International Energy Agency
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(ES TCP)

Task 38- "Ground Source De-Icing and Snow Melting Systems for Infrastructure"

Subtask 4:

Planning, construction, and monitoring

Deliverable 4.1:
Mapping of demonstration and existing plants

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PREFACE

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.

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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.

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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LIST OF ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
DH	District Heating
DHW	Domestic Hot Water
EHPS	Electric Heated Pavement System
GSHP	Ground Source Heat Pump
HHP	Hydronic Heated Pavement
HHPS	Hydronic Heated Pavement System
TRL	Technology Readiness Level

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.

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 1.

2.1 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.

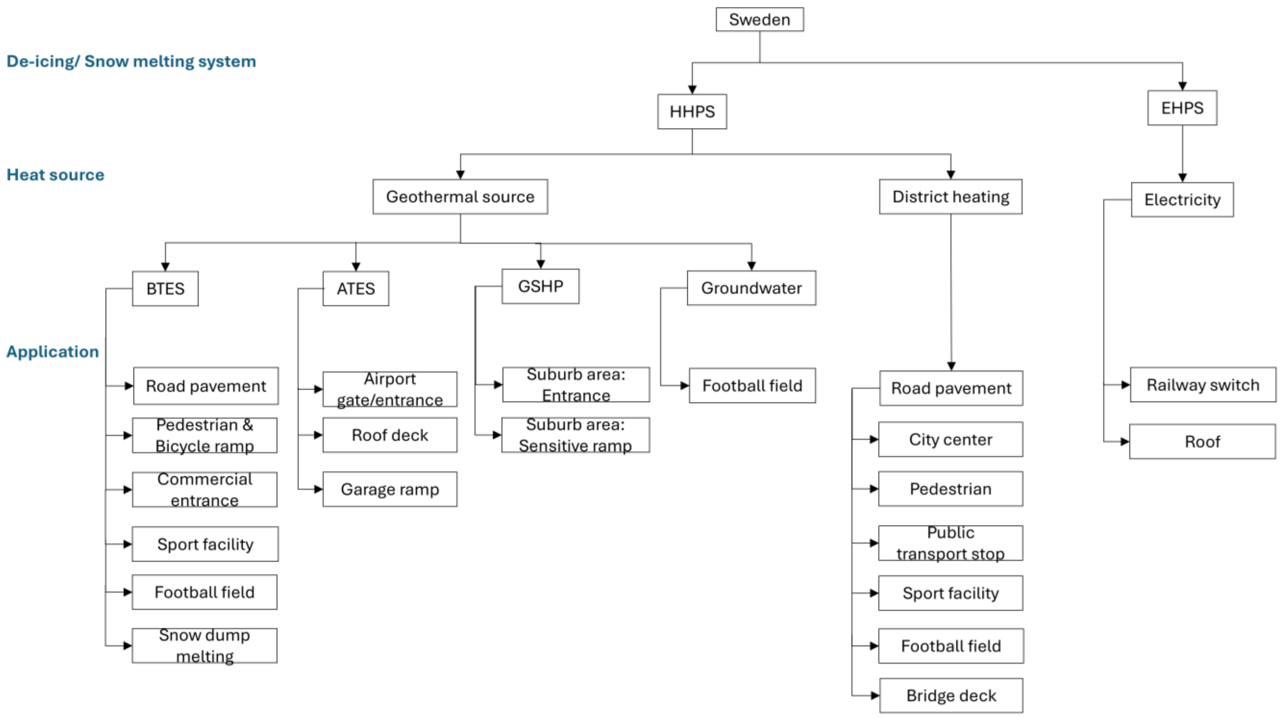

Figure 1. General mapping of de-icing and snow-melting applications in Sweden, describing the utilized techniques and the corresponding heat sources.

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 m² across Swedish cities, with power demands ranging from 250 to 350 W/m² and annual energy consumption of 300-350 kWh/m². 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.

2.2 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 2 and Figure 3 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.

