conditions. Regarding summertime, energy harvesting, the findings indicate that smaller pipe spacing not only results in lower temperatures throughout the pavement but also leads to a more homogeneous temperature distribution, which is beneficial for reducing thermal stresses within the pavement material. This feature is significant when the pavement is made of bitumen-based material, reducing the surface temperature by energy harvesting prolongs the lifetime of the asphalt. However, tight tubing can cause difficulties for concrete casting and asphalt pavement. Thus, optimizing pipe layout and dimensions is essential for maximizing the efficiency of the hydronic systems.

Pipe orientation also influences the system's performance. To provide smooth melting a reverse-return layout should be used. This allows the entire snow and ice melting surface to heat up equally.



Revers Return layout   Serpentine Layout

Figure 2: Revers return and serpentine layout. (Reference: Snow and ice melting, design and installation manual, Uponor)

Another measure for reducing energy demand and increasing system efficiency is to use insulation under pipes.

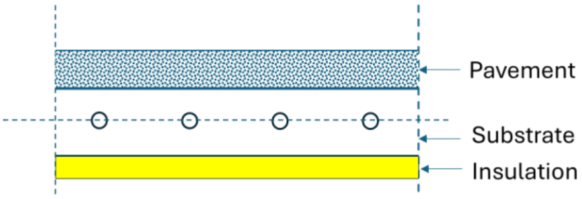


Figure 3: A sketch of embedded pipe in a pavement with isolation

Using insulation reduces the time response of the system. However, this design is not recommended for heavy vertical loads.

Heat Source

An appropriate heat source, for covering the thermal load, is vital for the system’s efficiency, reliability, and economic feasibility (the main cost of the system during operation depends on the energy costs).

Technically, the traditional heat sources work excellently, but the operational cost is often high and in many cases the greenhouse gas emissions are substantial. These disadvantages can be limited by using renewable energy.

- ***It recommends utilizing renewable energy options, like ground source heating and/or solar-assisted heating, to reduce reliance on fossil fuels, reduce operation costs, and design a sustainable energy system.***

Utilization of pavement as a solar collector in combination with underground thermal energy storage (UTES) is one of the more economically and environmentally feasible solutions. The selection of the thermal storage type for storing the harvested energy by the pavement is a key performance parameter. Different types of underground thermal energy storage technologies are available. Well-known and commercially available. The well-known technologies are Aquifer Thermal Energy Storage (ATES), Borehole Thermal Storage (BTES), and Pit Thermal Energy Storage (PTES). Less known and commercially developed technologies are Cavern Thermal Energy Storage (CTES) and underground Tank Thermal Energy Storage (TTES).

The selection of proper thermal energy storage technology depends on the location of the de-icing site, e.g. in an urban area it will be complex to use PTES and utilization of ATES is limited to areas where an aquifer is available. In rural areas with transport infrastructures, practically all technologies can be used.

The sizing of the thermal energy storage depends on several parameters e.g. the type of storage, the energy harvested by pavement, the geographical condition of the storage, and the energy demand of the de-icing system. The sum of the harvested and available geothermal energy should cover the energy demand by the de-icing system. The annual variation of the harvested energy should be accounted for.

According to the market analysis (report D1.2), the two most promising systems for larger applications are ATES and BTES systems.

ATES applications

This chapter describes the management of Aquifer Thermal Energy Storage (ATES). Generally, the design of an ATES varies with the hydrogeological conditions at the site, the working temperatures, and the operation mode (charging and discharging). The knowledge is gained from general experiences in methods for exploring groundwater for different usage with *Groundwater and Wells* (Driscoll 1988) as the main source. Information is also gained from IEA-IA-ECES *Annex VI, Environmental and Chemical Aspects of Thermal Energy Storage in Aquifers and Research and Development of Water Treatment Methods*.

Design methodology:

The design typically starts with feasibility studies (preferably in two steps) to find out if the ATES system is feasible or not. To be feasible, the following conditions should be fulfilled.

- The site geology contains one or several aquifers at or close to the site.
- The aquifer should be large enough and have a favorable geometry for placement of wells
- The aquifer shall have a feasible yield and not have an unfavorable chemical composition.
- The aquifer should not have regulation obstacles, that make it impossible to use

The design parameters are generally the same in all countries, but the tools used for design may vary. The main parameters would be the ambient underground temperature, the hydraulic properties, the flow rate, the energy loads for extraction and storage (kWh), and the maximum power loads (kW). The number and depth of wells, and the distance between wells, are then defined by a simulation/design model. Examples of commonly used tools are the MODFLOW and FEEFLOW calculation programs. To these programs, different modules can be connected to also simulate the hydrothermal behavior of the system.

Finally, the design is used as a technical description for tender documents and the environmental assessment analysis for permit procedures.

Prefeasibility study: A pre-feasibility study will typically be a desktop product. The content and layout of a report may vary, but the main chapter would be a description of the hydrogeological conditions at the site. This should be based on topographic maps, geological maps, hydrogeological maps, existing databases on wells and boreholes, groundwater chemistry, etc. Such information can be found in databases provided by the National Geological Services. The other main factors would be the size of the HHP system, the expected energy and power loads, and the desired working temperature. Based on this information a preliminary design is made, and the investment cost is estimated. Furthermore, legislation obstacles should be identified and valued. The outcome of this study may indicate or conclude that ATES is feasible or not.

Feasibility study: In this phase site investigations are made to survey the aquifer properties. Test drillings are made to document the geological conditions, and a pumping test is performed to analyze the hydraulic properties and the boundary conditions of the aquifer. The results are used to construct a hydrogeological model. Furthermore, chemical analyses of the groundwater are essential to address potential corrosion and well-clogging problems.

Design: Based on the results of the feasibility studies the ATES system is designed based on the energy and flow rate demands of the HHP system. The type and number of wells are defined, the well installation equipment, and their overall structure. Hydraulic and thermohydraulic models are used to simulate the spacing of the wells, but also the hydraulic and thermal impact in the surroundings. The simulation results are finally used for an environmental assessment report which is commonly asked for in the permit procedure.

BTES applications

Generally, the design of a BTES system varies with the borehole depth, the distance between boreholes, working temperatures, and operation mode (charging and de-charging). The final report of *IEA ECES ANNEX 27*, Quality Management in Design, Construction, and Operation of Borehole Systems (Reuss et al. 2020) can be used for designing BTES. In this chapter, the main steps in a project development are described.

Design methodology: The design phase typically starts with feasibility studies (preferably in two steps) and ends with a detailed design and call for bids (tender).

The design parameters are generally the same in all countries, but the tools used for design vary. The main design parameters would be the ambient underground temperature, the ground thermal conductivity, the monthly heat load extracted (kWh), and the maximum average extraction load (kW). The number, depth, and distance between boreholes is then preferably defined by a simulation/design model. Examples of tools used for the design of BTES and larger GSHP systems are EED, GLHEPRO, GEO-HANDlight, GEOSYST, GLD, EWS and GAIA.

Prefeasibility study: A pre-feasibility report will typically be a desktop study. Depending on the situation, the content and layout of a pre-feasibility report may vary. However, site plans, topographic maps, geological maps, hydrogeological maps, databases on existing wells and boreholes, energy load and temperature demands, predesign, and economic calculations to compare with other energy systems are important issues to cover.

Feasibility study: This study is a further development of the pre-feasibility study including site investigations with test drillings and Thermal Response Tests (TRT). Usually, one or several test holes are drilled, documented, and TRT tested. Furthermore, detailed data on heat load characteristics and temperature profiles are obtained and used as a basis for design. Environmental and legal aspects are also more thoroughly considered.

Detailed Design: Based on evaluated data from the information the site investigations combined with energy load profile simulations with software design tools are made. These simulations are used to design the final number of boreholes, their depth and spacing, and the borehole configuration. In addition, a design used as tender documents should cover the load profile over an average year, and temperature demands over the year. Furthermore, borehole heat exchangers, horizontal piping, and heat carrier fluid should be a part of the design.

Special Features of Two-Phase Thermosiphon Systems

A two-phase thermosiphon system is more suitable for small areas up to 100m². The system is suitable especially when no power supply is available or laying a connection is very expensive. However, the undisturbed soil temperature should be at least 10°C. Furthermore, the area to be heated should allow the connecting pipes between the heating surface and the borehole to be laid with a gradient of 2° throughout.

The heating system must be designed for a low-temperature difference of about 5 °C between the pipes and the surface. The system is self-regulating, and a control system is not necessary. The two-phase thermosiphon is a thermal diode. It cannot transfer heat from the surface to the ground.

Application to free-standing stairs or bridges is critical, as these often require higher heating output.

Control System Design

The control system should regulate the system's functioning by starting and stopping sequences based on load fluctuations. The major steps in controlling a system include collecting data related to variables, processing the collected data, and executing the required control action based on the processed data. These steps are achieved by integrating the sensors inside and outside the pavement and, a control unit merged with the system.

Proper control over the functioning of the hydronic system can be undertaken by embedded *sensors* in the pavement that measure the variables, a *controller* that receives the input from the sensor and processes the input and finally sends out the required control action to control the energy output/input to the surface. In a hydronic system with energy storage, the controller organizes the heat exchange between the pavement and the storage. The controller has two parts, the first part controls the supply temperature to the pavement in wintertime and the second part controls the circulation pump for harvesting.

The main task of a controller is to keep systems operating well within the designed set points. Figure 4 presents an example of a set-point design.

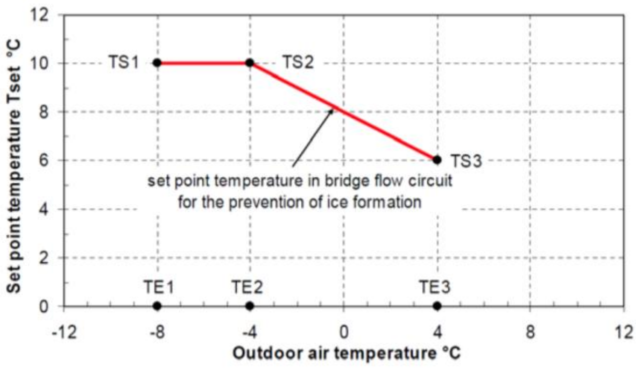


Figure Heating curve controlling the supply temperature to the pavement at different air temperatures (Pahud 2008)

The heating starts when the air temperature is below TE3 (4°C) and the supply temperature is adjusted according to the curve confined by TS1-TS3. When the air temperature is below -8 °C, the heating stops. The reason for this is the low likelihood of ice formation in those temperatures due to the low humidity content of the air.

The energy harvesting set point is a simple temperature setting for the start of a circulation pump. In charging mode, the circulation pump starts when the surface temperature is higher than the temperature of thermal storage. It is also possible to control the circulation pump by a set point involving the difference between the surface and the storage temperature.

When the set point is achieved, the signal will be sent to the heating system to start. It will take time until the heat front reaches the surface. This time delay, time lag, can cause snow accumulation or ice formation which is not desired in some applications. One possible solution to reduce the time lag of the system is to pre-heat the pavement to a temperature close to the designed de-icing and snow melting temperature. Another possibility is to add a local climate station and sensors embedded in the pavement to predict and forecast (Weather-Responsive Controls) the conditions that can lead to ice formation or snowfall.

9.2 Recommendations: Hydronic Pavement Design

Deliverables D1.1 and D1.2 reports contain limited information about detailed design procedures. The following recommendations are therefore more general and based on discussions within the Annex and literature information.

- ***Determine the climatological parameters, e.g. precipitation, snowfall, and wind speed patterns***
- ***Calculate the thermal load based on the climatological parameters.***
- ***Dividing the surface into zones for flexible operation. This aids in more efficient energy use.***
- ***Select the thermal storage technique. Determine the size of the thermal storage. The sum of the harvested and available renewable energy should cover the energy demand for the de-icing system.***
- ***The embedded pipe's depth should be as close to the pavement surface as possible. Generally, the pipe diameter is 18-25 mm, the distance between pipes is 100-300 mm, and the embedment depth is 50-70 mm.***
- ***A close pipe position to the pavement will also gain the potential for solar energy collection to be stored during the summer season***
- ***Insulation under pipes shall be considered to reduce energy demand.***
- ***In a hydronic system with energy storage, the control system organizes the heat exchange between the pavement and the storage.***
- ***The control system should be designed based on data from embedded sensors in the pavement, temperature, and flow rate sensors.***
- ***Calculate the time lag of the pavement and preheat the pavement to reduce the risk of snow accumulation or ice formation.***

9.3 Recommendations: Heat Source Design

In this chapter, the most essential recommendations for the two storage technologies ATES and BTES are given. The recommendations follow a stepwise development of the project which is common within other sectors using the same types of seasonal storage.

Pre-feasibility study

- **It is recommended to start any larger ATES or BTES applications by performing a desktop study based on information, that is inexpensive and easily achieved.**
- **A survey on underground piping and cables or other infrastructural installations beneath the surface should always be an issue at this stage.**
- **It is recommended that property borders and potential easements be checked to place the planned drill site according to legal conditions.**
- **Accessibility for the drill rig should be checked as well as areas for polluted soil, and how to deal with excess water from the drilling process.**
- **It is recommended that a local environmental risk analysis be performed to estimate the global environmental benefits such as greenhouse gas reduction.**
- **Expected energy load demands and the supply and return temperatures should be roughly estimated for a simplified design of the system.**
- **Based on the simple design a rough estimate of the investment cost, energy savings, and profitability should be performed as a decision point for the further project development**

Feasibility stage

- **Further development of the pre-feasibility study, mainly based on test holes and detailed information on energy load characteristics is recommended as a basis for design.**
- **Test holes shall preferably be placed inside the anticipated well or borehole field to be incorporated into the final system.**
- **If a permit for test hole drilling is required, it is recommended to have the permit before the drilling takes place.**
- **Test holes' depth and dimension should correspond to the depth and size of the final system for later use in the final system.**
- **For ATES applications at least two test wells are recommended, one for the warm and one for the cold side. These wells should be capacity tested and samples for chemical analyses taken. Furthermore, one of the wells should be used for a longer pumping test to define the hydraulic properties of the aquifer.**
- **For BTES applications as many test holes as required based on the size of the project, site-specific geological and hydrogeological conditions, and ambition of design quality should be used. As a minimum requirement, one test hole and one thermal response test (TRT) for each 10-30 boreholes is recommended.**
- **During drilling the geological layers should be documented by sufficiently accurate sampling, especially in sediments and sedimentary rock. In addition, it is recommended to measure the air-lift capacity (drilling with air) or loss of circulation (drilling with water or mud) to detect permeable layers or fractures.**
- **In boreholes drilled with air or at rotary drilling with clean water it is recommended to measure the groundwater level some hours after the drilling is completed.**
- **For ATES applications, hydrogeological expertise is recommended to analyze pumping test data and evaluate the hydraulic properties of the aquifer, as well as the risk for corrosion and well clogging from the water chemistry analyses.**

- **It is recommended to use experienced TRT service companies for commercial projects. Advanced service (DTRT/EGRT) is recommended for complex or scientific projects. TRT measurement methods recommended by IEA ECES Annex 21 should be used.**
- **In general, it is a mandatory requirement to comply with laws on groundwater protection and to follow any country-specific or local regulation related to this issue.**

Predesign

It is recommended to perform a pre-design of the system based on the findings during the feasibility stage and based on that perform economic analyzes according to the following recommendations.

- **A rough investment cost for the ATES or BTES system should be based on experience from similar projects in the same region or country.**
- **A rough estimate of the operational cost by using the expected amount of energy that is stored and produced, by using the country-specific price for electricity and the expected seasonal performance factor (SPF) should be calculated**
- **As an annual maintenance cost for ATES system a value of 2-5 % of the cost for wells can be used by experiences from the water well industry.**
- **As an annual maintenance cost for the BTES systems the cost can be considered practically none.**
- **As an annual maintenance cost for heat pumps in the systems, it is recommended to use 5 % of the cost for heat pumps.**
- **A rough estimate of profitability should be obtained by the use of straight pay-back time and/or the return rate of the investment.**
- **If life cycle cost analysis (LCC) is asked for in the feasibility stage it is recommended to use a lifetime of at least 40 years for both the ATES and BTES system, while the heat pumps have a lifetime of 20 years.**

Detail design

The form of contract will to some degree affect how and who is executing the detailed design. Typically, there are two options, one is known as Turnkey Contracts and the other is named Performance Contracts.

- ***It shall be aware that in turnkey projects the contractor is responsible for the design and function of the system based on the project frame specifications***
- ***For performance contracts, the customer should use consultants and experts to design the system and form the specifications***
- ***It is recommended to ensure high quality by requiring safety, quality, and environmental control certifications as well as references in the tender documents.***
- ***Drillers should be certified according to national and/or local legislation.***
- ***It is recommended to always, in one way or another, cover the responsibility for unforeseen damages in the contract, and demand that the people responding to the tender are certified and have correct insurance in place.***
- ***It is strongly recommended that environmental and economic risk analyses be conducted to show that such risks have been considered during the project development.***
- ***For the actual system design and the performance analysis (mathematical modeling) should always be used***

- *It is recommended to use monthly values for modeling smaller and less complex projects. For larger and more complex load characteristics hourly values should be considered, and both energy demand and power must be accounted for.*
- *The design of the supply temperature for the systems and the site-specific climate conditions must be considered.*
- *It is recommended to consider how much of the heat load shall be covered by the ATES or BTES system to define the size of the heat pump.*
- *If not already done in the feasibility or predesign phase, asking for a risk analysis in the contracting documents is recommended.*

In the technical descriptions in tender documents specifications of ATES or BTES wells or boreholes are commonly described. For such descriptions the following general recommendations are useful.

For ATES applications

- *In the design of the well, full use of the aquifer thickness should be a requirement to ensure the best well efficiency*
- *In aquifers with glaciofluvial material (eskers and deltas) it is recommended to use formation filter wells provided a grain size unconformity of more than 2,5*
- *In aquifers with less sorted material it is recommended to use gravel-packed wells*
- *In aquifers in consolidated formations such as sandstones and limestones an open well completion should be considered provided that the produced water will be free of solid particles.*
- *A well drilling method shall be chosen to meet the well design and the geological conditions at the site.*
- *A program for geological documentation of the geological layers and drilling performance and parameters shall be specified in tender documents.*
- *A program for capacity tests after the completion of each well shall be specified in the tender documents. The program shall describe the way the test shall be performed regarding flow rate, draw-down measuring, etc.*
- *The horizontal pipe system should be designed for the highest required flow rate with moderate friction losses and shall not be insulated except for parts that have direct contact with air.*
- *Preferably frequency-controlled submersible pumps shall be used, placed well below the lowest draw-down level in the wells.*
- *The system shall be designed not to allow air to enter the wells or the pipe system to avoid an increased potential for corrosion and precipitation of solid iron or manganese hydroxides.*

For BTES applications

- *The borehole system shall be designed concerning the required energy load characteristics and the thermal properties of the underground*
- *The number of boreholes, their depths, and configuration shall be adapted to the availability of ground and the geological conditions at the site*

- ***For BTES boreholes, air drilling with air should be used in hard or consolidated rocks and conventional rotary in unconsolidated geological settings. For very shallow boreholes other methods such as auger drilling should be considered***
- ***Borehole heat exchangers (U-pipes) should be chosen to fulfill the required flow rate, dimension of boreholes, borehole depth, temperature, and strength***
- ***The material for U-pipes, manifolds, and horizontal pipe systems should preferably consist of polyethylene PE100 or PE80 for storage temperatures up to +40oC. For temperatures above this level crosslinked PE must be used***
- ***It is recommended to use non-insulated horizontal pipes except for parts that are exposed to air, or situated close to a building foundation, or crossing water/sewage pipes.***
- ***The way each borehole shall be documented regarding depth, groundwater and geological unconformities shall be specified in the tender document***
- ***A program for pressure and flow testing the U-pipes and the horizontal system shall be specified in the tender documents***

9.4 Construction Practices

The construction of a hydronic pavement system with energy harvesting involves the construction of pavement, thermal storage, and finally the necessary devices and piping for coupling the pavement and thermal storage. The system boundaries between different parts of the system are shown in Figure 5.

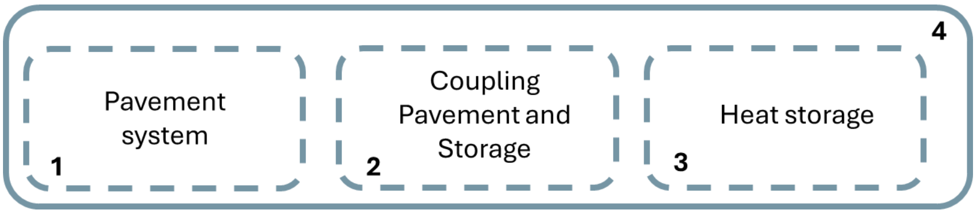


Figure 5: system boundaries of a hydronic pavement system

Construction of the pavement and heat storage involves different steps principally illustrated in Figure 6. However, the phases in more detail will certainly vary due to the conditions regarding the pavement material (concrete, asphalt, stone) and the technology used for storing heat.

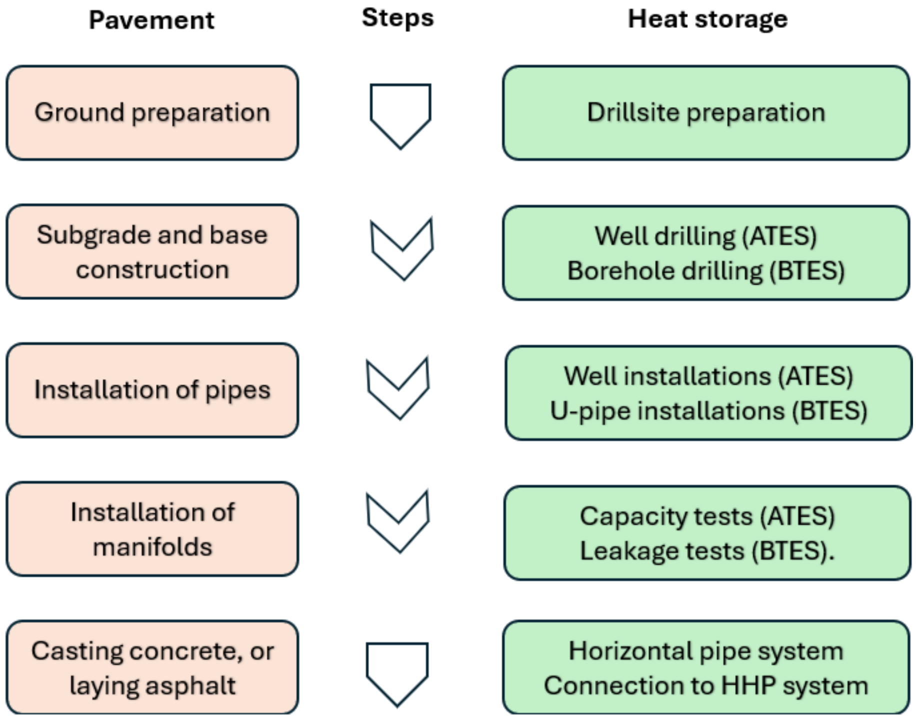


Figure 6. The principal construction phases for the pavement and the heat storage

In addition to the figure, there are several tests that must be performed to secure the function of later steps.

Pavement Construction

- The subgrade and base should be prepared according to standards and codes for the specific application, based on the vertical mechanical loads.

- The pipes can be installed using different solutions based on the type of pavement. An alternative technique for installation of the pipe a wire mesh is putting over the compacted base material and joining the pipes and the wire mesh by wire tie, see Figure 7.

Figure 7 pipes are tied with the wire mesh

(Source: https://www.bauhaus.se/)

Other alternatives can be used when the vertical loads are not heavy. An example is insulated panels for the installation of pipes. The advantage of these panels is that the insulated panels work as insulation of the pipe network and reduce the heat losses to the ground, see Figure 8.

Figure 8: Insulated panels

Source: https://alleguard.com/products/construction/ampex/

- The outlets and inlets should be connected to the manifold when the pipes are installed. After the piping installation is completed, pressure tests are required for at least 24 hours with a pressure of 4-5 bar, to ensure system reliability and integrity.

The piping network should be pressurized during concrete casting or asphalt laying. Both air and water can be used as pressurizing fluids. However, cold water should be used when laying asphalt to decrease the temperature of the pipe material.

- The pipes' material should resist mechanical stresses e.g. vertically (loads during pavement construction and traffic) and horizontally (shear and abrasion). Furthermore, the pipes should withstand high temperatures, i.e. the design temperature of the de-icing system. Generally, HDPE (high-density polyethylene) or PEX (Cross-linked polyethylene) plastic pipes are used as pipe materials.

- The snowfall and ice formation sensors should be installed before concrete casting. Figure 9 presents an embedded sensor in a concrete pavement. The sensor is a link between the pavement and the control system.

Figure 9 Embedded sensor in a concrete pavement.

- The water quality in a hydronic system depends on the local water quality. Generally, a pH value of around 9-10 at 25 °C is recommended. To prevent the corrosion of metallic components the presence of different types of salts in the water should be treated. In hydronic heated pavements, the fluid typically used is a mixture of water and propylene glycol. Propylene glycol acts as an antifreeze, preventing the fluid from freezing in cold temperatures.
- For long-term, maintenance-free operation, heat transfer fluids should only be diluted with good quality potable water with a pH between 9 and 10. Good quality water contains only minute traces of calcium (<50 ppm), magnesium (<50 ppm), chloride (<25 ppm), and sulfate (<25 ppm), and less than 100 ppm of total hardness as $CaCO_3$ (Snow and ice melting, design and installation manual, Uponor).
- The run-off from the snow-melt surface should be drained. Heating of the drainage system is needed to prevent refreezing of the run-off water.

Recommendations for the construction of pavement are given below based on discussions in Task 38 and literature studies.

- ***When pipes are installed, a pressure test is required for at least 24 hours with a pressure of 4-5 bar, to ensure system reliability and integrity.***
- ***The piping network should be pressurized during concrete casting or asphalt laying. Both air and water can be used as pressurizing fluids.***
- ***Embedded sensors should be controlled before laying the pavement.***
- ***The heat transfer fluid should be treated to achieve a long-term lifetime and reduce maintenance activities.***
- ***Integration of the heat source and the pavement needs a control system.***

Thermal Storage Construction

The main construction parts for ATES are the drilling and completion of wells, installation of well pipes and fittings, and the horizontal pipe system for connection to the HHP system. The well drilling and well installation issues have earlier been addressed in the EU project GEOTRAINET, *Training manuals for designers and drillers of shallow geothermal systems* (2011), from which several of the recommendations are reproduced.

Different steps for the construction of a BTES are published in a report within the International Energy Agency (IEA) Technical Collaboration Platform (TCP) Energy Conservation through Energy Storage (ECES) Annex 27 - *Quality Management in Design, Construction and Operation of Borehole Systems.* The publication is based on a survey, answered by seven countries, i.e., Belgium, Denmark, Finland, Germany, Netherlands, Sweden, and Turkey.

The construction of ATES and BTES systems should be specified in tender documents and established in a turnkey or performance contract.

General recommendations to be used in the construction phase of any ATES or BTES system:

- ***A fence surrounding the drill site, rig, materials, and other equipment related to the drilling process should be arranged and maintained throughout the entire drilling campaign.***
- ***It is recommended that the drilling contractor has responsibility for health and safety at the drill site as well as the responsibility for handling the disposal of water and cuttings. It is required that the appropriate health and safety plan always be present on the drilling site.***
- ***It is required that the drillers hold a certificate that ensures their understanding of the geological and surrounding environment where they are working.***
- ***It is recommended that all observations (regarding geology and hydrogeology) that are done during the drilling be reported in a driller log.***
- ***For ATES applications it is of great importance that the groundwater loop is constructed in a way that keeps the system airtight and always under pressure.***
- ***For BTES applications it is of great importance that leakage test and flow tests are executed according to the test program. Expert supervision of this work should be considered.***

Coupling a Pavement to Storage

The basic system layout of coupling a pavement to a heat source (thermal storage) is almost similar for all applications. However, the design of a system may differ in some components due to site-specific needs and the energy (heat) source. Figure 10 shows a simple coupling model for heat storage and pavement. It involves a circulation pump, a heat exchanger, several valves, temperature-regulated valves, and a control module.

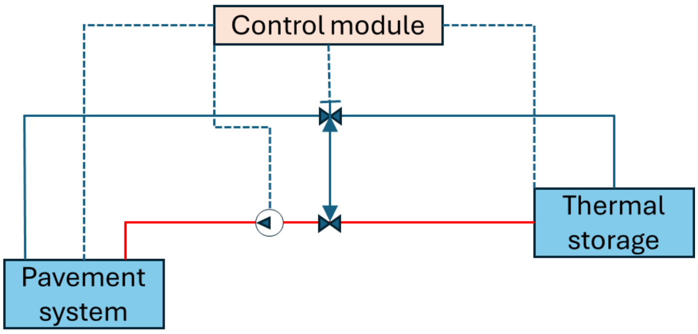


Figure 10 A simple schematic coupling possibility

The coupling becomes more advanced when the temperature level of storage is not enough for de-icing and snow melting. A ground heat source pump (GSHP) should be added to the system.

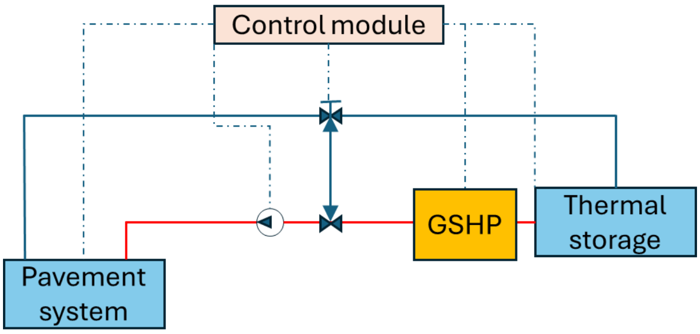


Figure 11 A simple schematic coupling with GSHP

The heat source in this chapter was selected as a thermal storage type and GSHP was suggested as a backup. However, any other heat source can be used.

It should be mentioned that almost all key players in the hydronic heating market provide a complete system including pavement and heat source integration.

Special Features of Two-Phase Thermosiphon Systems

In the case of a two-phase thermosiphon system, some features differ, which are discussed in this chapter. Since this heating system is powered directly by heat from the ground, special attention must be paid to the thermal resistance of the entire heating system. In particular, the thermal resistance from the condenser to the surface must be carefully designed so that sufficient heating output can still be achieved even when the borehole has already cooled down. Since the backflow of the condensate to the evaporator in the two-phase thermosiphon occurs exclusively by gravity, special attention must be paid to a sufficient inclination angle of both the condenser pipes and the connecting pipes up to the borehole. In the case of CO2, a minimum inclination angle of 1° must be maintained from the condenser to the borehole. However, it is recommended to use an angle of 2° for connecting pipes. Either copper or stainless steel can be used as the material for the condenser or the connecting pipes. However, if the surface to be heated is made of concrete, stainless steel is preferable because the copper pipes must not come into direct contact with the concrete. To protect the connecting pipes between the heating surface and the borehole, protective pipes or concrete channels are recommended. These also help to maintain the minimum angle of inclination everywhere and protect the pipe insulation.

Tightness is one of the biggest challenges with this heating system. Brazing is therefore recommended as a connection technique between the condenser, connecting pipes, and evaporator. A pressure test after completion is also strongly recommended. The heat transfer medium in the thermosiphon is usually either CO2 or propane. Pressure gauges are recommended for monitoring the circuits at the exit of the borehole. No control system is required for the two-phase thermosiphon. Snowfall and ice formation sensors are not required. Sensors for measuring environmental conditions (temperature, wind speed, ...) are also not necessary. There is also no need to worry about the heat transfer medium freezing.

9.5 Operation Practices

The best operation procedure for a hydronic system is the procedure that makes it possible to achieve the desired de-icing and snow-melting conditions. Each hydronic system is designed for a specific climate/surface condition e.g. snowfall can be 5 or 10 cm per day, the snow can be wet or dry, and other climatological parameters such as wind speed, see deliverable 2.1, Table 1, Classification and definition of surface conditions. Thus, the surface condition is dependent on the dynamic of climate conditions. An operation procedure should be able to cover the most possible surface conditions. An operation procedure that can be valid for all climate conditions and zones, is not realistic to define.

A successful operation of a hydronic heated system requires monitoring several parameters, e.g., inlet and outlet temperatures of thermal storage and the pavement, flow rate and pressure, surface temperature, and climate station close to the system. Monitoring these parameters makes it possible to operate a system more efficiently.

The goal is to achieve the desired de-icing and snow-melting using the minimum possible energy when the system is exposed to normal winter conditions. In extreme winter conditions, the need for energy will be higher. The selection of surface temperature (set point) for heating is fundamental for reducing unnecessary energy use. The required energy depends on several parameters, e.g., the depth of the buried pipes, the type of pavement material, and climate conditions. Tabel XX presents an example of operation set points at Arlanda Airport, Stockholm Sweden.

Table xx. Estimated interval of supply temperatures at different modes of operation at the HHP systems in Arlanda Airport (Persson 2007)

Mode of operation	**Surface temp. (°C)**	**Required power (W/m^2)**	**Supply temp. (°C)**
Keep surface warm before snowfall	+1,0	20-150	3-13
Snow melting (0,02-2,0 H2O/h)	+ 3,0	150-270	17-27
Evaporation of H2O after snow melting	+5,0	100-230	12-22

Weather forecasting could be an efficient way to optimize needed energy. Weather forecasting can eliminate the time lag of the hydronic heated pavement. However, weather forecasting needs local and regional climate data and software that calculates the time for snowfall.

Dividing the pavement into several zones and heating the zones where deicing is needed reduces the required energy. The required energy can also be reduced by operating the system with lower temperatures during off-peak hours.

Based on knowledge obtained from literature and discussions in Task 38 the following recommendations have been made.

- ***A successful operation of a hydronic heated system should require monitoring of several parameters mainly covering flow rates fluid temperatures in different parts of the system and climate conditions. This is also the case when the system is used for the collection of solar energy in summer.***

- ***Energy demand for de-icing and snow melting as well as for harvesting of solar energy should be optimized by selecting proper set points for the surface temperature that controls the flow rate and supply temperature.***
- ***Dividing the surface area into different zones should be considered to minimize the energy demand in the de-icing and snow-melting mode of operation.***
- ***At storage of solar energy, it shall be considered to keep the supply temperature to pavement pipe system as low as possible to optimize storage of heat***

Special Features of Two-Phase Thermosiphon Systems

In contrast to pumped systems, no control system is required for the directly operated two-phase thermosiphon because the heating system is self-regulating. For this reason, correct dimensioning plays a special role.

9.6 Maintenance Best Practices

Regular maintenance is fundamental to the longevity and efficiency of a hydronic heated pavement system. Before the winter season perform a thorough inspection of the system. The antifreeze concentration should be sufficient and, there should not be any leaks in the pipes. This preparation prevents any operational issues during the peak winter season. A detailed inspection and maintenance of the system should be performed after the winter season. Check for any damage caused by the freeze-thaw cycles and make necessary repairs.

An annual maintenance program is required when active chemicals are incorporated into the hydronic snow and ice melting system.

The maintenance of ATES systems is commonly related to cleaning the wells due to clogging. However, this is a process that seldom can be predicted and so is the frequency of cleaning. Whether a clogging process occurs or not can only be monitored by using flow rate, drawdown, and injection pressure as parameters.

To maintain the operational reliability of an ATES system it is essential that the system has a monitoring program for essential parameters and a maintenance program to follow.

The maintenance of the BTES system is limited if correctly designed and constructed. Some maintenance is associated with the heat pump, and a degree of control for system pressure and flow rates and heat carrier fluid quality is needed.

To maintain the operational reliability of the BTES system the minimum and maximum inlet temperatures and pressure drop over time in the ground loop should be monitored and checked.

Special Features of Two-Phase Thermosiphon Systems

In addition to what was already mentioned above the pressures of the individual circuits need to be checked regularly to notice possible leaks. However, these can also be visually recognized during operation in the winter months, initially by a decrease in heating output and later by the failure of individual heating circuits. These heating circuits are visible on the surface when it rains or snows. The affected circuits should be thoroughly examined, and leaks should be eliminated. When filling, make sure that there is enough refrigerant so that a pool of approx. 10 m is created at the bottom of the evaporator.

9.7 Conclusion

HHP systems, based on ATES or BTES as a heat source, would work efficiently and lower the energy cost significantly.

To design and construct heat sources, in this case ATES and BTES systems, there are existing guidelines for space heating and cooling. These have been reworked to fit de-icing and snow-meting systems. This will minimize design and construction mistakes in planning, constructing, and maintaining the ground-heated systems.

The ground source de-icing and snow melting systems are environmentally friendly and shall be regarded as practically sustainable by using renewable sources of energy. This will contribute to less emissions of greenhouse gases.

Special Features of Two-Phase Thermosiphon Systems

The thermal load depends on the condition of the source, just as the surface temperature depends on it. A coupled calculation of load profile and source is required. As part of the GERDI project [Staudacher 2024], a Python-based simulation tool was developed with which this heating system can be designed. The model was published as open-source software called GERDPy on ZAE's own GitHub at https://github.com/zae-bayern/GERDPy.

No control system is necessary. Just the pressure of the heating circuits should be monitored.

There is no time lag on the pavement as it is continuously heated. The piping network usually does not have to be pressurized during concrete casting or asphalt laying. The embedded pipe’s depth should be as close as possible to the pavement surface. Generally, the pipe diameter is 12-16 mm, the distance between pipes is 50-75 mm, and the embedment depth is 25-50 mm.

A Two-Phase Thermosiphon System can’t harvest solar energy. That is why larger distances are needed for the boreholes than with BTES.

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10 PLANNING, CONSTRUCTION, AND MONITORING, SUBTASK 4, DELIVERABLE 4.3: RECOMMENDATIONS ON MARKET AND TECHNOLOGY DEVELOPMENT FOR HYDRONIC HEATED PAVEMENT USING GROUND HEAT SOURCE

10.1 Introduction

Thermal de-icing and snow-melting systems have been used in cold climates to control winter conditions on infrastructure surfaces. These systems offer several advantages e.g. reducing the risk of slips, trips, and falls for pedestrians and sliding of vehicles, improving traffic safety, and minimizing accidents caused by skidding or loss of control. Furthermore, thermal de-icing reduces the need for de-icing by salts and thereby, prevents environmental damage to vegetation, waterways, and infrastructure. Finally, the pavement lifetime increases when the surface temperature is kept even.

Thermal de-icing and snow melting can be used in many applications such as railway switches, ramps, stairs and entrances, platforms, bridge decks, road parts (between tunnels, sensitive slopes, etc.), walking/biking paths, parking lots, aircraft parking areas, runway, and sports fields. Deliverables D1.1, D1.2, and D4.1 demonstrate the utilization of de-icing and snow-melting systems in various applications.

Traditionally, electricity, boilers, and district heating are used as heating sources for heated pavements. Changing the heat source to ground source heat has many advantages, for example, lower energy cost, less emission of greenhouse gases, and avoiding load peaks in the electrical power grid.

Almost all surface pavements are exposed to solar radiation. Thus, a paved surface can function as a solar collector. This in combination with hydronic heated pavement and storage of harvested energy from the pavement in a ground thermal storage facility can eliminate costs related to using energy for heating a pavement. Recently, there has been a growing interest in integrating energy-harvesting technologies. These systems can generate renewable energy while maintaining the benefits of hydronic heating.

This report aims to provide recommendations for market and technology development to promote the adoption of hydronic heated pavements using ground heat sources and energy-harvesting pavements. It is fully possible to create more sustainable and efficient urban infrastructure by leveraging these technologies.

10.2 Market Analysis

Key market drivers are several environmental, social, and economic benefits. Some of the advantages are mentioned in the following subchapters.

- *Environmental benefits:* One of the primary drivers of this market is environmental advantage. Traditional de-icing methods often rely on chemicals that can harm the environment. Hydronic systems that use renewable energy such as ground source heat minimize chemical runoff.

  Utilizing ground source heat (UTES) based on harvesting solar energy from the pavement surface can significantly reduce the emission of greenhouse gases and harmful substances.

- *Social benefits:* Using de-icing and snow-melting systems increases infrastructure accessibility during winter. In transportation infrastructure, improved accessibility leads to fewer traffic jams and accidents. In urban areas, heated pedestrian walkways and bicycle lanes enhance mobility options for residents.

- *Economic benefits:* Converting to ground source energy turns to lower operational costs and a more sustainable solution. The pavement's lifetime will be improved by reducing the freeze-thaw cycles that cause damage. This will also reduce maintenance costs. These benefits appeal to municipalities and governments, looking to invest in long-term infrastructure solutions.

Market analysis is divided into current market status, market potential, key players, and challenges. A short status of the part follows:

Current Market Status: The market for hydronic heated pavements is currently a niche, with adoption primarily in regions with severe winters. Hydronic systems can be used for pavement cooling in warm climates, preventing urban heat challenges. The demand for energy-harvesting pavements is emerging, with pilot projects demonstrating feasibility. Key markets include North America, Europe, and parts of Asia.

Market Potential: There is significant growth potential in urban areas, airports, and critical infrastructure. The increasing focus on smart cities and sustainable infrastructure is driving the demand. Potential applications include pedestrian walkways, bicycle paths, and roadways.

Key Players: The key players (supply) are major companies in the hydronic heating market such as Uponor, REHAU, Roth, Kermi, etc. Investment trends show a growing interest in R&D to improve system efficiency and integration.

The key players (users) are often municipalities and transport organizations, but also larger building construction companies that may use surface areas of various sizes with de-icing and snow melting systems. Other key players are national road and railway operators.

Challenges: A high initial investment cost, lack of awareness, and regulatory hurdles are major barriers to market growth. The effectiveness of ground source de-icing systems depends on the local climate and geological conditions and the type of system that can be used. Accurate techno-economic calculations are needed to convince stakeholders. Strategies to overcome these challenges include government incentives, public awareness campaigns, and collaboration with urban planners.

10.3 Technology Development

The technological development of hydronic heated pavement contains three subsystems: pavement, storage, and control system. However, merging the subsystems into one system can be developed further to increase the efficiency of the hydronic heated pavement system based on ground source energy.

Current Technologies: Existing hydronic heated pavement systems heat the fluid using mainly electric cables, boilers or district heating. Very few use ground source heat, from a market share point of view. The largest markets for ground source heat are currently Japan and Iceland.

Innovations: A further development is to use the pavement surface as a solar collector and store the harvested energy in thermal underground storage with or without a heat pump, which leverages stable temperatures to provide an efficient heat source. Smart control systems that optimize energy use based on weather forecasts are also emerging. Decreasing the albedo of the surface material to absorb more irradiation is ongoing.

Other innovative developments within ground source de-icing include thermosyphons for de-icing of paved surfaces and railway switches, and deeper ground heat probes (>500 m).

Case Studies: Hydronic heated pavements are being implemented in various pilot projects and full-scale installations worldwide. A list of projects is presented in D1.1-D1.2 and selected case studies are presented in D4.1. In two projects, one in Sweden and the other in Belgium, field stations have been set up to test the feasibility of using stored solar energy by the pavement to increase ground source energy. An example of using a groundwater system has successfully been used since 2009 for de-icing and snow melting at Stockholm Arlanda Airport. Furthermore, several airports in the USA and Europe are exploring utilizing thermal de-icing and snow-melting systems. The Louisville Muhammad Ali International Airport (SDF) in Kentucky, USA, has officially launched a geothermal heating and cooling system, harnessing energy from the largest geothermal field of any airport in the USA.

10.4 Recommendations

The recommendations below cover market strategies, technical advancement, and policy and regulation.

Market Strategies:

I) **A**wareness Campaigns: Educate stakeholders about the benefits of ground source heated hydronic and energy-harvesting pavements through public awareness campaigns and educational programs.

II) **I**ncentives: Government incentives and subsidies can help offset initial investment costs and encourage adoption.

III) **P**artnerships: Collaborate with urban planners, construction companies, and policymakers to integrate these systems into new projects and urban development plans.

Technological Advancements:

IV) **P**avements: Develop pavements with low albedo to increase solar energy harvesting. This can reduce reliance on external power sources and enhance sustainability. Furthermore, developing pavement material with a high diffusivity than the existing pavement material will reduce the time lag of the system.

V) **H**ybrid energy Systems: Combine other energy sources such as building surplus energy, especially in urban areas, with ground heat sources to create a hybrid system that maximizes energy efficiency.

VI) **D**urable Materials: Invest in research to develop durable materials, to increase the hydronic system's lifetime. The materials involved in hydronic pavement should withstand heavy traffic and harsh weather conditions.

VII) **C**ontrol system: Develop accurate weather forecasting programs to increase the efficiency of the hydronic system.

VIII) **S**ystem Monitoring: Integrating IoT sensors can help monitor the performance of both the thermal storage and the hydronic heating system. Real-time data can alert maintenance teams to issues before they become critical, ensuring the system operates efficiently.

IX) **C**onduct life cycle assessments to ensure that the systems are environmentally friendly and have a positive environmental impact.

Policy and Regulation:

X) **S**tandards Development: Establish industry standards for the installation, performance, and maintenance of ground source systems coupled with hydronic heated and energy-harvesting pavements.

XI) **R**egulatory Support: Advocate for policies that support using renewable energy sources and provide regulatory support for technology adoption.

XII) Variable electricity tariffs that reflect current fluctuations in the stock market should become mandatory for all consumers. This helps to replace consumers who are unfavorable to the power grid.

10.5 Conclusion

Ground source coupled hydronic heated pavements and energy-harvesting pavements offer significant benefits in terms of social, economic, and environmental challenges in urban and rural areas such as traffic safety, accessibility, improved mobility, and sustainability. Wider adoption of these technologies can be promoted by addressing market and technological challenges.

With continued innovation and supportive policies, hydronic heated pavements using ground heat sources and energy-harvesting pavements have the potential to become standard features in urban/rural infrastructures. The incorporation of these technologies can contribute to the development of smart cities and sustainable urban environments as well as social benefits from decreased number of accidents among vehicles and pedestrians.

SUMMARY SUBTASK 4: PLANNING, CONSTRUCTION, AND MONITORING

Introduction

Task 4 includes three subtasks namely 4.1. Mapping of demonstration and existing plants, 4.2. Best practices for design, construction, operation, and maintenance and finally 4.3. Recommendations on Market and Technology Development for Hydronic Heated Pavement Using Ground Heat Source. In the following chapters a summary of each task is presented.

Mapping of demonstration and existing plants

Focus:

Deliverable 4.1 maps out existing and pilot de-icing and snow-melting systems across seven countries (e.g., Sweden, Germany, France, Japan). The report also identifies what technologies are currently in use, such as electric heated pavement system (EHPS), hydronic heated pavement system (HHPS), and their energy sources (district heating, geothermal, solar).

It includes detailed case studies of demonstration plants like the HERO project in Sweden and the HEAL system in Belgium, showing how ground source energy is being applied in real-world settings.

The report also highlights challenges (e.g., high energy demand, climate variability) and opportunities (e.g., sports fields, airports, off-grid areas) for expanding renewable-based systems.

Best practices for design, construction, operation, and maintenance

Focus:

This document serves as a technical manual for designing and building hydronic de-icing systems using ground source energy.

It breaks down the system into three main components: the pavement, the heat source (e.g., ATES, BTES), and the control system.

It provides step-by-step guidance for each project phase: pre-feasibility, feasibility, predesign, and detailed design, including how to size and select thermal storage systems.

It also includes construction techniques, such as pipe layout, insulation, and sensor integration, and offers maintenance strategies to ensure long-term performance.

Special attention is given to two-phase thermosyphon systems, which are passive, self-regulating systems ideal for small-scale or off-grid applications.

Recommendations on Market and Technology Development for Hydronic Heated Pavement Using Ground Heat Source

This report synthesizes the findings from Subtasks 4.1 and 4.2 and translates them into strategic recommendations for broader adoption.

It outlines market strategies like public awareness campaigns, government incentives, and partnerships with urban planners and municipalities.

On the technology side, it recommends developing hybrid systems, using low-albedo pavements for better solar absorption, and integrating IoT-based monitoring for real-time performance tracking.

It also addresses policy needs, such as creating industry standards and promoting variable electricity tariffs to encourage off-peak energy use.

The goal is to scale up these systems from pilot projects to mainstream infrastructure, contributing to smart cities and climate-resilient urban planning.

APPENDICES SUBTASK1 – NATIONAL STATE-OF-THE-ART REPORTS: Deliverable 1.1

State-of-the-art report Belgium

State-of-the-art report France

State-of-the-art report Germany

State-of-the-art report Italy

State-of-the-art report Sweden

State-of-the-art report Türkiye

APPENDICES SUBTASK1 – NATIONAL STATE-OF-THE-ART REPORTS: Deliverable 1.2: CALCULATED SCENARIOS

In this Appendix some calculated examples are given as support for the statements made in this report concerning the efficiency of ground source HHP heating but also the profitability of these systems.

The scenarios reflect ground source HHP systems applied in Scandinavian climates but can be adapted to other climate conditions as well by changing the accumulated snow fall, the mean outdoor temperature, and the number of hours below the freezing point. Furthermore, additional investment costs can be applied to any country's specific values.

The accuracy of calculations is at the level of an early feasibility stage in real projects. Hence the values given cannot be used other than as indications. Real commercial projects will always be site specific under different conditions in different countries.

Assumptions

Price of energy sources

To run a ground source heated HHP system a certain amount of electricity is used. The price of electricity is country specific and varies with time as do the traditional heat sources. In the long run, the price of electricity tends to be close to the price of other sources used for heating. This has been the case historically and it is reasonable to believe that this is also true for the lifetime of an HHP system. As a matter of fact, the higher the future energy price is, the more profitable a ground source heated HHP system will be.

In these scenarios, the price of electricity has been set equal to all other forms of heat sources used in HHP systems at a general price of 200 Euro/MWh (in 2024).

Price of open loop wells

For shallow wells in glaciofluvial aquifers, drilled with DTH and completed with naturally developed screens, a typical cost of 400 Euro/m has been used, including pumps and well equipment. To this another 200 Euro/m of piping system has been added.

For wells drilled with the conventional rotary method and completed with gravel pack the price is set to 600 Euro/m and the well capacity is set to 40 m^3/h.

Price of closed loop boreholes

The cost for closed loop boreholes differs from country to country. However, the investment cost will be practically the same in the Scandinavian countries using DTH drilling methods and boreholes filled with groundwater. The current price for these types of boreholes has been set to 60 Euro/m, the collector and horizontal pipe system included.

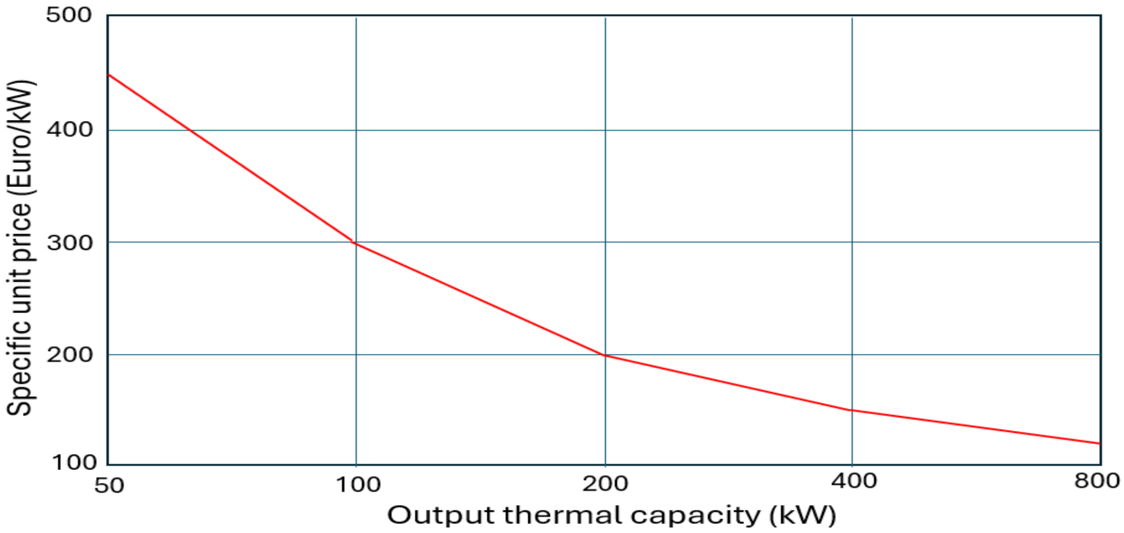
For countries using grouted boreholes the price of 70 Euro/m has been used also covering other drilling methods such as conventional rotary and hollow stem auger.

Price of heat pump systems

The market price for modern frequency-controlled heat pumps in the range 50-1000 kW is quite the same in Europe and most parts of the world. However, the price for a water-to-water unit will greatly vary with the size. Hence the specific unit price will vary depending on the thermal output capacity.

In these scenarios the specific cost is estimated by using the graph below. This represents mean values obtained from the price lists of main suppliers of heat pumps on the European market in late 2024 combined with information from some tender documents from realized GSHP and UTES systems in 2023-24.

For units larger than 1 000 kW a specific cost of 110 Euro/kW has been used.



In addition to the heat pump cost the installation cost shall be added, covering the HVAC work and control system. This cost also varies with the size of the system. Small units up to 150 kW are designed for easy installations. In these scenarios the installation cost is estimated to be 50 % of heat pump price, while medium sized units are estimated to 100 %, and single large units to 150 %.

Lifetime assessments and maintenance cost for open loop wells

Even if the lifetime of an open loop ground source well could be 50 years or more, there are also examples of wells that only last 10 years or less. The reason is lost capacity commonly caused by clogging. A reasonable assessment would therefore be 20 years for the wells, submersible pump included, and 50 years for the piping system.

The maintenance cost for the wells may also be an important cost factor. In this study 5% of the well investment cost has been used as annual maintenance cost.

Lifetime assessments and maintenance cost for closed loop boreholes

By experience the lifetime of closed loop boreholes is at least 50 years, and the same for the pipe system. The only part that may be replaced is the circulation pump.

If the borehole system is carefully constructed there is practically no maintenance cost. Only the heat carrier fluid may be replaced. In these calculations the maintenance cost is set to zero.

Lifetime assessments and maintenance cost for heat pumps

The lifetime of heat pumps in the ground source system should, by common practice, be set to 20 years. However, in this case 25 years is used based on the fact that they are operating less than heat pumps used for space heating.

In these calculations the maintenance cost is set to be 5% of the unit investment cost annually.

Seasonal Performance Factor (SPF)

In these calculations SPF is defined as the ratio between the produced ground source heat and the electricity used for the heat pump and the brine or groundwater circulation pumps.

It shall be noted that the energy savings (ES) is greatest in the lower part of the SPF differential scale, to be marginal in the upper scale. For instance, an increase from 2 to 4 means an increased ES of 25%, while from 10 to 20 comes out with an increase of 5%.

Due to a relatively low condenser temperature the SPF for heat pump is set to 5.0 in all of the scenarios.

Energy balance UTES applications

It is assumed that the heat extracted from the underground is balanced with heat injected + heat to compensate for any heat losses over a full year. The heat source for injections is solar energy capture or waste heat without any energy cost except for running circulation pumps.

Modell simulations

The closed loop systems with heat pumps have been roughly modelled using EED in order to estimate the number of boreholes and the brine temperatures over a season, while the system without heat pump (HT-BTES) has been modelled using the DST simulation model as well.

The simulations are based on actual climate data hour by hour representing the middle part of Sweden (Uppsala) in 2021. This year has the best fit as mean data for the period 2016-2024. Hence, the results would be different in other climate conditions.

In all cases no energy is extracted during the first winter season in order to initially heat up the rock volume used for BTES. In one case (Scenario 4) the injected heat is approximately doubled the first summer.

In all cases the boreholes are drilled with the DTH method in hard crystalline rock with a thermal conductivity of 3.5 W/m,°C. The borehole dimension is 115 mm, and the borehole heat exchanger consists of single U-pipes DN 40. The boreholes are filled with groundwater.

Several simulations have been made for each case with different spacing, numbers of boreholes and size of heat pump. The most favorable configuration when it comes to supply temperature, size of heat pump and thermal efficiency has been chosen for each scenario.

The simulation results are presented by graphs at the end of each scenario description

Profitability

As a simple way to express profitability the payback time method has been used. This is based on the annual energy cost savings using the ground source heating system compared to conventional heat sources. In the energy cost also the annual maintenance cost is included. The ratio dividing the additional investment cost by the annual savings forms the payback time (years).

Scenario 1. Additional use of GSHP systems for minor HHP systems

In this case a building with an existing GSHP system, an HHP system at the entrance to the building, a part of a sidewalk, and a minor parking lot shall be installed. Altogether the system covers 200 m^2. The main aim is to avoid slippery conditions around the freezing point and to melt light snowfall.

The mean outdoor temperature is +4°C and the duration of temperatures between +2 and -5 degrees is 1 500 hours.

There are two options for providing heat to the HHP system. One is a connection to district heating at an investment cost of 10 000 Euro. The other one is to connect to the internal HVAC system to the building with a second connection to the existing borehole loop. The latter connection makes it possible to store solar energy in the borehole system in summer. The connection to the HVAC system and the heat exchanger for solar heat capture will take an investment of 25 000 Euro. The basis for design of and the calculation results is summarized in the table below.

The existing GSHP	
Ground source	Vertical boreholes in rock
Heat pump capacity	200 kW
Condenser temp.	55/40°C (at zero degrees ODT)
Annual heat demand	500 MWh
SPF	3.0
The added HHP-system	
Surface area	200 m^2
Designed heating power	250 W/m^2
Mean operating power	40 kW
Operating time	1 500 hours
Annual heat demand	60 MWh
Maximum supply/return temp.	40/30°C
Economics	
Additional HVAC investment cost	15 000 Euro
Energy cost HHP w district heating	12 000 Euro
Annual energy cost HHP w GSHP	4 000 Euro
Savings	8 000 Euro
Straight payback time	1.9 year

Comment

The storage of heat during summer will complement the additional heat extraction in the winter.

Scenario 2. A shopping center using a GWHP system

In this example a shopping center is located in an area outside a city and below the surface there is a sandstone aquifer. The groundwater in the aquifer is brackish and cannot be used for other purposes. A test well shows that a gravel packed screen can be installed at a depth of 65-80 m. A pumping test shows a capacity of 60 m^3/h. The temperature is +12°C and steady throughout the year.

A HHP system is installed for most of the parking area and entrances to cover 4 000 m^2. The alternative heat source is a gas boiler at the investment of 50 000 Euro. The system is designed to melt a snow fall intensity of 3 mm/ H_2O hour. The system is also used to keep the surface preheated at +1°C for 1 200 hours per year. The main input data is shown in the table below.

HHP-system	
Surface area	4000 m^2
Annual heating time	1 000 hours
Maximum power snow melting	250 W/m^2
Maximum power preheating/evaporation	160 W/m^2 (at windy conditions)
Maximum supply/return temp.	25/10°C (at snow melting mode)
Annual heat consumption	400 MWh/year
GWHP-system with heat pump	
Free heating capacity	1 000 kW
Heat pump capacity	250 kW (in snow melting mode)
Maximum groundwater flow rate	30 l/s (at delta T 8°C)
Number of wells	2 + 2 of 80 m depth (gravel pack completion)
Groundwater working temperature	12-4°C
Energy turnover and efficiency	
Direct heating	300 MWh
Heating with the heat pump	100 MWh
COP direct heating	25
COP heat pump heating	5
Seasonal performance factor (SPF)	12.5
Economics	
Additional investment cost	275 000 Euro
Annual operation cost GWHP	17 300 Euro
Reference energy cost	80 000 Euro
Annual savings	62 700 Euro
Straight payback time	4.6 years

Scenario 3. Pedestrian streets and walkways using BTES

In this scenario, a HHP system is planned to be constructed in a busy city center covering an area of 10 000 m^2. In this case the BTES system is compared to conventional heating with an investment cost of 100 000 Euro.

The climate is semi-continental with a mean temperature of +6°C and with some 1500 hours of temperatures at or below the freezing point.

The system is designed for continuous snow melting at an intensity of 3 mm H_2O/hour. The pavement is preheated at temperatures below +2°C at a max power of 100 W/m^2. The demand at -10°C is 250 W/m^2. Below -10°C the system is not running at all.

The number of boreholes has been chosen to cover a major part of heat by direct heating in order to minimize the size of the heat pump. The basis for design and the result of EED calculation are shown in the table and the graphs below.

HHP-system	
Surface area	10 000 m^2
Annual heating time	1 500 hours
Maximum power snow melting	250 W/m^2
Maximum power preheating/evaporation	200 W/m^2
Maximum supply/return temp.	35/20°C (at snow melting mode)
Annual heat consumption	2 000 MWh
BTES-system with heat pump	
Direct heating power	1 000 kW
Heat pump power	1 500 kW
Number of boreholes	200 of 200 m depth
Brine working temperature	5-35°C
Energy turnover and efficiency	
Direct heating	1 200 MWh
Heating with the heat pump	800 MWh
COP direct heating (incl. heat capture)	20
COP heat pump heating	5
Seasonal performance factor (SPF)	9.1
Economics	
Additional investment cost	2 710 000 Euro
Annual operation cost BTES	49 000 Euro
Reference energy cost	400 000
Annual savings	351 000
Straight payback time	7.8 years

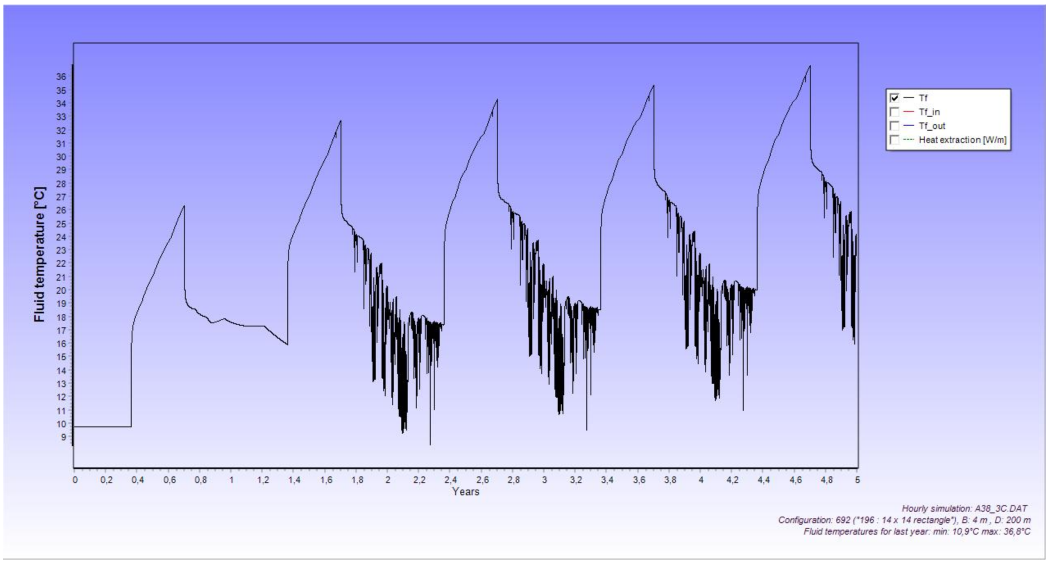
EED simulation

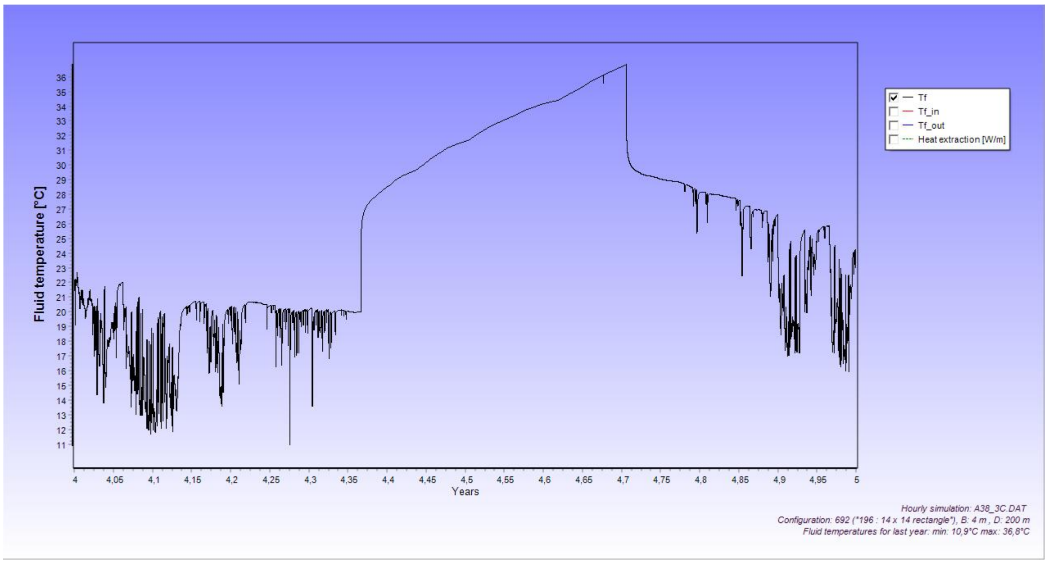
The most favorable alternative is to show number, spacing, depth of boreholes, and total flow rate. T_{fm} = mean temperature; T_{in} = minimum temp. to BTES; T_{out} = minimum temp. from BTES. Delta T times the flowrate indicates the load capacity.

No. BH	Configu-ration	Depth (m)	Length (m)	Space (m)	Max T_{fm} (°C)	Min T_{fm} (°C)	Flow rate (l/s)	Delta T (°C)	T_{out} (°C)	T_{in} (°C)
196	14x14	200	39200	4	36.8	10.9	117.6	5.26	13.53	8.27

The fluid temperature during the first five years of operation is shown in the upper graph illustrating that the efficiency of BTES is gradually increasing. The first winter there is no extraction of heat.

In the lower graph the fifth year is magnified in order to better see periods of heat extraction and the use of the heat pump for peak shaving.





Scenario 4. Pedestrian streets and walkways using HT-BTES

Many existing HHP systems in busy city environments in Scandinavia are heated by district heat produced by cogeneration plants.

The cogeneration plants will often produce surplus heat in the summer when the heating demand is low. The surplus heat has to be chilled either by cooling towers or by using surface water. An obvious alternative is to store the surplus heat in a HT-BTES system to be used for de-icing and snow melting in the winter.

In this scenario, the same size and the same HHP-demands as in Scenario 3 are used. The main differences are that the stored temperature is +80°C and that the system will work without supporting heat pumps. Furthermore, the high storage temperature requires thermal resistant plastic for the U-pipes and the horizontal pipe system that increases the cost for boreholes by 20%. The HVAC cost is estimated to 10% of the investment cost.

The basis for design of and results are summarized in the table below.

HHP system	
Surface area	10 000 m^2
Spec. capacity snow melting	350 W/m^2
Spec. capacity preheating/evaporation	200 W/m^2
Maximum supply/return temp.	40/25°C (in snow melting mode)
Annual heat consumption	2 000 MWh
HT- BTES system, energy balance and performance	
Number of boreholes	120 of 200 m depth
Brine working temperature	80-20°C
Minimum supply temp. from BTES	>30°C
Free heating capacity	3 500 kW
Direct heating	2 000 MWh
Seasonal performance factor (SPF)	20
Economics	
Additional investment cost	1 900 000 Euro
Energy cost district heating	400 000 Euro
Annual operation cost HT-BTES	20 000 Euro
Annual savings	380 000 Euro
Straight payback time	5.0 years

Comments

No insulation top layer has been used in this case. Insulation applied; the number of boreholes would be somewhat less.

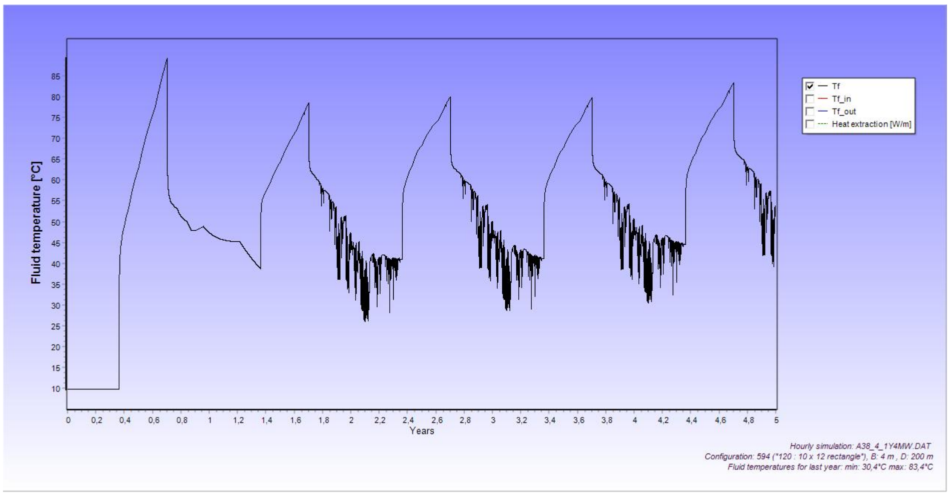
With grouted boreholes the additional investment cost increases to 2 220 000 Euro with a payback time of 5.9 years.

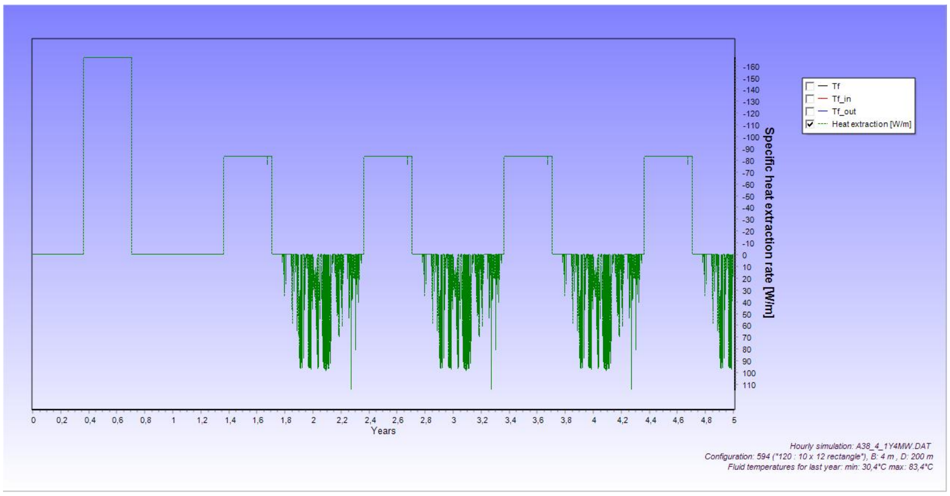
EED simulation

In this simulation the configuration of boreholes forms a cylindrical shape. The charging temperature should be + 80°C, but the EED loading conditions only accept prescribed heat transfer rates. The steady injection temperature condition is here approximated by fitting a simple scheme of heat injection rates that generate an average injection fluid temperature around 80°C (to be verified by simulations using the DST model). The injection rates are chosen to be 4 000 kW during the first year and 2 000 kW for subsequent years. The most favorable alternative is to show number, spacing, depth of boreholes and total flow rate. (T_{fm} = mean temperature; T_{in} = minimum temp. to BTES; T_{out} = minimum temp. from BTES. Delta T times the flowrate indicates the load capacity)

No. BH	**Configu-ration**	**Depth (m)**	**Length (m)**	**Space (m)**	**Max T_{fm} (°C)**	**Min T_{fm} (°C)**	**Flow rate (l/s)**	**Delta T (°C)**	**T_{out} (°C)**	**T_{in} (°C)**
120	10x12	200	24 000	4	83.4	30.4	72.0	9.08	34.94	25.26

The fluid temperature during the first five years of operation is shown in the upper graph illustrating that the efficiency of BTES is gradually increasing but will not be efficient enough to cover the peak demand occurring in April as a heavy snow fall, viable in the lower graph.



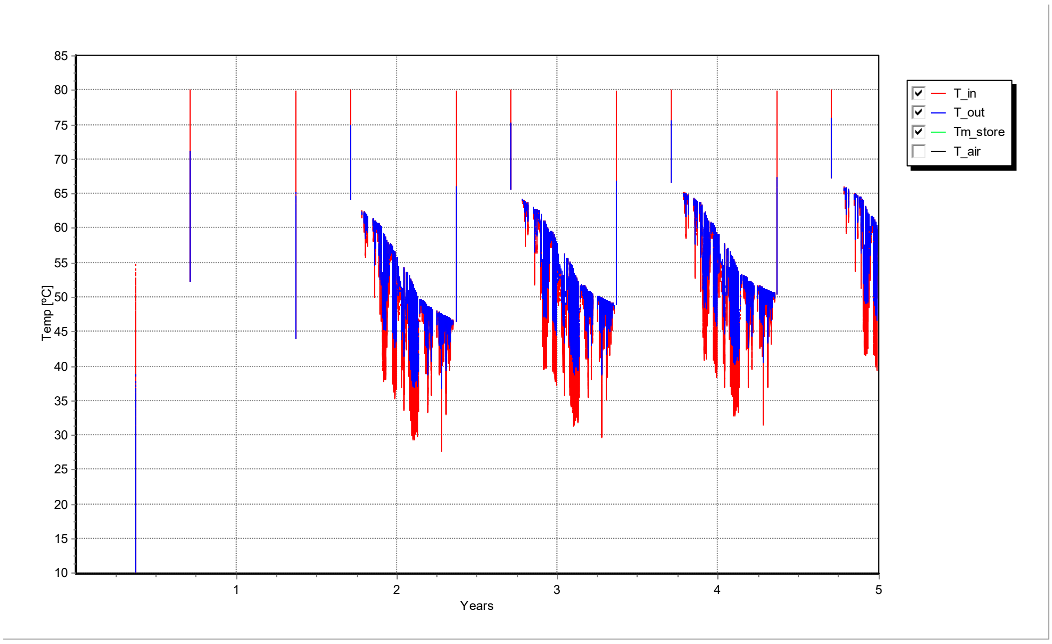


DST Simulation

In this model vertical boreholes are placed in a circular pattern. The BTES storage volume then becomes cylindrical, which is more favorable when it comes to heat losses and decreases the temperature drop. Furthermore, in the DST model the charging strategy would preferably be simulated by specifying an inlet temperature. The maximum charging temperature is set to +80°C, which is the normal summer supply temperature in district heating systems.

As indicated in the graph below, by using 120 boreholes with a spacing of 5 m the heavy peak demand can be handled with a supply temperature to the HHP system of about +40°C during the fifth year.

In this scenario the DST results have been used for the system design.



Scenario 5. Slippery road section using BTES

In this scenario a slippery section of a public road is analyzed. The configuration is 250 x 4 m, covering 1 000 m^2. The HHP pipes are placed at a depth of 50 mm beneath an asphalt pavement and the pipe spacing is 200 mm. The control system contains a weather forecast function for the prediction of snowfall. The reference heat source is an electric boiler with an investment cost of 25 000 Euro.

The system is designed to cover a snowfall intensity of 4 mm H_2O/hour. The total amount of snow represents 80 mm H_2O. The surface is kept free of frost at outdoor temperatures of +2 down to -10°C. Below -10°C the system is not running. The mean outdoor temperature is +5 degrees.

The basis for design of and the calculation results are summarized in the table below.

HHP-system	
Surface area	1 000 m^2
Annual heating time	1 400 hours
Max power snow melting	300 W/m^2
Max power preheating/ evaporation	200 W/m^2 (at windy conditions)
Annual heat consumption	250 MWh
Maximum supply/return temp.	35/20°C (at snow melting mode)
BTES-system with heat pump	
Direct heating power	110 kW
Heat pump power	150 kW
Number of boreholes	25 of 200 m depth
Brine working temperature	0-25°C
Energy turnover and efficiency	
Direct heating	200 MWh
Heating with the heat pump	50 MWh
COP direct heating (incl. heat capture)	20
COP heat pump heating	5
Seasonal performance factor (SPF)	12.5
Economics	
Additional investment cost	320 000 Euro
Annual operation cost BTES	5 500 Euro
Reference energy cost	50 000 Euro
Annual savings	44 500 Euro
Straight payback time	7.2 years

Comment

With grouted boreholes the additional investment cost increases to 440 000 Euro with a payback time of 9.9 years.

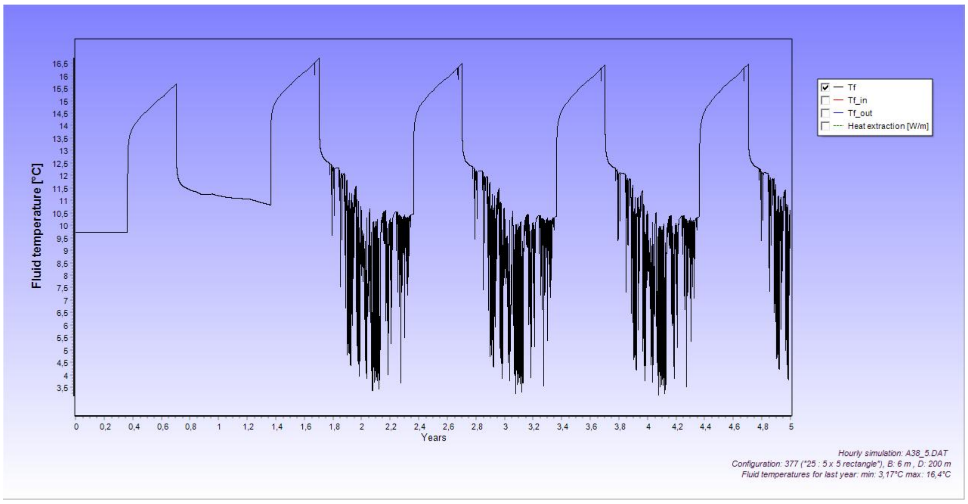
EED simulation

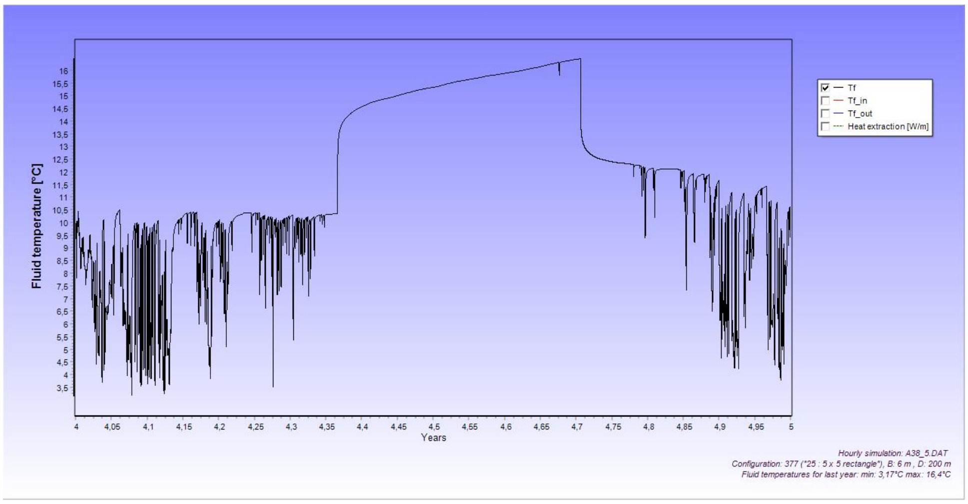
The most favorable alternative is to show number, spacing, depth of boreholes and total flow rate. T_{fm} = mean temperature; T_{in} = minimum temp. to BTES; T_{out} = minimum temp. from BTES. Delta T times the flowrate indicates the load capacity

No. BH	Configu-ration	Depth (m)	Length (m)	Space (m)	Max T_{fm} (°C)	Min T_{fm} (°C)	Flow rate (l/s)	Delta T (°C)	T_{out} (°C)	T_{in} (°C)
25	5.5	200	5 000	6	16.4	3.17	15.0	3.66	5.00	1.34

The fluid temperature during the first five years of operation is shown in the upper graph illustrating that the efficiency of BTES is gradually increasing. The first winter there is no extraction of heat.

In the lower graph the fifth year is magnified in order to better see periods of heat extraction and the use of the heat pump for peak shaving.





Scenario 6. Slippery road section using ATES

In this case, the BTES system in Scenario 5 is replaced by an ATES system using one warm and cold well placed close by the road section.

The aquifer consists of a shallow glaciofluvial deposit, and the wells are completed as a formation filter with a capacity of at least 10 l/s.

The ambient groundwater temperature is +5°C and since the road section is located in a remote area the aquifer is not used for other purposes such as drinking water.

The reference heat source is an electric boiler system with an investment of 25 000 Euro.

The basis for design of and the calculation results are summarized in the table below.

HHP-system	
Surface area	1 000 m^2
Annual heating time	1 400 hours
Maximum power snow melting	300 W/m^2
Maximum power preheating/evaporation	200 W/m^2 (at windy conditions)
Maximum supply/return temp.	35/20°C (at snow melting mode)
Annual heat consumption	250 MWh
ATES-system with heat pump	
Free heating capacity	200 kW
Heat pump capacity	100 kW
Number of wells	4 x 50 m
Maximum groundwater flow rate	12 l/s (at delta T 6°C)
Groundwater working temperature	5-25°C
Energy turnover and efficiency	
Direct heating	200 MWh
Heating with the heat pump	50 MWh
COP direct heating	25
COP heat pump heating	5
Seasonal performance factor (SPF)	13.9
Economics	
Additional investment cost	260 000 Euro
Annual operation cost ATES	7 500 Euro
Reference energy cost	50 000 Euro
Annual savings	42 500 Euro
Straight payback time	6.1 years

Scenario 7. Sports arena using BTES

In this scenario construction of a new full sized football field used for games and training is analyzed.

The field shall be equipped with artificial turf with the HHP pipes placed in the pad of the turf. The heating requirement is to keep the turf frost free down to -15°C. Heavy snowfall will be taken care of by mechanical snow removal.

The reference alternative is to connect district heating to an investment cost of 300 000 Euro.

The basis for design of and the calculation results are summarized in the table below.

HHP-system	
Surface area	8 000 m^2
Annual heating time	2 000 hours
Maximum power (at -15°C)	1 200 kW
Annual heat consumption	1 000 MWh
Maximum supply/return temp.	35/20°C (at -20°C)
BTES-system with heat pump	
Direct heating power	400 kW
Heat pump power	800 kW
Number of boreholes	120 of 200 m depth
Brine working temperature	0-25°C
Energy turnover and efficiency	
Direct heating	750 MWh
Heating by the heat pump	250 MWh
COP direct heating (incl. heat capture)	20
COP heat pump heating	5
Seasonal performance factor (SPF)	11.4
Economics	
Additional investment cost	1 360 000 Euro
Annual operation cost BTES	19 000 Euro
Reference energy cost	200 000 Euro
Savings	178 000 Euro
Straight payback time	7.6 years

Comment

With grouted boreholes the additional investment cost increases to 1 600 000 Euro with a payback time of 9.0 years.

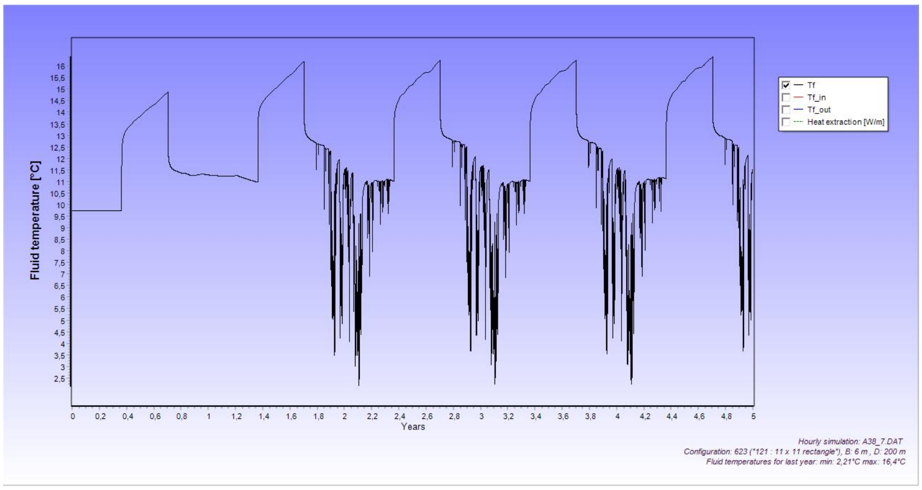
EED simulation

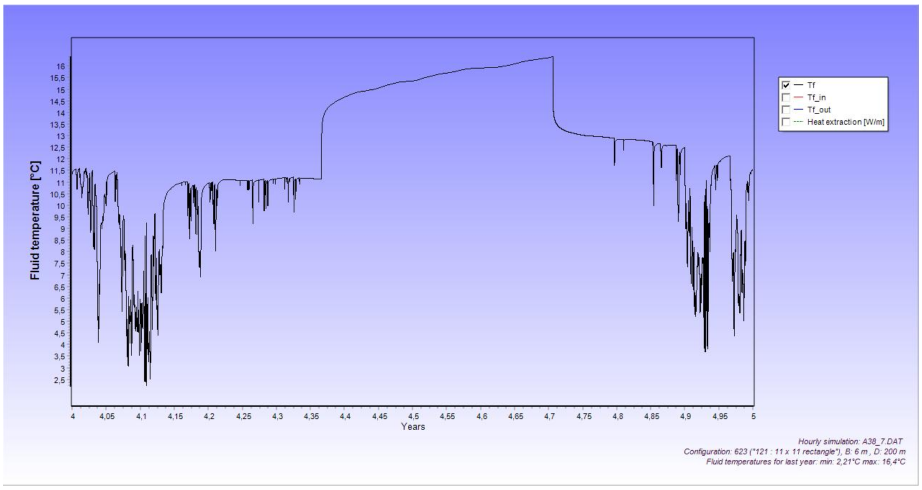
The most favorable alternative is to show number, spacing, depth of boreholes and total flow rate. T_{fm} = mean temperature; T_{in} = minimum temp. to BTES; T_{out} = minimum temp. from BTES. Delta T times the flowrate indicates the load capacity

No. BH	Configu-ration	Depth (m)	Length (m)	Space (m)	Max T_{fm} (°C)	Min T_{fm} (°C)	Flow rate (l/s)	Delta T (°C)	T_{out} (°C)	T_{in} (°C)
121	11x11	200	24 20	5	17.3	2.66	72.6	3.41	4.37	0.95

The fluid temperature during the first five years of operation is shown in the upper graph illustrating that the efficiency of BTES is gradually increasing. The first winter there is no extraction of heat.

In the lower graph the fifth year is magnified in order to better see periods of heat extraction and the use of the heat pump for peak shaving.





Sensitivity analysis of profitability

Unpredicted additional investment cost

Normally ground source systems are constructed at a fixed price according to a contract between a client and a contractor. However, there may be mistakes in the design phase that cause additional costs at the construction phase and that must be paid for by one or both contract parts. These costs could by experience be up to 30% of the contract sum, or in rare cases even more. In this analysis 30% has been used as a reasonable worst-case level.

The extra cost is commonly related to difficulties in drilling boreholes and wells due to unexpected geological settings and structures.

How an additional 30% investment cost affects profitability is shown in the table below (Cost in Euro and Payback time in years).

Scenario (Type)	Calculated Investment cost	Payback time	Worst case investment cost	Worst case Payback time
1 (HVAC)	15 000	1.8	20 000	2.5
2 (GWHP)	275 000	4.4	358 000	5.7
3 (BTES)	2 710 000	7.8	3 500 000	10
4 (HT-BTES)	2 210 000	5.0	2 470 000	6.5
5 (BTES)	320 000	7.2	416 000	9.3
6 (ATES)	260 000	6.1	338 000	8.0
7 (BTES)	1 360 000	7.6	1 770 00	9.9

Lowering of the SPF

By experience the seasonal performance factor (SPF) turns out to be lower than expected. A common cause is that the control system does not work as intended. These types of failures often occur in an early phase of operation and can usually be adjusted.

Scenario (Type)	Calculated SPF	Calculated payback time	Worst case SPF	Worst case payback time
1 (HVAC)	3.0	1.8	2.5	2.1
2 (GWHP)	12.5	4.4	6.0	4.9
3 (BTES)	9.1	7.7	4.5	8.9
4 (HT-BTES)	20.0	5.0	7.0	5.9
5 (BTES)	12.5	7.2	6.0	8.0
6 (ATES)	13.9	6.1	6.0	7.6
7 (BTES)	11.4	7.6	5.0	8.7

Another reason is that the SPF value is overestimated by the designer of the system or through errors in the design of the system. If this is the case, it will not be noticeable till after one or several years of operation. Such mistakes would be more difficult to rectify.

There is currently no way to specify what level should be applied to a worst-case SPF scenario, but in the table below a deterioration of approximately 10% has been used.

Climate changes

The calculations have been made for mean weather conditions at a specific site in the last 10 years.

A different climate with a smaller number of frost hours will mean lower energy consumption, which has a negative impact on the payback time. On the other hand, the effect will be the opposite if there is a colder winter than normal. However, the ongoing global warming trend may slowly lower heat demand and slightly increase the payback time.

Energy price changes

The long-term energy price is set equal for all energy sources at a price of 200 Euro/MWh. This an assumption that is based on that electricity within the next 10 years can compete with fossil fuel and district heating. This requires a continued expansion of fossil-free power in accordance with the goals that have been negotiated to combat global warming.

It is currently not possible to predict what real energy prices will prevail in the future and how they will vary during the plant's depreciation period. However, the most likely outcome is that the average price will be higher than the one spent. As a result, the profitability will increase over time since a major part of energy used in ground source systems is free of charge.

of the soil into which the heat collection pipes are embedded are recommended and a high degree of saturation of the soil in the stabilized temperature layer is desirable, while the volumetric flow rate should be controlled at or below 1.0 l/s, to avoid higher pressure in the pipes that leads to exceeding the strength of pipes materials.

Lastly, in most case studies, the use of a heat pump was found to be essential. The temperature variation achievable from a geothermal heat source is relatively limited, and when direct use of geothermal hot water is either unavailable or the fluid temperature is too low, a heat pump is needed to raise the temperature for effective operation. The coefficient of performance (COP), which indicates energy efficiency, varies significantly across cities due to differing weather conditions. However, in the majority of cases analysed, typical COP values were around 3. It can be calculated using various methods (Liu et al., 2019; Cao et al., 2024).

SURFACE COMPONENT DESIGN

Many design parameters, including geometric configurations, material properties, operational factors, control scenarios, and environmental circumstances, can affect the HHPS heating performance and its life-cycle cost.

The geometric configuration of a HHPS system mostly relies on pipe embedded depth, spacing, and inner radius. The pipe works in a serpentine configuration, perpendicular to the traffic direction on the road pavement. Some of these parameters, which are fundamental in modeling the heated surface of HHPS, are listed in Table 4, referencing specific case studies analysed in this report.

According to the ASHRAE Handbook (ASHRAE, 1997), placing the pipe at least 50 mm from the top and bottom of the slab in concrete pavements is recommended. In the study of Mehrabi et al. (2022), 75 mm depth is assumed as a typical clear cover for concrete bridge decks. In this study, the modelling was nonetheless extended to a shallower pipe placement depth of 50 mm, which mitigated thermal-induced damage, captured by plastic tensile strains. It should be emphasized that the impact of the traffic loads on the pipe is more significant in the case of a shallower placement. Concerning the pipe spacing, according to Spitler & Ramamoorthy (2000) it typically ranges from 150 mm to 300 mm. Similarly, in the modelling approach proposed by Liu et al. (2007), pipe spacing ranging from 100 to 300 mm was investigated. Such parameters were related to the duration of the pre-heat stage, namely the idling time. As pipe spacing is reduced, shorter idling times are required to provide the same snow-melting performance. Besides, according to Zhu et al. (2022), increased spacing was found to increase the shear strength of the pipe.

Concerning the thickness of the pipe, in the experimental activity carried out by Li et al. (2020), a 6 mm thick pipe was employed to circulate heat-carrying fluid within a bridge deck. A smaller thickness of 2.3 mm was instead set in the numerical simulation models presented by Mirzanamadi et al. (2020), in which the materials, thickness, and diameter of embedded pipes in the HHP system and the geothermal heat source are considered to be the same.

The recommendations for nominal pipe diameters are 18 – 25 mm (Spitler & Ramamoorthy, 2000). As pointed out by Mirzanamadi et al. (2020), as well as pipe spacing and inner radius, the pipe length affects the temperature difference between the inlet and outlet fluid and in turn the annual required energy for anti-icing the road surface. However, such energy consumption is also strictly related to fluid features, i.e. its density and specific heat capacity.

Since HHPS aim at providing surface temperatures higher than both freezing and dew temperature (Mirzanamadi et al., 2020), the heat transfer process is noticeably affected by thermic parameters of pavement materials such as thermal conductivity, density, and specific heat capacity. It is to be stressed that materials' parameters are frequently chosen based on the published literature (Mehrabi et al., 2022). Furthermore, to maintain surface conditions at a level no worse than wet, it is necessary to achieve surface temperatures above the freezing point of water before the accumulation of snow or ice, and to sustain these temperatures until the completion of snow or ice buildup. The heating strategy is thus governed by several local environmental factors including snowfall rate, air temperature, relative humidity, and wind speed (Mehrabi et al., 2022).

Polyethylene is the prevalent material utilized in the fabrication of heating pipes. Specifically, cross-linked polyethylene (PEX) tubing featuring an oxygen barrier layer is preferred for HHPS applications. This choice is attributed to its capability to prevent the infiltration of air or oxygen into the radiant heating system, as Li et al. (2020) highlighted.

The temperatures of the fluid and the surrounding environment assume significant importance in assessing the heat transfer performance of the adopted system and ascertaining the stable temperature conditions of the heated pavement. Li et al. (2020) carried out a numerical analysis in which they explored a range of water temperatures spanning from 21.1 to 37.8 °C, alongside ambient temperatures varying from 4.4 to 16.7 °C.

Table 4. Heated surface component modelling parameters listed for some of the selected case studies.

Parameter	Reference	Value min	Average/Typical value
Pipe embedment depth	ASHRAE (1997)	50 mm	50 mm
	Mehrabi et al. (2022)	50 mm	75 mm
Pipe spacing	Liu et al. (2007)	100 mm	300 mm
Pipe diameter	Spitler and Ramamoorthy (2000)	18 mm	18 – 25 mm
Pipe thickness	Mirzanamadi et al. (2020)	2.3 mm	2.3 mm

CONCLUSIONS

Recently, the use of **Shallow Geothermal Energy (SGE)** to support **Hydronic Heating Pavement Systems (HHPS)** for winter maintenance of paved surfaces—such as viaducts, roads, walkways, airport aprons, and helicopter pads—**demonstrated considerable potential** as an alternative to conventional heat sources.

This technical report aimed to analyze the availability, development, and capabilities of models required for the effective design and control of geothermal energy storage, de-icing, and snow-melting systems for rail, pavement, and bridge deck applications. To achieve this, an overview of the **modelling methods for HHPS** was provided, incorporating **over 20 illustrative examples** from existing literature, which were compiled into a dedicated database. This database served as a valuable resource, enabling the extraction of detailed information about the components of the analyzed systems and the **most prevalent and effective modelling approaches**. Furthermore, it facilitated the creation of **detailed fact sheets** for each case study, thereby establishing a **practical tool** to support the **efficient design and implementation** of these systems, considering their broad potential.

The analysis conducted on the select case studies permitted us to evaluate the most common approaches utilized in the different phases of the modelling processes of these systems and to draw the following remarks:

- The collected **climatic data** are crucial for calculating the heat required to de-ice or melt snow on the heated surface. However, the phenomena governing this energy demand are highly complex for several reasons: the heat and mass transfer mechanisms involved in the snow melting process are intricate and require the treatment of phase change phenomena; during the snow melting process, surface conditions can vary not only temporally due to changing weather conditions but also spatially at a given moment because of the discrete arrangement of heat sources; weather conditions during storm events are highly variable. Any model must account for changes in precipitation, temperature, humidity, wind speed, and solar radiation. This complexity has led to the development of various models for calculating heat flux, some more advanced than others. After analysing the case studies selected for this work, it was found that the most commonly used approach is the 1D steady-state analysis model. This model calculates heat flux through energy balance equations on the surface of a bridge deck or pavement, using a simple formula that incorporates different contributions to the supplied heat flux: q_s, the sensible heat flux, q_m, which accounts for the heat required to melt snow, q_h, which represents convective losses to the ambient air at temperature, and radiative losses to the surroundings that maintain a mean radiant temperature, while q_e accounts for the heat flux required for evaporation.
- Geothermal-based HHPS offer significant advantages by utilizing the ground as a renewable heat source. Ground-source heat exchangers capture and store excess solar heat from the summer, which is then used during winter to prevent freezing. These systems, such as Switzerland's SERSO, demonstrate how geothermal energy can efficiently maintain surface temperatures above 0°C, reducing the formation of ice and snow accumulation. By leveraging underground thermal energy, geothermal heat

exchangers ensure consistent and sustainable heating, while minimizing energy consumption and environmental impact.

- The selection of operational parameters for geothermal systems is complex, as it depends on multiple interrelated factors that must be considered in conjunction to effectively model snow-melting and de-icing geothermal systems. A key element is the geothermal heat exchanger, whose performance is influenced by the thermal properties of the ground, such as thermal mass and its consequent relatively slow response to temperature changes. The geothermal heat source plays a central role by extracting heat from the ground and facilitating heat transfer through a heat pump to the system. Accurate parameter identification—such as the ground temperature distribution, soil thermal conductivity, and heat exchanger/sink configuration—is essential for assessing the energy extraction rate, which determines the system's efficiency in snow melting and de-icing operations.

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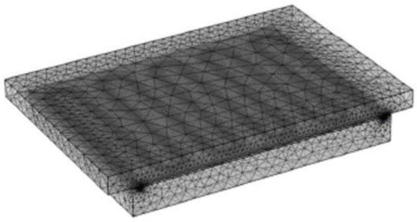
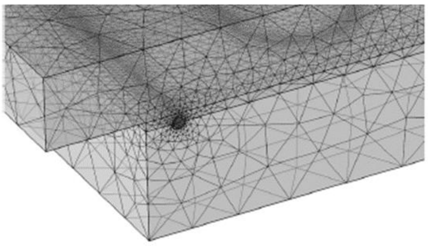
APPENDICES SUBTASK2 – Melting Systems for Infrastructure, Deliverable 2.1: The state of the art in system modelling and design load assessment

Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature

Fact Sheet N-01

Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**





Ref. Li, T., Yu, X., Lei, G., Habibzadeh-Bigdarvish, O., Hurley, M. (2020). Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature. Applied Thermal Engineering, 174, 115255.
https://doi.org/10.1016/j.applthermaleng.2020.115255

DESCRIPTION OF THE STUDY

Model setup: A three-dimensional finite element bridge deck model was developed in COMSOL to replicate the laboratory deck in the environmental chamber:

- A transient model was employed to analyze the heating processes with the time change and steady-state model to obtain the final temperature at equilibrium state.
- Heat transfer processes, including conduction, convection, and radiation heat transfer, were modeled in these numerical analyses.
- The heated slab and the ambient air were set to have the same temperature.
- The water flow model was initiated with the same measured temperature input at the inlet.

Initial and boundary conditions: The adjusted inlet fluid temperatures are the average of the measured temperatures in the environmental chamber and were utilized as the boundary condition of the inlet in the COMSOL model.

- In COMSOL, the module interfaces of the pipe-concrete slab, pipe-geofoam slab, and pipe-inlet fluid were set as perfect surface contacts due to the excellent bonding of these interfaces.
- A thermal contact was created in COMSOL to simulate the gap between the concrete bottom surface and the cement paste layer.

Modeling approach for the heating surface installation: The model was solved with a transient method, with the simulation time the same as that of the lab test temperature of the injected fluid and of the porous asphalt flow rate on the road surface temperature were analyzed. The simulated time-dependent heating curves were verified with the laboratory-measured data at the thermocouple locations.

Modeling approach for the geothermal source: --

HIGHLIGHTS

3D model for a hydronic bridge deck heated externally | Calibration and validation with 16 test cases | Thermal contact model developed for the attached loop | The heat flux near the deck surface can be estimated using 1D heat conduction

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from underground loops.

HEATING SYSTEM

External hydronic heating system composed by attached insulated, cross-linked polyethylene (PEX) pipe loop. The loop consists of a PEX pipe, an aluminum plate, polyurethane foam insulation, and a high-density polyethylene jacket.

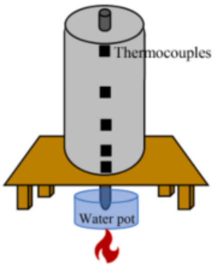
GEOTHERMAL HEAT SOURCE

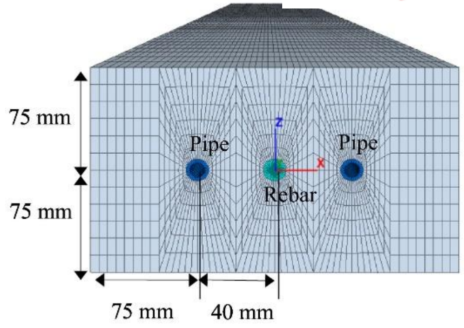
A heated water bath was used to simulate the ground heat exchanger (GHE) for heating the system.

Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar

Fact Sheet N-02

Location: **Buffalo, NY**
Country: **USA**
Year: **2022**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system (among others)**
Type of geothermal heat sources: **Not specified**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**





Ref. Mehrabi, R., Atefi-Monfared, K., Kumar, D., Deshpande, A. A., & Ranade, R. (2022). Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar. *Cold Regions Science and Technology*, *194*, 103466.
https://doi.org/10.1016/j.coldregions.2021.103466

DESCRIPTION OF THE STUDY

Model setup: This study investigates the thermo-mechanical behavior of a large-scale heated bridge deck under cyclic thermal loading in Hydronic Heated-Pavement (HHP) and Electrically Heated-Pavement (EHP) systems, factoring in realistic mechanical and thermal boundary conditions and the thermal degradation of concrete properties. It also explored the feasibility of a new heating system, the "Heated Rebar Deck Deicing" (HRDD) system, which uses embedded rebars in the top conventional reinforcement layer of a concrete bridge deck as heat conductors. This proposed system may be less damaging to the structural and material integrity of the bridge deck compared to existing HHP and EHP systems. This work presents novel finite difference-based numerical models for the above analysis, which is calibrated using small-scale laboratory experiments. The numerical model aimed to evaluate the thermal efficiency and damage resilience of three heated bridge deck systems (EHP, HHP, and HRDD) across different heating scenarios.

Initial and boundary conditions: The model was first stabilized under gravitational loads. Then, a heat source was applied within the embedded conductor, generating thermally induced strains and stresses. Heat transfer from the concrete's exposed surfaces to the environment was modeled with convective boundary conditions.

Modeling approach for the heating surface installation: The model assumes isotropic heat conduction as the primary heat transfer mechanism. Thermo-mechanical stresses and strains are driven by temperature and the three heat flux components, connected through the energy-balance equation and transport laws based on Fourier's law of heat conduction.

Modeling approach for the geothermal source: In the experimental prototype, boiling water served as the heat source, with thermocouples linked to a data acquisition system via amplifiers to record temperature data. In the numerical model, temperatures were controlled and set as boundary conditions on the slab surface.

HIGHLIGHTS

Hydronic Heated-Pavement Systems | Electrically Heated-Pavement Systems | De-icing and Snow-melting of a bridge deck | Finite Difference-based numerical model | Heated Rebar Deck Deicing system

MAIN PURPOSE

To obtain a fundamental understanding of the thermo-mechanical behavior of a large-scale heated bridge deck subjected to internal cyclic thermal loading in HHP and EHP systems.

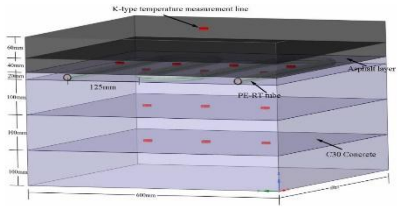
SURFACE HEATING SYSTEM

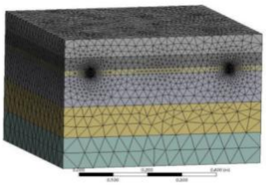
Hydronic Heated-Pavement (HHP) and Electrically Heated-Pavement (EHP) systems are explored. Additionally, the feasibility of a novel "Heated Rebar Deck Deicing" (HRDD) system is investigated, using embedded rebars as heat conductors in the deck's top reinforcement layer.

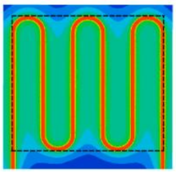
Experimental study on road deicing using circulated heating produced from geothermal fluid

Fact Sheet N-03

Location: **Wuhan**
Country: **China**
Year: **2024**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchangers**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**







Ref. Chen, Z., Xu, H., Feng, D., Wang, J., Xiao, H., & Tian, Y. (2024). Experimental study on road deicing using circulated heating produced from geothermal fluid. *Renewable Energy*, *235*, 121083.
https://doi.org/10.1016/j.renene.2024.121083

DESCRIPTION OF THE STUDY

Model setup: A 1:1 numerical model based on the indoor experimental setup was developed. The model includes heat exchange pipes, an asphalt layer, a concrete layer, and aluminum foil tape. An expansion grid division method is used for the circulating fluid to improve computational accuracy, while the remaining structural layers are meshed using a tetrahedral method. Throughout the simulation, all materials are treated as isotropic. The material properties incorporated in the model, including density, specific heat capacity, and thermal conductivity, are consistent with those of the experimental model materials.

Initial and boundary conditions: The same experimental conditions as those in Case 1 of the reference paper were applied: the road surface temperatures were set to -5 °C and -10 °C, and the water temperature was adjusted to 40 °C and 50 °C. The circulation valve was opened, and the flow rate was maintained at a constant 0.45 m/s.

Modeling approach for the heating surface installation: When the road system is heated, the energy stored in the road is calculated in *Qh* (kJ) using the following formulas:

$$Q_h = mC_P(T_s - T_r)$$

$$m = \rho V$$

$$V = v\pi R^2 \cdot \Delta t$$

Modeling approach for the geothermal source: The coefficient of performance (COP_{sys}) of the road system combined with the heat pump system is defined as follows:

$$COP_{sys} = Q_h / Q_g$$

HIGHLIGHTS

Ground source heat pump | Energy consumption ratio | De-icing performance | Temperature fluctuations | Critical de-icing temperature

MAIN PURPOSE

To investigate the performance coefficients of both the heat pump and road systems during road preheating experiments, as well as their de-icing effectiveness.

SURFACE HEATING SYSTEM

A hydronic heating system heats up the road surface.

GEOTHERMAL HEAT SOURCE

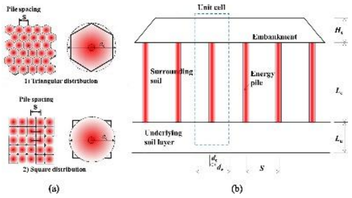
Underground heat exchange pipes and heat pump units are selected as the geothermal heat source for the system.

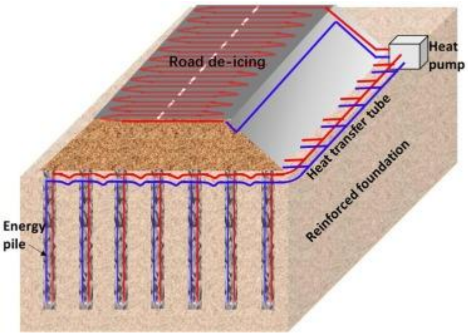
A simplified model for energy pile-supported embankment

Fact Sheet N-04

Location: **Nanjing, Jiangsu**
Country: **China**
Year: **2024**
Type of infrastructure: **Embankment**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Theoretical model validated with a numerical model**

Ref. Zhou, Y., Wang, J., Li, C., & Kong, G. (2024). A simplified model for energy pile-supported embankment. *Computers and Geotechnics*, *169*, 106184. https://doi.org/10.1016/j.compgeo.2024.106184





DESCRIPTION OF THE STUDY

Model setup: A simplified model is proposed to predict the behavior of energy pile-supported embankments. The constraint at the pile head is achieved by mobilizing load transfer mechanisms, including the soil arching effect within the embankment. The model incorporates the thermo-mechanical stress-strain responses of both the piles and the foundation soil, analyzing stress continuity and settlement compatibility across the embankment, reinforced foundation, and underlying soil. Thermal effects on load transfer behavior are explored, and the model is validated against numerical simulations. Additionally, parametric studies examine the influence of factors such as the foundation soil's thermal expansion coefficient and temperature variations on load transfer and settlement.

Initial and boundary conditions: Using the equivalent area assumption, a unit cell comprising a pile and surrounding soil can be extracted from the energy pile-supported embankment. The embankment fill, pile, and soil are modeled using elastoplastic behavior with the Mohr-Coulomb failure criterion. Temperature boundary conditions (T = 40°C) are applied to the sides and top of the pile, with the radial boundary closed. The initial foundation temperature is set to +20°C.

Modeling approach for the heating surface installation: Heat transfer is assumed to occur within the piles and surrounding soil, while temperature changes in the embankment and underlying soil are neglected. The unit cell in the embankment is divided into an inner cylinder (above the pile) and an outer cylinder (above the foundation soil).

Modeling approach for the geothermal source: A unit cell, consisting of a pile and surrounding soil, can be extracted from the energy pile-supported embankment to analyze heat transfer interactions between piles. This unit-cell concept is also applied to study the temperature distribution in the pile-reinforced foundation using steady-state heat transfer analysis. When a thermal load of +20°C is applied to the pile, the temperature distribution within the foundation becomes uniform. The pile-soil interface is modeled using interface elements.

HIGHLIGHTS

Geothermal Energy | De-icing System | Energy pile-supported embankment | Thermal Effect |Settlement

MAIN PURPOSE

To predict the behavior of energy pile-supported embankments by considering the thermo-mechanical stress-strain response of the piles and foundation soil, while analyzing stress continuity and settlement compatibility among the embankments, reinforced foundation, and underlying soil.

SURFACE HEATING SYSTEM

A Hydronic Heating System was selected to heat the surface of the embankment.

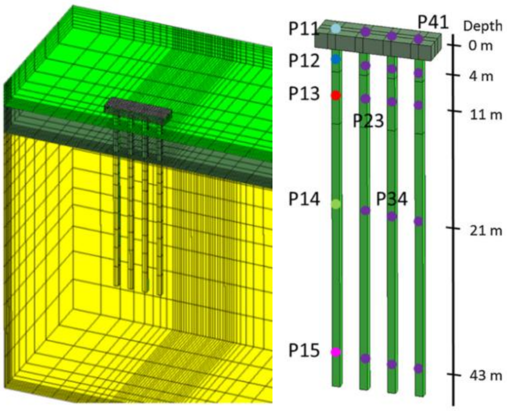
GEOTHERMAL HEAT SOURCE

An energy pile system serves as a geothermal energy source for the hydronic system.

Heat-exchanger piles for the de-icing of bridges

Fact Sheet N-05

Location: **Rhône Valley**
Country: **Switzerland**
Year: **2014**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**



Ref. Dupray, F., Li, C., & Laloui, L. (2014). Heat-exchanger piles for the de-icing of bridges. *Acta Geotechnica*, *9*, 413-423.
https://doi.org/10.1016/j.compgeo.2013.08.004

DESCRIPTION OF THE STUDY

Model setup: A three-dimensional finite element model was developed in *Lagamine* software to simulate an alternative design of an eight-pile bridge foundation, which includes energy piles for the de-icing of the bridge deck. These energy piles are designed for heat exchange with the ground and to capture solar energy.

Initial and boundary conditions: The adjusted inlet fluid temperatures are the average of the measured temperatures in the environmental chamber and were utilized as the inlet's boundary condition in the COMSOL model.

- Thermal B. C.: The downstream boundary maintains a constant temperature, similar to the upstream and rear sides of the model. The top surface and the plane of symmetry are adiabatic.
- Hydraulic B. C.: The lateral, top, and bottom surfaces are impermeable, while a pressure gradient of 20 kPa is applied between the upstream and downstream sides, corresponding to the natural slope of the area.
- Mechanical B. C.: The long, short, and bottom sides are blocked in the y-, x-, and z-directions, respectively, while the top surface is free.

Modeling approach for the heating surface installation: After energy needs are evaluated considering two different scenarios (geothermal scenario and solar scenario), a fully coupled simulation of the problem is conducted with a finite-element code. The geothermal scenario in the model includes an imposed natural groundwater flow, while the solar scenario operates without groundwater flow.

Modeling approach for the geothermal source: The heat exchange is represented by a heat source/sink in the volume of the pile.

Considering the above-mentioned scenarios, different levels of constant power are applied to each pile to ensure that the minimum temperature in the pile remains at 0°C.

HIGHLIGHTS

Energy Piles | De-icing of a bridge deck | Seasonal storage and natural thermal reload | 3-D Finite Element thermo-hydro-mechanical model| Various underground water flow

MAIN PURPOSE

Determining the geotechnical and energy design parameters for heat exchanger piles for the de-icing of bridges through thermo-hydro-mechanical simulations.

SURFACE HEATING SYSTEM

A hydronic heating system heats up the bridge deck and collects solar energy in summer.

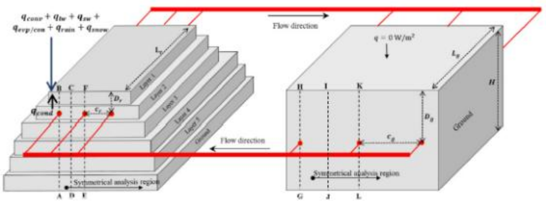
GEOTHERMAL HEAT SOURCE

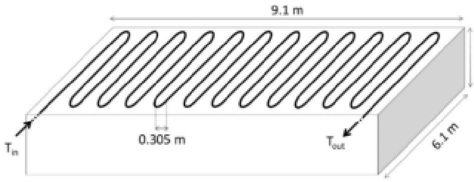
Eight Energy Piles supporting all but one of the foundations (six in total) and representing the heat exchanger components of the system.

Coupling a Hydronic Heating Pavement to a Horizontal Ground Heat Exchanger for harvesting solar energy and heating road surfaces

Fact Sheet N-07

Location: **Gothenburg**
Country: **Sweden**
Year: **2019**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic Heating Pavement**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **No**





Ref. Mirzanamadi, R., Hagentoft, C. E., Johansson, P. (2020). Coupling a Hydronic Heating Pavement to a Horizontal Ground Heat Exchanger for harvesting solar energy and heating road surfaces. Renewable Energy, 147, 447-463. https://doi.org/10.1016/j.renene.2019.08.107

DESCRIPTION OF THE STUDY

Model setup: A hybrid 3D numerical simulation model is used to analyze the harvesting and anti-icing operations. Furthermore, a 2D numerical simulation model is used to calculate the heat loss from the HGHE to the surrounding ground. The climate data are obtained from Östersund, a city in the middle of Sweden with long and cold winter period.

Initial and boundary conditions:

- The surface of the HGHE is fully insulated and the boundary condition at the surface of the HGHE is adiabatic.
- The total depth of the HHP and the HGHE is truncated to five times the periodic penetration depth of the ground.
- The boundary condition at the bottom of the ground is set to be adiabatic.
- The inlet temperature of the HHP system is equal to the outlet temperature of the HGHE.
- The outlet temperature of the HHP system is equal to the inlet temperature of the HGHE.

Modeling approach for the heating surface installation: The heat fluxes are conductive heat from the ground and pipes q_{cond}, convective heat from ambient air, q_{conv}, longwave radiation, q_{lw}, shortwave radiation, q_{sw}, latent heat of evaporation and condensation, $q_{evp/con}$, sensible heat from rain, q_{rain} and sensible heat from snow, q_{snow}. In this study, four 2D vertical cross sections are used to numerically simulate the HHP system.

Modeling approach for the geothermal source: Another four 2D vertical cross sections are used to numerically simulate the HGHE.

Parametric study of the HGHE: (i) pipe distance, (ii) pipe length, (iii) fluid flow rate and (iv) ground thermal properties.

HIGHLIGHTS

Ice-free road | Heat loss | Anti-icing | Required energy | Hydronic pavement

MAIN PURPOSE

Winter maintenance of road surfaces using anti-icing

HEATING SYSTEM

Hydronic Heating Pavement (HHP) System

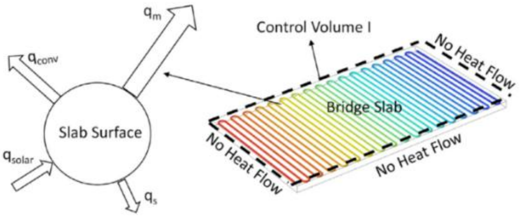
GEOTHERMAL HEAT SOURCE

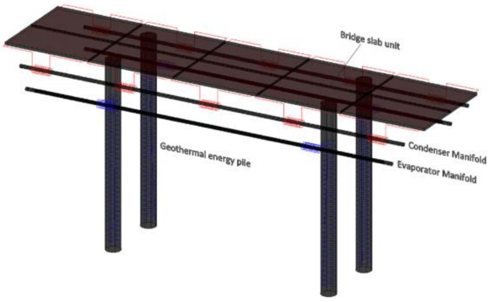
Horizontal Ground Heat Exchanger (HGHE)) for harvesting solar energy during summer and anti-icing road surfaces during winter

Feasibility study of snow melting system for bridge decks using geothermal energy piles integrated with heat pump in Canada

Fact Sheet N-08

Location: **Winnipeg**
Country: **Canada**
Year: **2019**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **No**





Ref. Liu, H., Maghoul, P., Bahari, A., & Kavgic, M. (2019). Feasibility study of snow melting system for bridge decks using geothermal energy piles integrated with heat pump in Canada. *Renewable Energy*, *136*, 1266-1280.
https://doi.org/10.1016/j.renene.2018.09.109

DESCRIPTION OF THE STUDY

Model setup: This study designs a snow melting system for a bridge deck powered by geothermal energy piles, involving: i) assessment of boundary heat flux on the bridge slab surface based on local weather conditions; ii) calculation of heating loads (qH) for a hydronic snow melting system to keep the bridge slab surface above freezing; iii) estimation of the heat extraction rate (qL) for a geothermal energy pile; and iv) determination of the COP and potential savings for a large-scale bridge. The key assumptions in this paper are as follows: the snow melting system is designed for immediate melting upon snowfall. The design is intended to handle at least 90% of snowfall events. A fully developed velocity profile is considered across the entire pipe section, with a constant average bulk mean velocity along the pipe. Both the evaporator and condenser are deemed to function perfectly for the heat pumps.

Initial and boundary conditions: An energy balance at the bridge slab surface and adiabatic conditions at the bottom and side surfaces due to the insulation. Ground temperature is assumed to remain constant at deep depths, an essential aspect for shallow geothermal energy applications. Lastly, the inlet temperature for the geothermal heat exchanger is set at 4°C.

Modeling approach for the heating surface installation: The hydronic heating system model analyzes heat transfer in the pipes and concrete bridge slabs. One equation defines the fluid's temperature profile along the pipe, while another considers the concrete slab's density and thermal conductivity to capture heat transfer through it.

Modeling approach for the geothermal source: Following the assessment of heating loads for a single bridge slab unit, the dimensions of a pile and the underground temperature were established. The loop configuration, optimal flow rate, and thermal recharging methods were selected to determine the energy extraction rate of a single pile.

HIGHLIGHTS

Energy Piles | Snow-melting and De-icing of a bridge deck | Energy balance equations | 3-D Finite Element thermo-hydro-mechanical model

MAIN PURPOSE

To study the feasibility of geothermal snow melting systems in six major cities (Calgary, Edmonton, Montreal, Ottawa, Toronto and Winnipeg) in Canada.

SURFACE HEATING SYSTEM

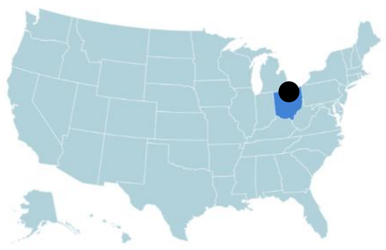
A hydronic heating system heats up the bridge deck. The diameter of pipe are assumed to be 20 mm and pipe spacing is taken as 200 mm. The burial depth of hydronic pipe is taken as 5 cm (measured from the bridge slab surface).

GEOTHERMAL HEAT SOURCE

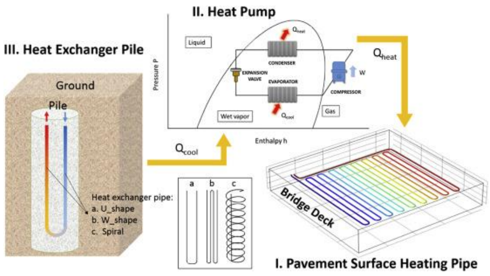
A single Energy Pile was studied as the ground heat exchanger component of the system.

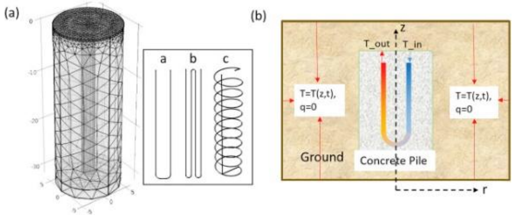
Feasibility of geothermal heat exchanger pile-based bridge deck snow melting system: A simulation-based analysis

Fact Sheet N-09



Location: **Cleveland**
Country: **United States**
Year: **2017**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **No**





Ref. Han, C., & Yu, X. B. (2017). Feasibility of geothermal heat exchanger pile-based bridge deck snow melting system: A simulation-based analysis. *Renewable energy*, *101*, 214-224.
https://doi.org/10.1016/j.renene.2016.08.062

DESCRIPTION OF THE STUDY

Model setup: Computational model-assisted analyses are conducted to assess the feasibility of a geothermal heat exchanger pile-based snow melting system for bridge decks. Ten cities in various climate regions across the United States are selected for these analyses. A 3D finite element model is developed to analyze the performance of a single geothermal heat exchanger pile.

Initial and boundary conditions: The pipe flow is simplified to a one-dimensional flow, neglecting the heat exchange process in the radial direction within the pipe. The Churchill friction model is applied to account for thermal dissipation in the longitudinal direction of the pipe. The inlet temperature is assumed to be -4 °C. Simplifications in the study assume that the thermal properties of the ground remain constant. A Dirichlet boundary condition is applied at the borders of the computational domain, with the temperature set to the undisturbed ground temperature.

Modeling approach for the heating surface installation: The determination of heating requirements for snow and ice removal, typically expressed as surface heat flux, is essential for designing the system's capacity. According to the *ASHRAE Handbook 2007*, the heating needs for snow melting are influenced by five atmospheric parameters: air dry-bulb temperature, snowfall rate, relative humidity, wind velocity, and apparent sky temperature. Scenarios in 10 selected cities are analyzed, with corresponding heat flux demands calculated based on ASHRAE criteria.

Modeling approach for the geothermal source: The numerical simulation couples two key physical processes: non-isothermal pipe flow, which describes heat transfer within the circulating fluid, and general heat transfer, which describes the heat exchange between the heat exchanger pile and the surrounding ground.

HIGHLIGHTS

Energy Piles | Snow and Ice removal on a bridge deck | Heat pump | 3-D Finite Element thermo-hydro-mechanical model

MAIN PURPOSE

To investigate the feasibility of a geothermal heat exchanger pile-based snow melting system for bridge decks, ten cities across different climatic regions in the United States are selected for analysis.

SURFACE HEATING SYSTEM

The pavement surface heating system has a hydraulic heat exchanger pipe installed beneath the pavement surface.

GEOTHERMAL HEAT SOURCE

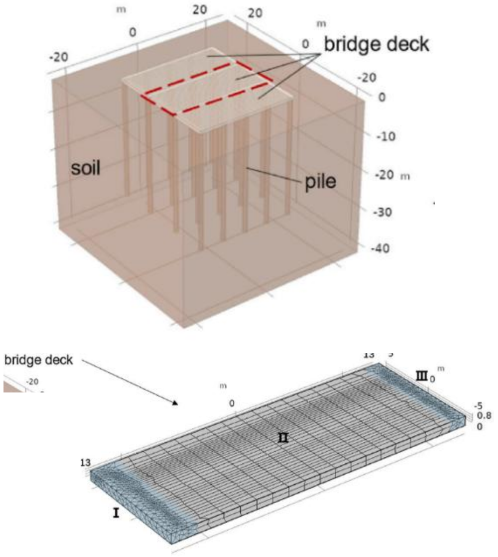
A single Energy Pile was studied as the ground heat exchanger component of the system.

Feasibility assessment of implementing energy pile-based snowmelt system on a practical bridge deck in diverse climate conditions across China

Fact Sheet N-10

Location: **Shangai**
Country: **China**
Year: **2024**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Water circulation heating system**
Type of geothermal heat sources: **Geothermal heat exchanger pile**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **No**

Ref. Cao, X., Kong, G., & Han, C. (2024). Feasibility assessment of implementing energy pile-based snowmelt system on a practical bridge deck in diverse climate conditions across China. Energy, 290, 130317.



DESCRIPTION OF THE STUDY

Model setup: To assess the energy extraction efficiency of energy piles across different geographical and climatic contexts, a numerical simulation model was devised. Leveraging the specifications of a prototype bridge situated in Jiangsu, China, a numerical model of the bridge deck's water circulation heating system was constructed. This model enables the calculation of the net energy extraction from the system. The viability of this approach hinges upon evaluating whether the net energy extraction suffices to meet the heat demand for snowmelt.

Initial and boundary conditions: The soil boundary is set to be adiabatic and the ground temperature is assumed to be a function of depth and time. For the solid heat transfer process of the bridge, the surrounding area of the bridge and the bottom are set as adiabatic boundaries. The bridge deck is designated as a convective boundary, the external ambient temperature is the local dry bulb temperature. The temperature of the bridge is calculated by solving the energy conservation equation. The initial temperature of the bridge deck is set to ambient temperature.

Modeling approach for the heating surface installation: The determination of the heat flux demand at the snow-melting surface (the upper surface of the bridge deck) during a snowfall is calculated according to ASHRAE steady-state energy balance equation of the bridge deck $q_0 = q_s + q_m + A_r (q_h + q_e)$. The heat transfer of the circulating fluid is simulated by the non-isothermal pipe flow module of COMSOL Multiphysics Software; the heat transfer process of the bridge is simulated by the solid heat transfer module; the two physical processes are coupled to calculate the heat flux provided by the bridge deck.

Modeling approach for the geothermal source: The non-isothermal pipe flow module of COMSOL Multiphysics Software is used to simulate the heat transfer process of the heat exchange tube; the pipe flow is simplified to one dimensional flow, ignoring the radial heat transfer process inside the pipe. The solid heat transfer module is used to simulate the heat transfer process of heat exchange tubes, piles, and soil.

HIGHLIGHTS

Geothermal energy | Energy pile | Snow-melting system | Bridge deck | Finite element analysis

MAIN PURPOSE

To evaluate the feasibility of the energy pile-based snow melt system in diverse climatic zones across China

HEATING SYSTEM

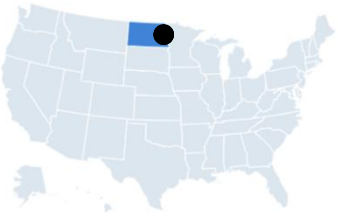
The heat supplied by the heat pump serves as the heat source to raise the inlet temperature of the circulating fluid of the bridge deck system.

GEOTHERMAL HEAT SOURCE

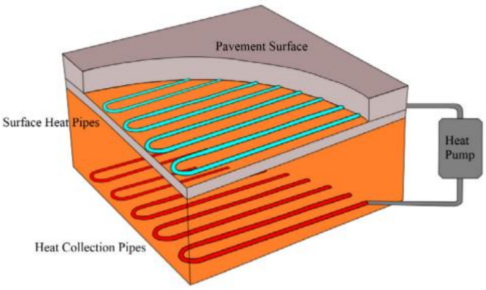
The energy pile serves as the central component of the system, extracting thermal energy from the surrounding ground. The heat pump transfers the heat from the energy pile to the bridge deck water circulation heating system.

Numerical modeling of heat production using geothermal energy for a snow-melting system

Fact Sheet N-11



Location: **Grand Forks, North Dakota**
Country: **USA**
Year: **2017**
Type of infrastructure: **Pavement surface**
Type of surface heating system: **Surface heat pipes**
Type of geothermal heat sources: **Heat collection pipes**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **No**



Ref. Ho, I.H., Dickson, M. (2017). Numerical modeling of heat production using geothermal energy for a snow-melting system. Geomechanics for Energy and the Environment, 10, 42-51. http://dx.doi.org/10.1016/j.gete.2017.06.002

DESCRIPTION OF THE STUDY

Model setup: An existing COMSOL model was modified to simulate the heat produced from pipes in the snow-melting system. Thermal conductivity and volumetric flow rate, which significantly govern the characteristics of the heat collection pipes, were examined. The numerical modeling of the heat collection system includes the soil properties, pipe properties, fluid properties and heat transfer mechanisms.

Initial and boundary conditions: A heat collection pipe is embedded in a stable temperature zone six meters below the ground surface. The heat flux that comes from the soil is transferred to the pipe by conduction, and the heat that is transferred from the pipe to the fluid is by convection. The interface between the soil and the pipe is different from the interface between the pipe and the fluid. The four vertical planes (2 x–z and 2 y–z planes) are the thermal insulation layers, while the x–y plane was defined as the plane that allows heat flux. The general inward heat flux (heat flux from the soils to the pipes), q_0, depends on the thermal conductivity of the soil, k, and the seasonal thermal gradient. The initial temperature of the soil is defined as 7°C, which is the subsurface temperature recorded in eastern North Dakota.

Modeling approach for the heating surface installation: The heat supply required for the daily demand is assumed to be 48 kWh for a duration of 12 h per day. The thermal gradient from the ground surface to the desired depth for the heat collection pipe embedment is 1.17 for January and varies according to seasonal changes.

Modeling approach for the geothermal source: The initial fluid temperature was considered to be 7°C (consistent with the ground temperature). The ratio of the specific heats is 1.0, the heat capacity of the liquid is 1 J/kg K, and the density is 1 kg/m^3. Heat transfer between the soil and the pipe as well as between the pipe and the fluid, are both defaulted in COMSOL. The power of the heat pump is 4 kW, which is equivalent to a total heat supply of about 13,649 BTU produced per hour.

HIGHLIGHTS

Geothermal energy | Renewable and sustainable | Snow-melting system | Finite element analysis | Heat transfer mechanism

MAIN PURPOSE

Computations for the heat production that is required in a snow-melting system for eastern North Dakota based on the average climatic data and precipitation.

HEATING SYSTEM

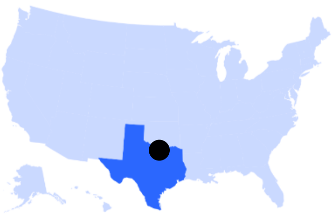
The warm fluid delivers heat to the pavement surface to melt the snow by means of surface heat pipes and then returns to below the ground.

GEOTHERMAL HEAT SOURCE

The heat collection pipes are embedded horizontally in the constant temperature layer. The fluid in the pipes circulates to the pavement surface through a heat pump.

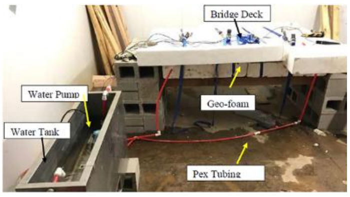
Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature

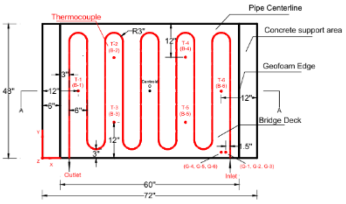
Fact Sheet P-01

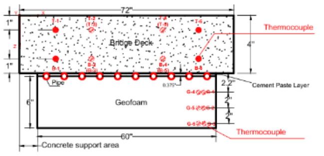


Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Ref. Li, T., Yu, X., Lei, G., Habibzadeh-Bigdarvish, O., Hurley, M. (2020). Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature. Applied Thermal Engineering, 174, 115255.
https://doi.org/10.1016/j.applthermaleng.2020.115255







DESCRIPTION OF THE STUDY

Model setup: The prototype bridge deck was constructed using a standard 1.8 m x 1.2 m x 0.1 m precast concrete panel (PCP) and then installed in an environmental chamber in which a minimum temperature of 4.4 °C. could be attained. Two 1.1 m high concrete pedestals, each with 152 mm of landing space, supported the concrete slab. A geofoam block encapsulating the hydronic heating system was directly attached to the bottom surface of the concrete slab by straps and wood. A flat interface zone, created by covering the pipe system with a fine cement paste, made the heat transfer at the base of concrete slab more uniform and efficient.

Design approach for the heating surface installation: Cross-linked polyethylene (PEX) tubing with an inner diameter of 13 mm and an outer diameter of 19 mm was employed to circulate heat carrying fluid within the bridge deck. An oxygen barrier layer was selected for hydronic heating to prevent air/oxygen from infiltrating the radiant heating system.

Design approach for the geothermal source: The loop inlet was connected to a water pump that was submerged in a water tank and capable of providing a constant flow rate of 0.13 kg/s; the loop outlet was connected to a water tank that could provide warm water at the desired temperature.

Monitored parameters: Thermocouples were installed 25 mm above and below the concrete bottom and top surface, respectively. Moreover, two thermocouple sets were installed in the geofoam block. Sixteen heating response test programs were conducted under various water and ambient temperatures to evaluate the heat transfer performance of the investigated system and to determine the steady-state temperature of the heated slab.

HIGHLIGHTS

Prototype hydronic bridge deck | External heating | Testing campaign under various water and ambient temperatures | Calibration and validation of a 3D model with collected data

MAIN PURPOSE

To study the heating performance of an external heating system directly attached to the bottom surface of a hypothetical bridge deck.

HEATING SYSTEM

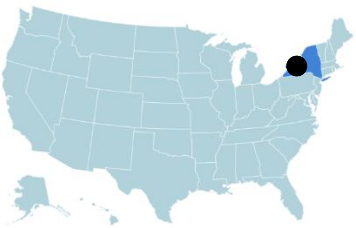
External hydronic heating system composed by attached insulated, cross-linked polyethylene (PEX) pipe loop. The loop consists of a PEX pipe, an aluminium plate, geofoam insulation, and a high-density polyethylene jacket.

GEOTHERMAL HEAT SOURCE

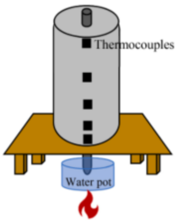
A heated water bath was used to simulate the ground heat exchanger (GHE) for heating the system.

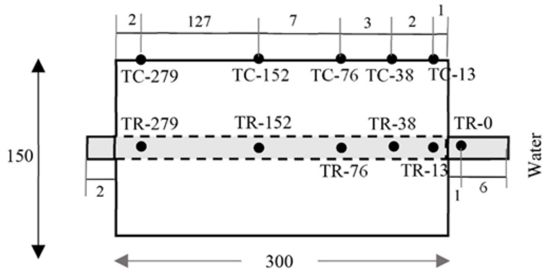
Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar

Fact Sheet P-02



Location: **Buffalo, NY**
Country: **USA**
Year: **2022**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Heated Rebar Deck Deicing (among others)**
Type of geothermal heat sources: **Not specified**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**





Ref. Mehrabi, R., Atefi-Monfared, K., Kumar, D., Deshpande, A. A., & Ranade, R. (2022). Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar. *Cold Regions Science and Technology*, *194*, 103466. https://doi.org/10.1016/j.coldregions.2021.103466

DESCRIPTION OF THE STUDY

Model setup: A cylindrical specimen was cast for the experimental study. The cylinder measured 15 cm in diameter and 30 cm in length, with a 40 cm long steel rebar (nominal diameter: 16 mm) embedded longitudinally at the centre. A heating–cooling protocol was applied to the specimen, in which the rebar was immersed in water at room temperature (21°C) at time $t = 0$. The water temperature was then increased to its boiling point over a 30-minute period. The temperature was maintained at 100°C for 2.5 hours, after which the heat source was removed, and the specimen was left to cool down to room temperature. The cylindrical specimen was also simulated numerically to calibrate the linear thermal expansion coefficient, specific heat, and thermal conductivity of both the concrete and the steel rebar. These parameters were calibrated using independent temperature data collected from multiple thermocouples.

Design approach for the heating surface installation: The HRDD system used embedded rebars in the top conventional reinforcement layer of a concrete bridge deck as heat conductors.

Design approach for the geothermal source: Boiling water served as the heat source, with thermocouples linked to a data acquisition system via amplifiers to record temperature data. The specimen was heated by directly immersing the rebar into the boiling water in a steel pot placed over a portable pan stove.

Monitored parameters: To measure the temperature profiles over time, Type-K thermocouples were embedded near the central rebar (approximately 6 mm from the surface of the rebar) at five locations along the longitudinal axis of the cylinder. Five additional thermocouples, labelled "TC-X", were installed along the outer surface of the cylinder at the same longitudinal distances as the embedded thermocouples. One thermocouple (TR-0) was installed outside of concrete on the rebar, approximately 13 mm away from the specimen end, and one thermocouple was placed in the heating water in order to monitor heat transition from the heat source.

HIGHLIGHTS

Heated Rebar Deck De-icing (HRDD) system | model calibration | thermal properties

MAIN PURPOSE

To Assess the feasibility of the proposed HRDD system, as well as to calibrate the thermal parameters required for numerical modelling of the coupled thermo-mechanical behaviour of a bridge deck.

SURFACE HEATING SYSTEM

A novel HRDD system is investigated, using embedded rebars as heat conductors in a cylindrical cement concrete specimen.

GEOTHERMAL HEAT SOURCE

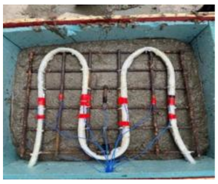
A heated water bath was used as the heat source.

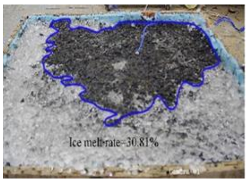
Experimental study on road deicing using circulated heating produced from geothermal fluid

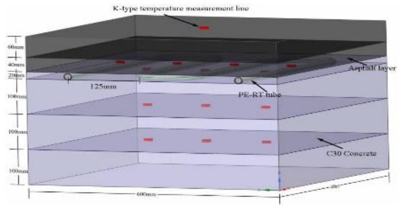
Fact Sheet P-03

Location: **Wuhan**
Country: **China**
Year: **2024**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchangers**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Ref. Chen, Z., Xu, H., Feng, D., Wang, J., Xiao, H., & Tian, Y. (2024). Experimental study on road deicing using circulated heating produced from geothermal fluid. *Renewable Energy*, *235*, 121083. https://doi.org/10.1016/j.renene.2024.121083







DESCRIPTION OF THE STUDY

Model setup: The prototype pavement slab measured 60 cm × 60 cm × 42 cm and consisted of a 10 cm thick asphalt concrete upper layer over a 32 cm thick cement concrete base. During the preheating phase, the ambient temperature was set to −5°C and −10°C, while the water temperature was adjusted to 40°C and 50°C. The circulation valve was opened, maintaining a constant flow rate of 0.45 m/s. For the de-icing performance investigation, the ambient temperature was set to −2°C, −5°C, and −8°C, and the water temperature was again adjusted to 40°C and 50°C. Before running the system for the experiments, a 0.5 cm thick layer of ice was formed on the road surface. The circulation valve was then opened, with the flow rate held constant at 0.45 m/s.

Design approach for the heating surface installation: A Polyethylene of Raised Temperature Resistance (PERT) heating pipe with a diameter of 16 mm ×12 mm and a spacing of 125 mm was installed at a depth of 12 cm below the road surface.

Design approach for the geothermal source: The geothermal fluid circulation (GFC) system for snow melting and de-icing included underground heat exchange pipes, heat pump unit, and embedded heat exchange pipelines within the road structure.

Monitored parameters: K-type thermocouple wires were distributed across four layers within the pavement slab: one at the surface, seven in the pipe-laying layer, and three in the remaining layers. During the preheating stage (6 hours), the temperatures of each asphalt road prototype layer, the supply water temperature, and the power consumption were recorded. Additionally, during the heating phase (8 hours), the ice melting rate was also recorded. The performance of the heating and de-icing systems was evaluated using the coefficient of performance (COP) and the energy consumption per square meter (q_{ice}) in kW/m^2, respectively.

HIGHLIGHTS

Ground source heat pump | Energy consumption ratio | De-icing performance | Temperature fluctuations | Critical de-icing temperature

MAIN PURPOSE

To investigate the performance coefficients of both the heat pump and road systems during road preheating experiments, as well as their de-icing effectiveness.

HEATING SYSTEM

A hydronic heating system heats up the road surface.

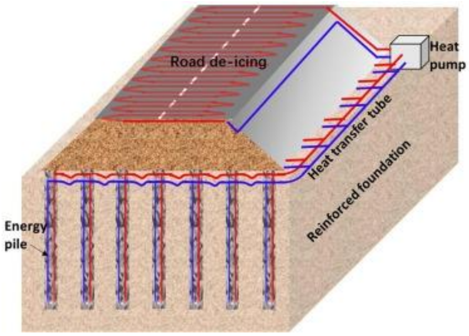
GEOTHERMAL HEAT SOURCE

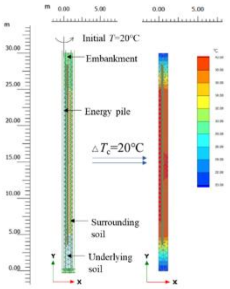
Underground heat exchange pipes and heat pump units are selected as the geothermal heat source for the system

A simplified model for energy pile-supported embankment

Fact Sheet P-04

Location: **Nanjing, Jiangsu**
Country: **China**
Year: **2024**
Type of infrastructure: **Embankment**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation: **Theoretical model validated with a numerical model**





Ref. Zhou, Y., Wang, J., Li, C., & Kong, G. (2024). A simplified model for energy pile-supported embankment. Computers and Geotechnics, 169, 106184. https://doi.org/10.1016/j.compgeo.2024.106184

DESCRIPTION OF THE STUDY

Numerical model setup: A hypothetical case of an energy pile-supported embankment subjected to a thermal load on the piles was set up to validate the proposed analytical model. To this end, a simplified 2D axisymmetric FE model was adopted using Plaxis 2D.

Initial and boundary conditions: The embankment fill, pile, and soil were modelled using elastoplastic behaviour with the Mohr-Coulomb failure criterion. Temperature boundary conditions (T = 40°C) were applied to the sides and top of the pile, with the radial boundary closed. The initial foundation temperature was set to +20°C. The fifteen-node triangular continuum elements were used in the Plaxis modelling. The method of steady-state heat transfer was used to analyse the foundation temperatures. The interface between the pile and the soil was modelled using interface elements. A shear strength reduction factor (Rinter = 0.7) was applied in Plaxis at the interface to match the parameters of the proposed theoretical method.

Model parameters: The piles were located on an underlying soil layer with a depth of 5 m. The pile diameter and the length of the pile were 0.8 m and 20 m, respectively. The thermal expansion coefficient of the pile and the surrounding soil was 0.00001/℃ (usually used in concrete materials) and 0.000001/℃. A thermal load of +20 ◦C was applied on piles. The embankment height was 5 m.

Validation data: results from the theoretical model and the FE model were compared in terms of settlements at the surface of the foundation and settlements along the embankment height. Finally, the skin friction along the energy pile was analysed. The validation procedure overall demonstrated the adequacy of the theoretical model.

HIGHLIGHTS

Geothermal Energy | De-icing System | Energy pile-supported embankment | Thermal Effect |Settlement

MAIN PURPOSE

Predict the behavior of energy pile-supported embankments by considering the thermo-mechanical stress-strain response of the piles and foundation soil, while analyzing stress continuity and settlement compatibility among the embankments, reinforced foundation, and underlying soil.

SURFACE HEATING SYSTEM

A Hydronic Heating System was selected to heat the surface of the embankment.

GEOTHERMAL HEAT SOURCE

An energy pile system serves as a geothermal energy source for the hydronic system.

A novel full-scale external geothermal heating system for bridge deck de-icing

Fact Sheet P-05

Location: **Arlington, Texas**
Country: **USA**
Year: **2021**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Ref. Habibzadeh-Bigdarvish, O., Yu, X., Li, T., Lei, G., Banerjee, A. and Puppala, A.J. (2021). A novel full-scale external geothermal heating system for bridge deck de-icing. Applied Thermal Engineering 185: 116365. https://doi.org/10.1016/j.applthermaleng.2020.116365

DESCRIPTION OF THE STUDY

Model setup: The geothermal bridge was fully instrumented and tested during a series of winter events:

- Construction of the bridge deck prototype and installation of the internal heating loops. The external heating pipes are attached to the bottom surface of the externally heated zone.
- A thermal insulation foam is applied to the entire surface to prevent heat loss from the bottom, and valves are installed to control the operation mode and the heated section of the bridge deck.
- Construction of the GLHE: header pipes of 3.17 cm diameter were connected to the GLHE using socket fusion coupling, and the sensor's cable was laid down on the bottom of the trench. The trench was then backfilled with the excavated soil. The horizontal header pipes were bundled together during the backfill process.
- Building of a control room to host the system's main components, which included one heat pump, two flow centres, four circulating pumps, and one expansion tank.

Design approach for the heating surface installation: Only a section was assigned for the application of the external heating system. The hydronic loops at the bridge deck consisted of 1.27 cm internal diameter PEX pipes with a 20.32 cm centreline spacing. The remaining portion of the bridge deck was considered as the control section.

Design approach for the geothermal source: A ground-coupled heat pump system that utilizes the heat output of the system to de-ice and melt snow on the surface, was utilized. The heat carrier fluid circulated in a closed loop between the ground loop heat exchangers and hydronic pipes in contact with the deck to transfer the heat from the ground to the bridge deck surface. Both the traditional type of GHDS, which uses a hydronic pipe embedded in the concrete slab, and the newly developed method, which utilizes an external hydronic pipe that is attached to the bottom surface of the bridge deck and encapsulated in a layer of foam, were utilized.

HIGHLIGHTS

Full-scale externally heated geothermal bridge de-icing system | Bridge surface above freezing and ice-free during all winter events | Average COP of the de-icing system 4.6 | Average surface heat flux of 236.2 W/m^2 during a winter test | Approximately 55% of the supplied heat transferred to the bridge deck surface.

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from a geothermal borehole.

HEATING SYSTEM

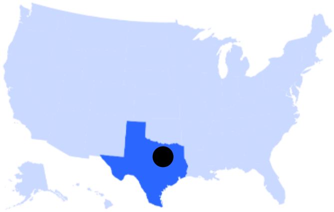
The de-icing system consists of eight polyethylene (PEX) hydronic loops attached to the bridge.

GEOTHERMAL HEAT SOURCE

One geothermal borehole and five temperature-monitoring boreholes drilled and equipped with temperature sensors.

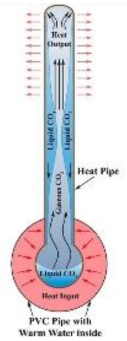
Feasibility study of a new attached multi-loop CO_2 heat pipe for bridge deck de-icing using geothermal energy

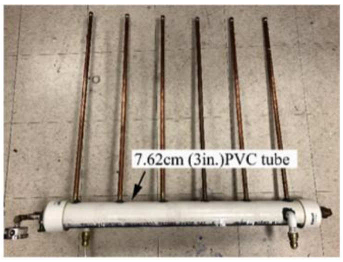
Fact Sheet P-06

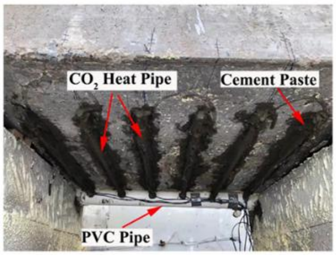


Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Existing bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Geothermal heat pump**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Ref. Lei, G., Yu, X., Li, T., Habibzadeh-Bigdarvish, O., Wang, X., Mrinal, M. and Luo, C., 2020. Feasibility study of a new attached multi-loop CO_2 heat pipe for bridge deck de-icing using geothermal energy. Journal of Cleaner Production, 275, p.123160. 46, p.101280. https://doi.org/10.1016/j.jclepro.2020.123160







DESCRIPTION OF THE STUDY

Model setup: A concrete slab, placed atop two concrete masonry unit blocks spaced approximately 0.85 m apart, was selected for the heating tests using the developed multi-loop CO_2 heat pipe. The dimensions of the slab were 1.2 m 0.9m 0.2m, while its thermal conductivity was approximately 2.18 W/(mK). Fiberglass insulation and expanded polystyrene (EPS) geofoam board were chosen as insulation materials and were attached to the concrete slab base. The heated slab was tested at two freezing temperatures of 3.89 C and 6.67 C with the water bath temperature ranging from 25 to 45 C.

Design approach for the heating surface installation: The CO_2 heat pipe system consisted of six smaller single copper pipe branches attached to the main larger copper pipe chamber, which was housed inside a PVC pipe filled with hot water. Each copper pipe was 76 cm long and was affixed to the bottom surface of the slab using pipe straps, with spacing intervals of 15.24 cm. Cement paste was used to fill the gaps between the copper pipes and the bottom surface of the slab to enhance thermal contact. The heat pipe was insulated with four layers of insulation, with a total thickness of 10 cm, after installation. The first two layers consisted of 5 cm of fiberglass, while the third and fourth layers were made of geofoam. The heat pipe (tube or chamber) transports heat from a heat source to a heating area via a two-phase flow heat transfer. The liquid CO_2 evaporates in the evaporating section by absorbing thermal energy, resulting in a difference in pressure within the pipe. The vapor is then driven by the pressure difference from the evaporator to the condensing section (tip of the pipe), where the condensation of the vapor occurs at the surface, releasing the latent heat. With the condensation, the gaseous CO_2 converts into a liquid phase, and the capillary pressure, generated by the porous wick lining on the inner surface of the pipe and the gravity forces the condensed liquid back to the evaporator for re-vaporization

Design approach for the geothermal source: The hot water that filled the PVC pipe was supplied from a thermostatic water bath. The inlet temperature simulated a typical output temperature from a geothermal heat pump.

HIGHLIGHTS

CO2 heat pipe | Bridge de-icing | Geothermal energy | Fourier's law

MAIN PURPOSE

To evaluate the feasibility and effectiveness of a new attached multi-loop CO2 heat pipe system for bridge deck de-icing using geothermal energy.

HEATING SYSTEM

Multi-loop CO2 heat pipe heating (MCHP) system, using CO2 as the working fluid.

GEOTHERMAL HEAT SOURCE

A water bath was used to supply hot water and simulate a typical output temperature from a geothermal heat pump.

Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks

Fact Sheet P-07

Location: **Elazig**
Country: **Turkey**
Year: **2010**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Balbay, A., & Esen, M. (2010). Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks. Scientific Research and Essays, 5(24), 3955-3966. http://www.academicjournals.org/SRE

DESCRIPTION OF THE STUDY

Model setup: The prototype concrete slabs for snow/ice melting on their top surfaces were constructed using a wooden frame, which subsequently remain attached to the slab. The snow/ice on surfaces of the bridge-slab and pavement-slab were heated and melted by the GSHP. The slabs have been insulated on all four sides to minimize edge losses. The serpentine pipe configuration is used for both slabs. Eight parallel lines of Polyethylene PX-b pipes were embedded in each frame evenly spaced in the direction of length.

Design approach for the heating surface installation: The heat transfer between the ground and the HP, or vice versa, is facilitated by circulating a fluid or water-antifreeze solution through the BHE. The fluid transfers its heat to the refrigerant fluid in the evaporator, which acts as a heat exchanger between the water-antifreeze solution and the refrigerant. The refrigerant, flowing through another closed loop in the HP system, evaporates by absorbing heat from the water-antifreeze solution circulating through the evaporator. It then enters the hermetic compressor. Meanwhile, the water-antifreeze solution in the BHEs loop collects heat from the ground and transfers it to the HP. After absorbing heat from the ground, the closed-loop BHEs circulate the heat exchange fluid through pipes.

Design approach for the geothermal source: Vertical drilling of boreholes for a Ground Source Heat Pump (GSHP) unit at three different depths (30, 60, and 90 m). Each borehole consists of a high-density polyethylene tube with a diameter of 40 mm. These vertical single U-type borehole heat exchangers were connected to a heat pump unit located in a house, constructed using national facilities. The U-pipe heat exchangers were installed in marl-type ground. To complete a closed loop, it is necessary to fill the space between the heat exchanger pipe and the borehole wall with material, such as grout or fill. The power input to the compressor, the evaporator's water antifreeze circulating pump, the condenser's water antifreeze circulating pump and the COP of the GSHP were calculated using the equations in the reference. The water-antifreeze solution flow rate passing BHE and BS or PS is set to 0.36 and 0.056 L/s, respectively as an optimum flow rate throughout the experiments.

HIGHLIGHTS

Snow/ice melting | Ground source heat pump | Bridge deck | Pavement

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from a geothermal borehole.

HEATING SYSTEM

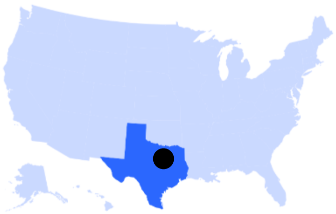
Two prototype slabs (bridge-slab (BS) and pavement-slab (PS), a circulation pump, and pipe circuits.

GEOTHERMAL HEAT SOURCE

Vertical drilling of Borehole Heat Exchangers (BHE) for a vertical Ground Source Heat Pump (GSHP) system.

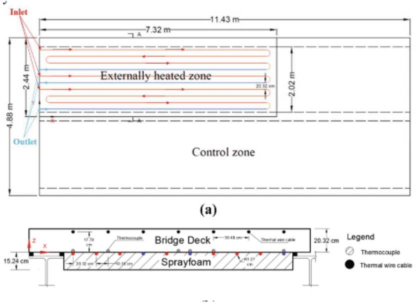
Heating performance of a novel externally-heated geothermal bridge de-icing system: field tests and numerical simulations

Fact Sheet P-08



Location: **Arlington, Texas**
Country: **USA**
Year: **2021**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **Yes**

Ref. Li, T., Yu, X., Habibzadeh-Bigdarvish, O., Lei, G. and Puppala, A.J., 2021. Heating performance of a novel externally-heated geothermal bridge de-icing system: field tests and numerical simulations. Sustainable Energy Technologies and Assessments, 46, p.101280. https://doi.org/10.1016/j.seta.2021.101280



DESCRIPTION OF THE STUDY

Model setup: A total of 12 standard 2.43 m × 1.82 m × 10.16 cm PCP panels were employed to construct the prototype bridge deck, which was built on top of three standard I-beams fixed on two standard concrete traffic barriers. Although the dimensions of the entire mock-up bridge deck were 10.97 m × 4.87 m × 20.32 cm, only the externally heated zone with an area of 7.31 m × 4.8 m was used to perform the heating scenarios. The hydronic loops were covered by fine cement paste to increase the surface contact with the deck base and were attached to the bottom surface of the externally heated zone, where they were encapsulated by a layer of spray foam for heat insulation. Different operation scenarios, including non-heating, heating, and heating and de- icing tests were analysed. A numerical model was then fully calibrated by the test data acquired in the field using transient analyses.

Design approach for the heating surface installation: The extracted underground fluid was circulated within the bridge deck through a PEX pipe with an inner diameter of 13 mm and an outer diameter of 19 mm. The external heating system consisted of 3 inlets and 3 outlets. The hydronic loop spacing was set to 20.32 cm. The thermal conductivity of the concrete deck was 2.16 W/mK.

Design approach for the geothermal source: A single borehole, measuring 132.5 m in length and 14.6 cm in diameter, was used to supply heat energy for snow melting and de-icing on the mock-up bridge deck. The fluid then flowed from the ground loops into the circulation pump and heat pump, both housed in an on-site control room. Finally, the heat-carrying fluid was pumped into the hydronic loop system to deliver the required heat flux to the bridge deck surface.

Monitored parameters: The temperature sensors included thermal wire cables (Pile Dynamics) and Type-T thermocouples (N.I.). The former allowed for multiple measurements along the cable, while the latter captured the temperature response at a specific point. The sensors are placed both within the deck's cross-section (at the concrete base) and 2.5 cm below the concrete surface.

HIGHLIGHTS

Externally-heated geothermal bridge | Bridge de-icing | Geothermal energy | Finite element model | Thermal contact model

MAIN PURPOSE

To evaluate the heating performance of a novel externally heated geothermal bridge de-icing system in maintaining a snow-free bridge deck during winter events.

HEATING SYSTEM

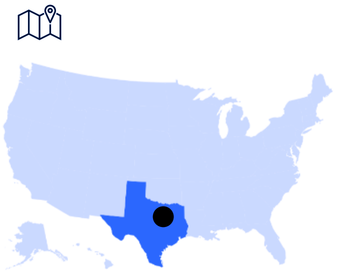
Pipes that circulate a heat-carrying fluid.

GEOTHERMAL HEAT SOURCE

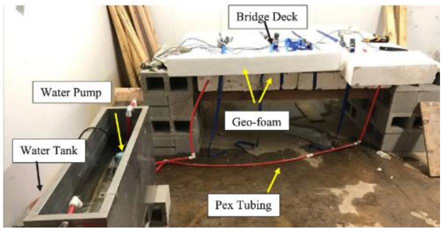
A borehole heat exchanger (BHE) extracts heat from the ground, which is then transferred to the fluid in the hydronic loops.

Experimental feasibility study of a new attached hydronic loop design for geothermal heating of bridge decks

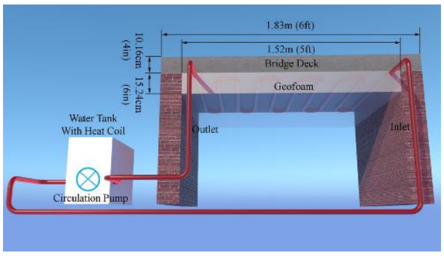
Fact Sheet P-09



Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Existing bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Geothermal heat pump**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **No**



Ref. Yu, X., Hurley, M.T., Li, T., Lei, G., Pedarla, A. and Puppala, A.J., 2020. Experimental feasibility study of a new attached hydronic loop design for geothermal heating of bridge decks. Applied Thermal Engineering, 164, p.114507. https://doi.org/10.1016/j.applthermaleng.2019.114507



DESCRIPTION OF THE STUDY

Model setup: A prestressed concrete panel measuring 1.8 m × 1.2 m × 0.1 m was selected for the construction of the heated bridge deck prototype. The panel was installed on a 1.1 m-high concrete pedestal with 15 cm of landing space on each side. The heated bridge deck was placed inside an environmental chamber. PEX tubing with an oxygen barrier was used, with the barrier layer preventing air and oxygen from infiltrating the radiant heating system. Expanded polystyrene geofoam, with a density of 21.6 kg/m³, and polyurethane foam were used to encapsulate the hydronic pipes, providing thermal insulation. Once the tubing was secured to the geofoam block with adhesive, a layer of fine cement paste was applied over the pipe layout to create a flat interface between the bridge slab and the geofoam. A series of 16 environmental chamber tests were conducted to evaluate the heating response under different ambient temperatures (4°C to 17°C) and supplied water temperatures (21°C to 38°C). Finally, sub-freezing conditions (1°C, −10°C, and −14°C) were investigated. To this end, a small geofoam box designed to contain 3.6 kg of dry ice was placed on the deck's surface to create localized freezing conditions.

Design approach for the heating surface installation: A serpentine hydronic loop was designed, consisting of 10 parallel pipes and 9 turns. The inner and outer diameters are 13 mm and 19 mm, respectively. The PEX pipe was cut to the desired length and embedded within a geofoam block measuring 1.5 m × 1.2 m × 13 cm. A pipe spacing of 15 cm was used.

Design approach for the geothermal source: The hydronic loop is connected to a water tank through a hydraulic pump. The water tank, equipped with heating coils, allows for water bath temperature control and was used to simulate warm fluids supplied by ground loop heat exchangers (GLHEs) and ground source heat pumps (GSHPs). The water tank was placed beside a wooden box with 3 cm of geofoam insulation. With a volume capacity of 95 L, the water tank was positioned near the concrete panel and contains a heating coil along its base. The heating process was initiated by turning on the water pump, operating at a constant flow rate of 1.2 m/s.

HIGHLIGHTS

Heated bridge | Hydronic loops |Geothermal energy | Heat transfer

MAIN PURPOSE

To evaluate the feasibility and effectiveness of a new attached hydronic loop design for geothermal heating of bridge decks.

HEATING SYSTEM

Hydronic heating loop, which consists of hydronic pipes and foam insulation materials. Hydronic pipes are attached to the bottom of the bridge deck through metal fixtures.

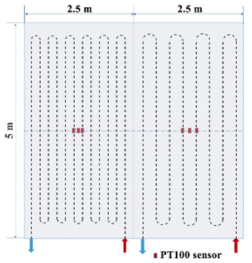
GEOTHERMAL HEAT SOURCE

A water bath was used to supply hot water and simulate a typical output temperature from a geothermal heat pump.

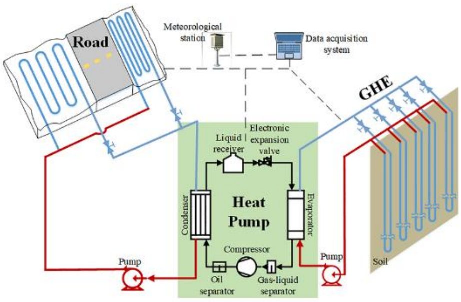
Experimental heating performances of a ground source heat pump (GSHP) for heating road unit.

Fact Sheet P-10

Location: **Harbin**
Country: **China**
Year: **2020**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with numerical analysis: **No**



Ref. Zhao, W., Zhang, Y., Chen, X., Su, W., Li, B. and Fu, Z., 2020. Experimental heating performances of a ground source heat pump (GSHP) for heating road unit. Energy Conversion and Management: X, 7, p.100040. https://doi.org/10.1016/j.ecmx.2020.100040



DESCRIPTION OF THE STUDY

Model setup: The experimental system was mainly composed of a road unit, a heat pump unit, a ground heat exchanger (GHE) unit and a data acquisition system. The road unit was constructed in a total area of 25 m^2, 5 m in width and 5 m in length. The heating performances of supplied water temperature, road surface temperature, energy efficiency as affected by the set water temperature (25, 30 and 35 °C) and flow rate (2, 3 and 4 m^3/h) were detailed to analyse and evaluate the heating process of GSHP road heating system.

Design approach for the heating surface installation: The road unit featured two 2.5 m × 5.0 m road bases, one with the 200 mm tube-pitch and the other with the 300 mm tube-pitch. An ethylene glycol mixture with a freezing point of −30 °C was used as circulating liquid in the condenser and evaporator water loops, to avoid freezing in cold winter conditions.

Design approach for the geothermal source: The heat pump unit was mainly composed of a compressor, an evaporator, a condenser, and an expansion valve, and the work fluid in the heat pump was R22. An ethylene glycol mixture with a freezing point of −30 °C was used as the circulating liquid in the condenser and evaporator water loops, to avoid freezing in cold winter conditions. The ground heat exchanger unit consisted of ten boreholes with a depth of 100 m.

Monitored parameters: The temperature, pressure, and flow rate of the supplied water was measured using a PT100 sensor, pressure gauge, and turbine flowmeter, respectively. The road surface temperature was measured using PT100 sensors.

HIGHLIGHTS

Ground source heat pump | Heating performance | Supplied water temperature | Water flow rate

MAIN PURPOSE

To evaluate the heating performance of a ground source heat pump (GSHP) system for heating a road unit.

HEATING SYSTEM

Pipes that circulate a heat-carrying fluid.

GEOTHERMAL HEAT SOURCE

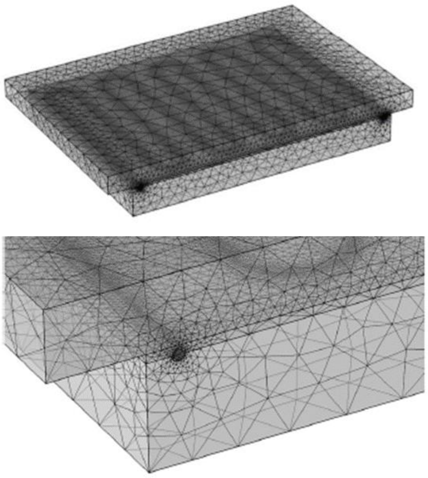
Ground Heat Exchanger (GHE) Unit, consisting of ten boreholes, each 100 meters deep, this unit extracts geothermal energy from the ground.

APPENDICES SUBTASK2 – Melting Systems for Infrastructure, Deliverable 2.2: Assessment of model capabilities and validation processes

Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature

Fact Sheet N-01

Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**



Ref. Li, T., Yu, X., Lei, G., Habibzadeh-Bigdarvish, O., Hurley, M. (2020). Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature. Applied Thermal Engineering, 174, 115255.
https://doi.org/10.1016/j.applthermaleng.2020.115255

DESCRIPTION OF THE STUDY

Model setup: A three-dimensional finite element bridge deck model was developed in COMSOL to replicate the laboratory deck in the environmental chamber:

- A transient model was employed to analyze the heating processes with the time change and steady-state model to obtain the final temperature at equilibrium state.
- Heat transfer processes, including conduction, convection, and radiation heat transfer, were modeled in these numerical analyses.
- The heated slab and the ambient air were set to have the same temperature.
- The water flow model was initiated with the same measured temperature input at the inlet.

Initial and boundary conditions: The adjusted inlet fluid temperatures are the average of the measured temperatures in the environmental chamber and were utilized as the boundary condition of the inlet in the COMSOL model.

- In COMSOL, the module interfaces of the pipe-concrete slab, pipe-geofoam slab, and pipe-inlet fluid were set as perfect surface contacts due to the excellent bonding of these interfaces.
- A thermal contact was created in COMSOL to simulate the gap between the concrete bottom surface and the cement paste layer.

Modeling approach for the heating surface installation: The model was solved with a transient method, with the simulation time the same as that of the lab test temperature of the injected fluid and of the porous asphalt flow rate on the road surface temperature were analyzed. The simulated time-dependent heating curves were verified with the laboratory-measured data at the thermocouple locations.

Modeling approach for the geothermal source: --

HIGHLIGHTS

3D model for a hydronic bridge deck heated externally | Calibration and validation with 16 test cases | Thermal contact model developed for the attached loop | The heat flux near the deck surface can be estimated using 1D heat conduction

MAIN PURPOSE

De-icing of bridge deck using e shallow geothermal energy extracted from underground loops.

HEATING SYSTEM

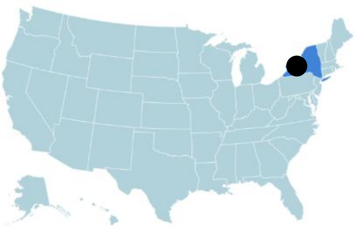
External hydronic heating system composed by attached insulated, cross-linked polyethylene (PEX) pipe loop. The loop consists of a PEX pipe, an aluminum plate, polyurethane foam insulation, and a high-density polyethylene jacket.

GEOTHERMAL HEAT SOURCE

A heated water bath was used to simulate the ground heat exchanger (GHE) for heating the system.

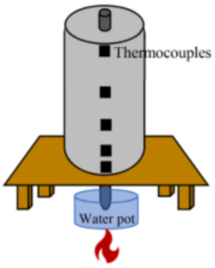
Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar

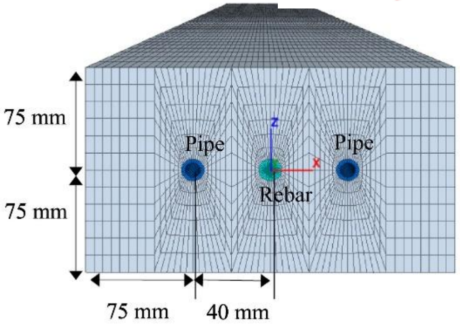
Fact Sheet N-02



Location: **Buffalo, NY**
Country: **USA**
Year: **2022**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system (among others)**
Type of geothermal heat sources: **Not specified**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**

Ref. Mehrabi, R., Atefi-Monfared, K., Kumar, D., Deshpande, A. A., & Ranade, R. (2022). Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar. *Cold Regions Science and Technology*, *194*, 103466.
https://doi.org/10.1016/j.coldregions.2021.103466





DESCRIPTION OF THE STUDY

Model setup: This study investigates the thermo-mechanical behavior of a large-scale heated bridge deck under cyclic thermal loading in Hydronic Heated-Pavement (HHP) and Electrically Heated-Pavement (EHP) systems, factoring in realistic mechanical and thermal boundary conditions and the thermal degradation of concrete properties. It also explored the feasibility of a new heating system, the "Heated Rebar Deck Deicing" (HRDD) system, which uses embedded rebars in the top conventional reinforcement layer of a concrete bridge deck as heat conductors. This proposed system may be less damaging to the structural and material integrity of the bridge deck compared to existing HHP and EHP systems. This work presents novel finite difference-based numerical models for the above analysis, which is calibrated using small-scale laboratory experiments. The numerical model aimed to evaluate the thermal efficiency and damage resilience of three heated bridge deck systems (EHP, HHP, and HRDD) across different heating scenarios.

Initial and boundary conditions: The model was first stabilized under gravitational loads. Then, a heat source was applied within the embedded conductor, generating thermally induced strains and stresses. Heat transfer from the concrete's exposed surfaces to the environment was modeled with convective boundary conditions.

Modeling approach for the heating surface installation: The model assumes isotropic heat conduction as the primary heat transfer mechanism. Thermo-mechanical stresses and strains are driven by temperature and the three heat flux components, connected through the energy-balance equation and transport laws based on Fourier's law of heat conduction.

Modeling approach for the geothermal source: In the experimental prototype, boiling water served as the heat source, with thermocouples linked to a data acquisition system via amplifiers to record temperature data. In the numerical model, temperatures were controlled and set as boundary conditions on the slab surface.

HIGHLIGHTS

Hydronic Heated-Pavement Systems | Electrically Heated-Pavement Systems | De-icing and Snow-melting of a bridge deck | Finite Difference-based numerical model | Heated Rebar Deck Deicing system

MAIN PURPOSE

To obtain a fundamental understanding of the thermo-mechanical behavior of a large-scale heated bridge deck subjected to internal cyclic thermal loading in HHP and EHP systems.

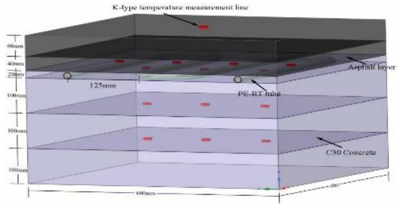
SURFACE HEATING SYSTEM

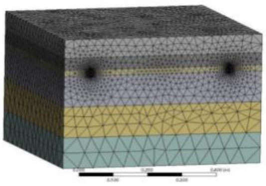
Hydronic Heated-Pavement (HHP) and Electrically Heated-Pavement (EHP) systems are explored. Additionally, the feasibility of a novel "Heated Rebar Deck Deicing" (HRDD) system is investigated, using embedded rebars as heat conductors in the deck's top reinforcement layer.

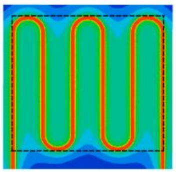
Experimental study on road deicing using circulated heating produced from geothermal fluid

Fact Sheet N-03

Location: **Wuhan**
Country: **China**
Year: **2024**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchangers**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**







Ref. Chen, Z., Xu, H., Feng, D., Wang, J., Xiao, H., & Tian, Y. (2024). Experimental study on road deicing using circulated heating produced from geothermal fluid. *Renewable Energy*, *235*, 121083.
https://doi.org/10.1016/j.renene.2024.121083

DESCRIPTION OF THE STUDY

Model setup: A 1:1 numerical model based on the indoor experimental setup was developed. The model includes heat exchange pipes, an asphalt layer, a concrete layer, and aluminum foil tape. An expansion grid division method is used for the circulating fluid to improve computational accuracy, while the remaining structural layers are meshed using a tetrahedral method. Throughout the simulation, all materials are treated as isotropic. The material properties incorporated in the model, including density, specific heat capacity, and thermal conductivity, are consistent with those of the experimental model materials.

Initial and boundary conditions: The same experimental conditions as those in Case 1 of the reference paper were applied: the road surface temperatures were set to -5 °C and -10 °C, and the water temperature was adjusted to 40 °C and 50 °C. The circulation valve was opened, and the flow rate was maintained at a constant 0.45 m/s.

Modeling approach for the heating surface installation: When the road system is heated, the energy stored in the road is calculated in *Qh* (kJ) using the following formulas:

$$Q_h = mC_P(T_s - T_r)$$

$$m = \rho V$$

$$V = v\pi R^2 \cdot \Delta t$$

Modeling approach for the geothermal source: The coefficient of performance (COP_{sys}) of the road system combined with the heat pump system is defined as follows:

$$COP_{sys} = Q_h / Q_g$$

HIGHLIGHTS

Ground source heat pump | Energy consumption ratio | De-icing performance | Temperature fluctuations | Critical de-icing temperature

MAIN PURPOSE

To investigate the performance coefficients of both the heat pump and road systems during road preheating experiments, as well as their de-icing effectiveness.

SURFACE HEATING SYSTEM

A hydronic heating system heats up the road surface.

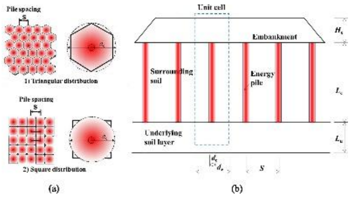
GEOTHERMAL HEAT SOURCE

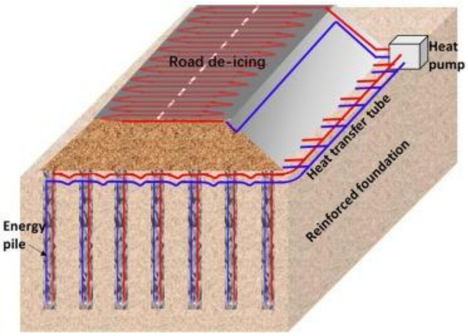
Underground heat exchange pipes and heat pump units are selected as the geothermal heat source for the system.

A simplified model for energy pile-supported embankment

Fact Sheet N-04

Location: **Nanjing, Jiangsu**
Country: **China**
Year: **2024**
Type of infrastructure: **Embankment**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Theoretical model validated with a numerical model**





Ref. Zhou, Y., Wang, J., Li, C., & Kong, G. (2024). A simplified model for energy pile-supported embankment. *Computers and Geotechnics*, *169*, 106184. https://doi.org/10.1016/j.compgeo.2024.106184

DESCRIPTION OF THE STUDY

Model setup: A simplified model is proposed to predict the behavior of energy pile-supported embankments. The constraint at the pile head is achieved by mobilizing load transfer mechanisms, including the soil arching effect within the embankment. The model incorporates the thermo-mechanical stress-strain responses of both the piles and the foundation soil, analyzing stress continuity and settlement compatibility across the embankment, reinforced foundation, and underlying soil. Thermal effects on load transfer behavior are explored, and the model is validated against numerical simulations. Additionally, parametric studies examine the influence of factors such as the foundation soil's thermal expansion coefficient and temperature variations on load transfer and settlement.

Initial and boundary conditions: Using the equivalent area assumption, a unit cell comprising a pile and surrounding soil can be extracted from the energy pile-supported embankment. The embankment fill, pile, and soil are modeled using elastoplastic behavior with the Mohr-Coulomb failure criterion. Temperature boundary conditions (T = 40°C) are applied to the sides and top of the pile, with the radial boundary closed. The initial foundation temperature is set to +20°C.

Modeling approach for the heating surface installation: Heat transfer is assumed to occur within the piles and surrounding soil, while temperature changes in the embankment and underlying soil are neglected. The unit cell in the embankment is divided into an inner cylinder (above the pile) and an outer cylinder (above the foundation soil).

Modeling approach for the geothermal source: A unit cell, consisting of a pile and surrounding soil, can be extracted from the energy pile-supported embankment to analyze heat transfer interactions between piles. This unit-cell concept is also applied to study the temperature distribution in the pile-reinforced foundation using steady-state heat transfer analysis. When a thermal load of +20°C is applied to the pile, the temperature distribution within the foundation becomes uniform. The pile-soil interface is modeled using interface elements.

HIGHLIGHTS

Geothermal Energy | De-icing System | Energy pile-supported embankment | Thermal Effect |Settlement

MAIN PURPOSE

To predict the behavior of energy pile-supported embankments by considering the thermo-mechanical stress-strain response of the piles and foundation soil, while analyzing stress continuity and settlement compatibility among the embankments, reinforced foundation, and underlying soil.

SURFACE HEATING SYSTEM

A Hydronic Heating System was selected to heat the surface of the embankment.

GEOTHERMAL HEAT SOURCE

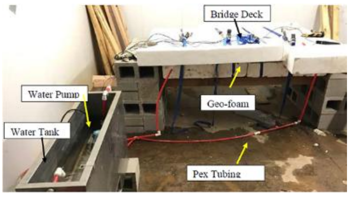
An energy pile system serves as a geothermal energy source for the hydronic system.

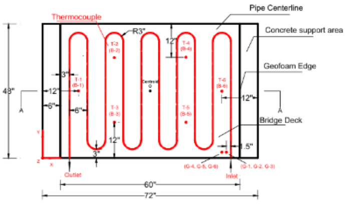
Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature

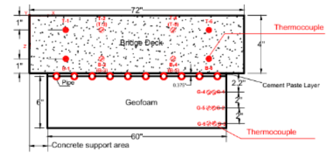
Fact Sheet P-01

Location: **Arlington, Texas**
Country: **USA**
Year: **2020**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchanger**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**

Ref. Li, T., Yu, X., Lei, G., Habibzadeh-Bigdarvish, O., Hurley, M. (2020). Numerical analyses of a laboratory test of a geothermal bridge deck externally heated under controlled temperature. Applied Thermal Engineering, 174, 115255.
https://doi.org/10.1016/j.applthermaleng.2020.115255







DESCRIPTION OF THE STUDY

Model setup: The prototype bridge deck was constructed using a standard 1.8 m x 1.2 m x 0.1 m precast concrete panel (PCP) and then installed in an environmental chamber in which a minimum temperature of 4.4 °C. could be attained. Two 1.1 m high concrete pedestals, each with 152 mm of landing space, supported the concrete slab. A geofoam block encapsulating the hydronic heating system was directly attached to the bottom surface of the concrete slab by straps and wood. A flat interface zone, created by covering the pipe system with a fine cement paste, made the heat transfer at the base of concrete slab more uniform and efficient.

Design approach for the heating surface installation: Cross-linked polyethylene (PEX) tubing with an inner diameter of 13 mm and an outer diameter of 19 mm was employed to circulate heat carrying fluid within the bridge deck. An oxygen barrier layer was selected for hydronic heating to prevent air/oxygen from infiltrating the radiant heating system.

Design approach for the geothermal source: The loop inlet was connected to a water pump that was submerged in a water tank and capable of providing a constant flow rate of 0.13 kg/s; the loop outlet was connected to a water tank that could provide warm water at the desired temperature.

Monitored parameters: Thermocouples were installed 25 mm above and below the concrete bottom and top surface, respectively. Moreover, two thermocouple sets were installed in the geofoam block. Sixteen heating response test programs were conducted under various water and ambient temperatures to evaluate the heat transfer performance of the investigated system and to determine the steady-state temperature of the heated slab.

HIGHLIGHTS

Prototype hydronic bridge deck | External heating | Testing campaign under various water and ambient temperatures | Calibration and validation of a 3D model with collected data

MAIN PURPOSE

Study the heating performance of an external heating system directly attached to the bottom surface of a hypothetical bridge deck.

HEATING SYSTEM

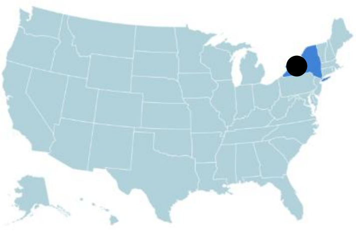
External hydronic heating system composed by attached insulated, cross-linked polyethylene (PEX) pipe loop. The loop consists of a PEX pipe, an aluminum plate, geofoam insulation, and a high-density polyethylene jacket.

GEOTHERMAL HEAT SOURCE

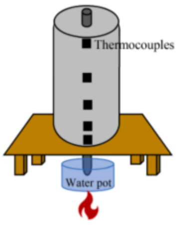
A heated water bath was used to simulate the ground heat exchanger (GHE) for heating the system.

Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar

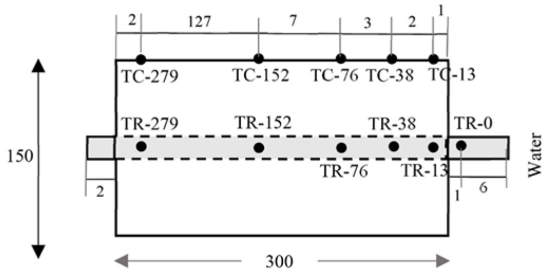
Fact Sheet P-02



Location: **Buffalo, NY**
Country: **USA**
Year: **2022**
Type of infrastructure: **Bridge deck**
Type of surface heating system: **Heated Rebar Deck Deicing (among others)**
Type of geothermal heat sources: **Not specified**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**



Ref. Mehrabi, R., Atefi-Monfared, K., Kumar, D., Deshpande, A. A., & Ranade, R. (2022). Thermo-mechanical assessment of heated bridge deck under internal cyclic thermal loading from various heating elements: pipe, cable, rebar. *Cold Regions Science and Technology*, *194*, 103466.
https://doi.org/10.1016/j.coldregions.2021.103466



DESCRIPTION OF THE STUDY

Model setup: A cylindrical specimen was cast for the experimental study. The cylinder was 150 mm in diameter and 300 mm in length, with a 400 mm long 16 mm rebar (nominal diameter of 15.87 mm) embedded longitudinally at the center. A heating-cooling protocol was applied to the specimen, where the rebar was immersed in water at room temperature (21 ◦C) at time t =0. The water temperature was then ramped up to its boiling point over 30 min duration. The water temperature was maintained at 100 ◦C for 2.5 h, after which the source was removed, and the sample was left to cool down to the room temperature. The cylindrical specimen was simulated numerically to calibrate the linear thermal expansion, specific heat, and thermal conductivity of concrete and steel rebar. These were calibrated using independent temperature data from multiple thermo-couples

Design approach for the heating surface installation: The HRDD system utilizes embedded rebars in the top conventional reinforcement layer of a concrete bridge deck as heat conductors.

Design approach for the geothermal source: Boiling water served as the heat source, with thermocouples linked to a data acquisition system via amplifiers to record temperature data. The specimen was heated by directly immersing the rebar into the boiling water in a steel pot placed over a portable pan stove.

Monitored parameters: To measure the temperature profiles over time, Type-K thermocouples were embedded near the central rebar (approximately 6 mm from the surface of the rebar) at five locations along the longitudinal axis of the cylinder. Five additional thermocouples, labeled “TC-X", were installed along the outer surface of the cylinder at the same longitudinal distances as the embedded thermocouples. One thermocouple (TR-0) was installed outside of concrete on the rebar, approximately 13 mm away from the specimen end, and one thermocouple was placed in the heating water in order to monitor heat transition from the heat source.

HIGHLIGHTS

Heated Rebar Deck Deicing (HRDD) system | model calibration |thermal properties

MAIN PURPOSE

Assess the feasibility of the proposed HRDD system, as well as to calibrate the thermal parameters required for numerical modeling of the coupled thermo-mechanical behavior of a bridge deck.

SURFACE HEATING SYSTEM

A novel HRDD system is investigated, using embedded rebars as heat conductors in a cylindrical cement concrete specimen.

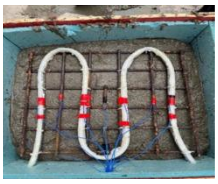
GEOTHERMAL HEAT SOURCE

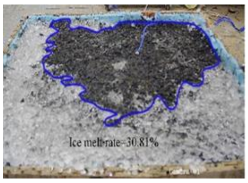
A heated water bath was used as the heat source.

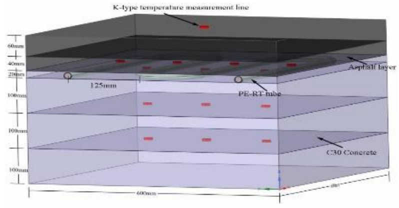
Experimental study on road deicing using circulated heating produced from geothermal fluid

Fact Sheet P-03

Location: **Wuhan**
Country: **China**
Year: **2024**
Type of infrastructure: **Road**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Ground Heat Exchangers**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation with experimental prototype: **Yes**







Ref. Chen, Z., Xu, H., Feng, D., Wang, J., Xiao, H., & Tian, Y. (2024). Experimental study on road deicing using circulated heating produced from geothermal fluid. *Renewable Energy*, *235*, 121083.
https://doi.org/10.1016/j.renene.2024.121083

DESCRIPTION OF THE STUDY

Model setup: The prototype pavement slab measured 600 mm x 600 mm x 420 mm and consisted of a 100 mm thick asphalt concrete upper layer over a 320 mm thick cement concrete base. During the pre-heating phase, the ambient temperature was set to -5°C and -10°C, while the water temperature was adjusted to 40°C and 50°C. The circulation valve was opened, maintaining a constant flow rate of 0.45 m/s. For the de-icing performance investigation, the ambient temperature was set to -2°C, -5°C, and -8°C, and the water temperature was adjusted to 40°C and 50°C. Before running the system for the experiments, a 5 mm thick layer of ice was laid on the road surface. The circulation valve was then opened, with the flow rate again held constant at 0.45 m/s.

Design approach for the heating surface installation: A Polyethylene of Raised Temperature Resistance (PERT) heating pipe with a diameter of 16 mm ×12 mm and a spacing of 125 mm was installed at a depth of 12 cm below the road surface.

Design approach for the geothermal source: The geothermal fluid circulation (GFC) system for snow melting and de-icing included underground heat exchange pipes, heat pump unit, and embedded heat exchange pipelines within the road structure.

Monitored parameters: K-type thermocouple wires were distributed in four layers within the pavement slab: one at the surface, seven in the pipe-laying layer, and three in the remaining layers. During the preheating stage (6 hours), the temperatures of each layer of the asphalt road prototype, the supply water temperature, and the power consumption were recorded. Besides, during the heating phase (8 hours), the ice melting rate was recorded as well. The performance of the heating and the de-icing systems was evaluated using the coefficient of performance (COP) and the energy consumption per square meter (q_{ice}) (kW/m^2), respectively.

HIGHLIGHTS

Ground source heat pump | Energy consumption ratio | De-icing performance | Temperature fluctuations | Critical de-icing temperature

MAIN PURPOSE

To investigate the performance coefficients of both the heat pump and road systems during road preheating experiments, as well as their de-icing effectiveness.

HEATING SYSTEM

A hydronic heating system heats up the road surface.

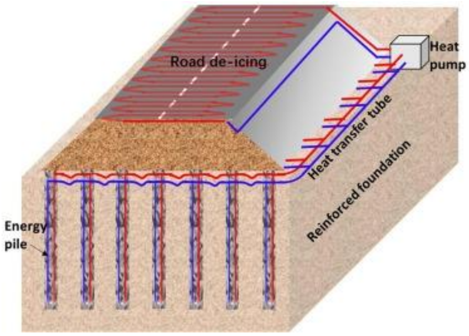
GEOTHERMAL HEAT SOURCE

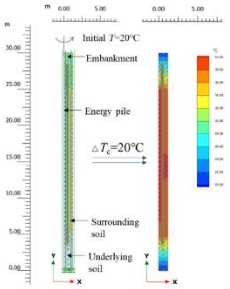
Underground heat exchange pipes and heat pump units are selected as the geothermal heat source for the system

A simplified model for energy pile-supported embankment

Fact Sheet P-04

Location: **Nanjing, Jiangsu**
Country: **China**
Year: **2024**
Type of infrastructure: **Embankment**
Type of surface heating system: **Hydronic system**
Type of geothermal heat sources: **Energy Piles**
Presence of hybrid energy collection: **No**
Annual assessment and evaluation: **--**
Validation: **Theoretical model validated with a numerical model**





Ref. Zhou, Y., Wang, J., Li, C., & Kong, G. (2024). A simplified model for energy pile-supported embankment. Computers and Geotechnics, 169, 106184. https://doi.org/10.1016/j.compgeo.2024.106184

DESCRIPTION OF THE STUDY

Numerical model setup: A hypothetical case of an energy pile-supported embankment subjected to a thermal load on the piles was set up to validate the proposed analytical model. To this end, a simplified 2D axisymmetric FE model was adopted using Plaxis 2D.

Initial and boundary conditions: The embankment fill, pile, and soil were modeled using elastoplastic behavior with the Mohr-Coulomb failure criterion. Temperature boundary conditions (T = 40°C) were applied to the sides and top of the pile, with the radial boundary closed. The initial foundation temperature was set to +20°C. The fifteen-node triangular continuum elements were used in the Plaxis modeling. The method of steady-state heat transfer was used to analyze the foundation temperatures. The interface between the pile and the soil was modeled using interface elements. A shear strength reduction factor (Rinter = 0.7) was applied in Plaxis at the interface to match the parameters of the proposed theoretical method.

Model parameters: The piles were located on an underlying soil layer with a depth of 5 m. The pile diameter and the length of the pile were 0.8 m and 20 m, respectively. The thermal expansion coefficient of the pile and the surrounding soil was 0.00001/℃ (usually used in concrete materials) and 0.000001/℃. A thermal load of +20 ◦C was applied on piles. The embankment height was 5 m.

Validation data: results from the theoretical model and the FE model were compared in terms of settlements at the surface of the foundation and settlements along the embankment height. Finally, the skin friction along the energy pile was analyzed. The validation procedure overall demonstrated the adequacy of the theoretical model.

HIGHLIGHTS

Geothermal Energy | De-icing System | Energy pile-supported embankment | Thermal Effect |Settlement

MAIN PURPOSE

Predict the behavior of energy pile-supported embankments by considering the thermo-mechanical stress-strain response of the piles and foundation soil, while analyzing stress continuity and settlement compatibility among the embankments, reinforced foundation, and underlying soil.

SURFACE HEATING SYSTEM

A Hydronic Heating System was selected to heat the surface of the embankment.

GEOTHERMAL HEAT SOURCE

An energy pile system serves as a geothermal energy source for the hydronic system.

APPENDICES SUBTASK4, D4.1: Mapping of demonstration and existing plants

Country	Application	De-icing/ Snow-melting system	Heat source	Required power/energy	Control system/ Operation scheme	Additional information
Sweden						
General cases						
1	Roof	EHPS	-	-	-	Smaller surfaces (e.g., villa entrances, roofs)
2	Railway Switch	EHPS	-	100-130 GWh per year, Plates: power of 100 W	Cable heaters turned on at 6-8 °C outdoor	7000 out of 12300 switches are electrically heated. Future goal: addition of point heaters turned on at 0 °C
3	(Busy) City Centers: Pedestrian streets, sidewalks, squares, public transport stops	HHPS	DH (mostly return)	250-350 W/m^2	Automatically controlled by surface temperature/weather forecasts/manually	At least 600 000 m^2 in total
4	Suburb Areas/outer urban environments: Entrances, sensitive ramps	HHPS	GSHP	-	-	100-300 m^2
5	Stockholm Arlanda Airport: gates and entrances	HHPS	ATES system): waste heat from cooling system. Gates used as solar collectors	-	Automatically controlled	100 000 m^2 of which 75 000 m^2 gates. Supplied heat and cold of 10 GWh/a, respectively.
6	Sport facilities: Football fields (mainly artificial turf), outdoor gyms, water park, ORC track, padel and tennis courts	HHPS	DH/industrial waste heat	Average of 800-900 MWh/field	Not specified/ a case of automatically controlled by temperature and precipitation setpoints	580 000 m^2 (assuming average area of 7000 m^2 per field)
7	Roads and bridge decks with steep slopes and slip-sensitive curves	HHPS	DH return	350 W/m^2	Temperature sensors in pavement	-
Specific cases						

8	Administrative Building (Kristallen) in Lund: Pedestrian/bicycle ramp	HHPS	BTES	-	-	-
9	Prison, Helsingborg: Roof deck rest area, garage ramp	HHPS	ATES	-	-	Rest area: 60 m^2, garage ramp: 40 m^2
10	Football field (artificial turf) in Backavallen, Katrineholm	HHPS	BTES	-	Automatically controlled	400 MWh harvested from solar heat, additional energy from waste heat
11	Entrance of Several IKEAs	HHPS	BTES	-	-	A size of approximately 1 MW
12	Kungsängen Sport Center	HHPS	BTES (waste heat from indoor ice-making)	-	-	40 boreholes, 180 m deep
13	Football field-Täby arena	HHPS	BTES	-	-	90 boreholes, 300 m deep
14	Sport center: Torvalla arena	HHPS	BTES	-	-	91 boreholes, 230 m deep
15	HERO Experimental Site in Östersund: Road	HHPS	BTES/ solar collector	-	-	Road: 20 x 3.5 m^2, 4 boreholes: 210 m depth, supply temperature of 7-8 °C and return of 2-3 °C
16	Snow Dump Melting experiment at Arlanda Airport	HHPS	BTES/ solar collector	55 MWh of heat supplied to melt approximately 600 tons of snow (ice)	-	10 boreholes, 200 m depth, recharged with 90 MWh during summer, an average power of 35 kW
17	Hallsberg Football Field	HHPS	Groundwater from wells/occasionally condenser heat from an ice hockey rink	-	-	Maximum heating capacity: 1500 kW, capable of keeping turf unfrozen at -12°C outdoor, constant ground water temperature of 8°C, max and min supply return temperature

of 14 and 3.5 °C respectively

Country	Application	De-icing/ Snow-melting system	Heat source	Required power/energy	Control system/ Operation scheme	Additional information
Germany						
General cases						
1	Driveways, sidewalks, stairs, roofs	EHPS	-	200-400 W/ m^2 for open spaces, 300-500 W/m^2 for stairs		100-300 operation hours/year
Specific cases						
2	Loading area at Roth Plastic Technology	HHPS	Process waste heat from injection molding production	-	-	750 m^2, Waste heat sufficient for de-icing up to -6 °C
3	Underground parking ramp in Unterföhring	HHPS	Gas condensing boiler	50 kW (278 W/m^2)	Temperature and Humidity sensors, de-icing activates when below 3 °C	180 m^2
4	Metro Station Therese-GiEHPSe-Allee Munich	Multiple solutions: pumped system, Two-phase CO2-thermosyphon system, EHPS	Ground Water/Electric Resistance	250 W/m^2	Temperature and Humidity control	200 m^2, heating medium temperature: 30 °C
5	Canal Bridge Berkenthin	HHPS	Geothermal Wells/ ground water	Two stage heat pump: First stage: 65 kW (110 W/m^2), Second stage: 135 kW (225 W/m^2)	Measurement, control and regulation systems: Temperature control when necessary	Around 600 m^2, Ground water temperature: 11 °C, Heat pump needed, Heat exchanger to increase the heating liquid to 55 °C.
6	Underpass/ Bus lane Bergsonstrasse Munich	Mastic Asphalt System	Groundwater Heat Pump	-	-	400 m^2
7	Garage Ramps at Audi in Ingolstadt	Mastic Asphalt System	Geothermal Energy	-	-	2200 m^2, 20,000 m of tubes
8	Exit ramp: Fire Department Access in Bad Waldsee	CO$_2$-Thermosyphon System	BTES			165 m^2
9	Railway switches: Pintch Aben Geotherm Switch Point Heating System + three other pilot plants with same technology	CO$_2$-Thermosyphon System	BTES	300 W/m of rail, 1000 W/m^2	-	-

10	Railway switches: Triple.S-Systeme Switch Point Heating System technology	HHPS	Ground Source Heat Pump (GSHP), Wells, Geothermal Probes, DH, Waste heat	-	Control based on air temperature, rail temperature, air pressure, humidity, precipitation, and snow drifts	-
11	Railway Platforms: Bad Lauterberg/ Barbis (Harz): Triple.S-Systeme Platform Heating System technology	HHPS	BTES	-	-	600 m², Expected lifetime: at least 10 years, BHs: 9x200 m
12	Tram-Switch Heating technology: Demo plant in Karlsruhe: Vossloh	HHPS	DH	-	-	The technology allows other heat sources such as geothermal
13	Railway Switches: ESA Grimma Switch Point Heating System technology	HHPS	-	-	-	The product is no longer offered due to lack of demand
14	Tram Platform, Switch Heating: Demo plant in Dresden	two-phase Thermosyphon	BTES	Heating output: 5 kW		120 m², BHS: 3 m x 100 m
15	Road: Demo plant in Füssen Border Tunnel	HHPS	Geothermal heat/ Mountain Water	Heating output: 400 W/m²	Automatic control: onsite measurements of climate conditions and forecasts	-

Country	**Application**	**De-icing/ Snow-melting system**	**Heat source**	**Required power/energy**	**Control system/ Operation scheme**	**Additional information**
France						
General cases						
1	Railroad Switches, Sidewalks, Pavement structures	EHPS	Electricity	300 W/m^2	Automatic control systems available	Total installation cost: €50-100/m^2; Electricity prices: €0.20-0.25/kWh in 2024
2	Football fields	EHPS/HHPS	Gas or Electricity	-	Control of temperature and working hours	90 % of the fields in France are equipped with de-icing/snow-melting system. Construction cost: €250,000 - €1,000,000,

						Energy cost: €25,000 - €140,000, The cost of the cancelation of a game: up to 250 000 €.
Specific cases						
3	Road Pavement: Demo plant in Lyon-ICCAR project	Electroconductive paint	Electricity	-	-	Undergoing research project; optimization of thermal properties; automatic control system development
4	Road surface: Demo plant- Power Road in Egletons	Asphalt solar collector & EHPS 'Power Road'	Solar radiation	-	-	660 m^2, Connected to the city DH, Construction cost: 250000 €
5	Roadway de-icing, Building heating: Autoroute A10 in Saint-Arnoult-en-Yvelines	Energy-positive asphalt	Geothermal (vertical probes), heat pump	-	Remote monitoring and maintenance, Energy exchange monitoring	500 m² of roadway for de-icing, plus energy storage for heating building floors
6	Porous asphalt: Demo plant-Dromotherm project in Chambéry	Asphalt solar collector using porous asphalt	Solar radiation TTES		-	TTES: 40 m^3, Undergoing research project 2020-2024

Country	Application	De-icing/ Snow-melting system	Heat source	Required power/energy	Control system/ Operation scheme	Additional information
Belgium						
General cases						
1	Pedestrian streets, entrences, fotbool fields	HHPS	DH, Heating/Ventilation air volumes from building	-	-	-
2	Entrances, ramps	EHPS	Electricity	-	-	-
Specific cases						
3	Bicycle path at University of Antwerp - Demo plant: Heat exchange asphalt layer (HEAL)	Heat Exchanging Asphalt Layer (HEAL)	Solar radiation/ BTES	-	Temperature control	65 m², two BHs with a depth of 100 m. Supply temperature up to 35 °C in wintertime using the

						boreholes and a heat pump.
4	Underfloor heating, DHW production: Zonnige kempen social housing complex	Asphalt Solar Collector with ground storage and solar collectors	Solar collectors, Ground storage	-	Central control system with priority given to domestic hot water production before underfloor heating	13 homes (social housing), During first 4 months: 13,201 kWh of electricity used to produce 46,191 kWh of heat. 32% energy savings, COP of 3.5

Country	**Application**	**De-icing/ Snow-melting system**	**Heat source**	**Required power/energy**	**Control system/ Operation scheme**	**Additional information**
Italy						
General cases						
1	Residential ramp tracking, Exterior stair tracking, Helicopter area	EHPS	Electricity	-	Continuous power supply	High power demand, 100-300 operational hours per year
Specific cases						
-	-	-	-	-	-	

Country	**Application**	**De-icing/ Snow-melting system**	**Heat source**	**Required power/energy**	**Control system/ Operation scheme**	**Additional information**
Türkiye						
General cases						
1	Roofs	EHPS	Electricity	Minimum 30 W/m at 10 °C	-	-
2	Ramp and roads	HHPS/ EHPS	Electricity, Hot Water, Geothermal Fluid	300-500 W/m^2, 85 W/m^2 in Istanbul	Air and humidity sensors	-
3	Football Fields	HHPS/ EHPS	Natural Gas/ Electricity			HHPS: 157,080 m^2, Electrical: 71,400 m^2, Design parameters: outdoor temperature -10 °C, 50°C supply, 34°C return
4	Stadiums, Shopping Malls, Ramps/Parking Areas, Highways, Airport Connection	EHPS	Electricity	Heat output: 18-30 W/m or 300-375 W/m^2 for the cities of	Air and humidity sensors	

	Roads, Bridges/Intersections, Greenhouses, Helipads			Ankara, Istanbul and Erzurum		
Specific cases						
-	-	-	-	-	-	

Country	**Application**	**De-icing/ Snow-melting system**	**Heat source**	**Required power/energy**	**Control system/ Operation scheme**	**Additional information**
Japan						
General cases						
1	Ground and Roof	Sprinkled Snow-melting: Pipe buried/Bleeding	Groundwater, River water, Sea water, Hot spring water, Urban drainage			Suitable for warm snowy areas: temperature in January above 0 °C
2	Ground and Roof	Non-Sprinkled Snow-melting: hot water pipe/Heat pipe	Groundwater heat, geothermal heat, solar heat, air heat, wind power, seawater/lake heat, woody biomass	-	-	-
3	Turnouts and railway tracks	Electric cables and Hot Air Snow-melting	Electricity	-	-	-
Specific cases						
4	Road Heating in Sapporo city	EHPS/ HHPS	Electricity, gas, hot water, hot spring water		Based on weather data using multi-sensor in each area of 4-5 km mesh: (snowfall, temperature, wind speed)	52 Km/ 221000 m^2, 84% electric, 11% gas hot water system, 5% hot spring water