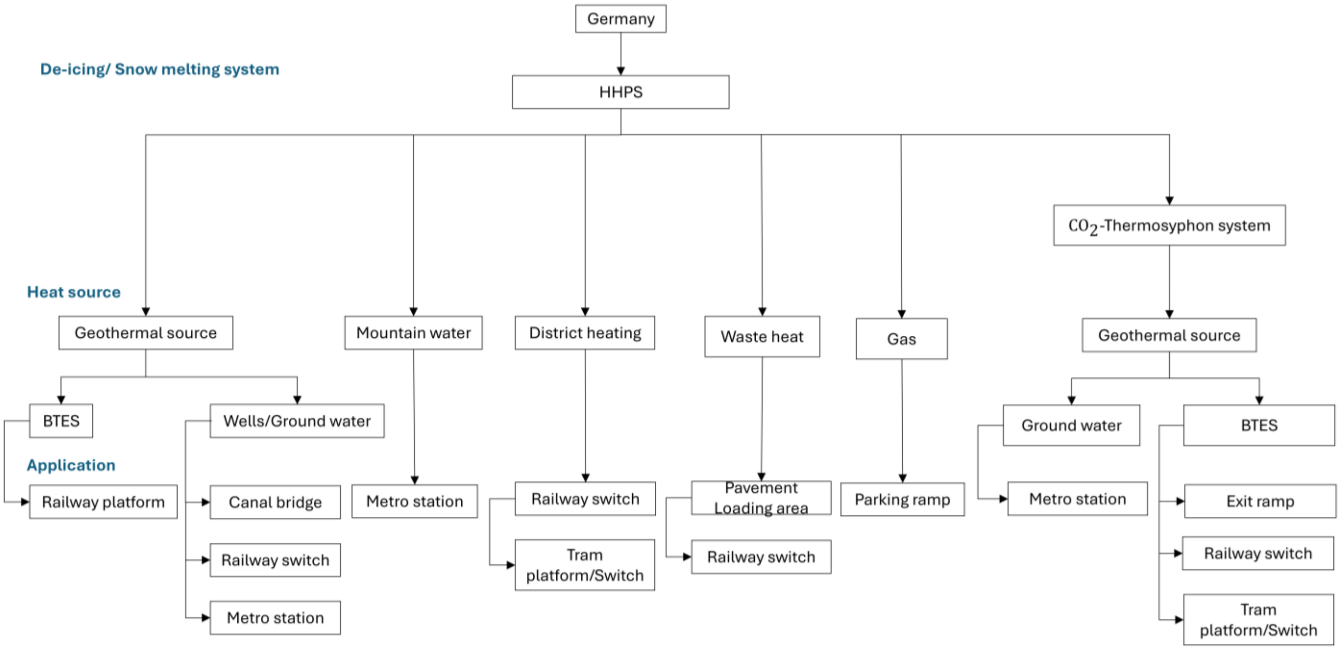

Figure 2. General mapping of de-icing and snow-melting applications in Germany utilizing hydronic heated pavement system, and the corresponding heat sources.

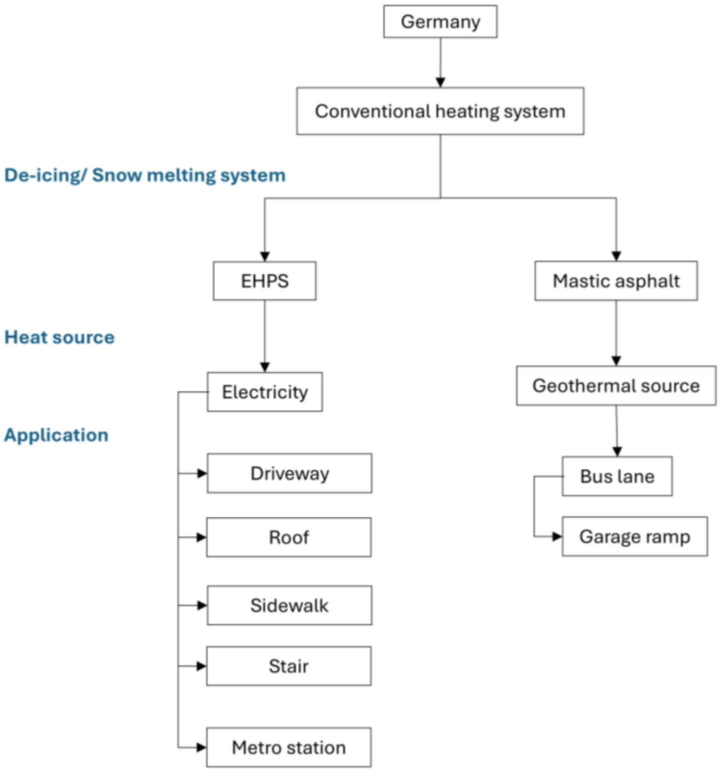

Figure 3. General mapping of de-icing and snow-melting applications in Germany utilizing non-hydronic heated pavement system, and the corresponding heat sources.

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/m^2, (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.

2.3 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 4 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.

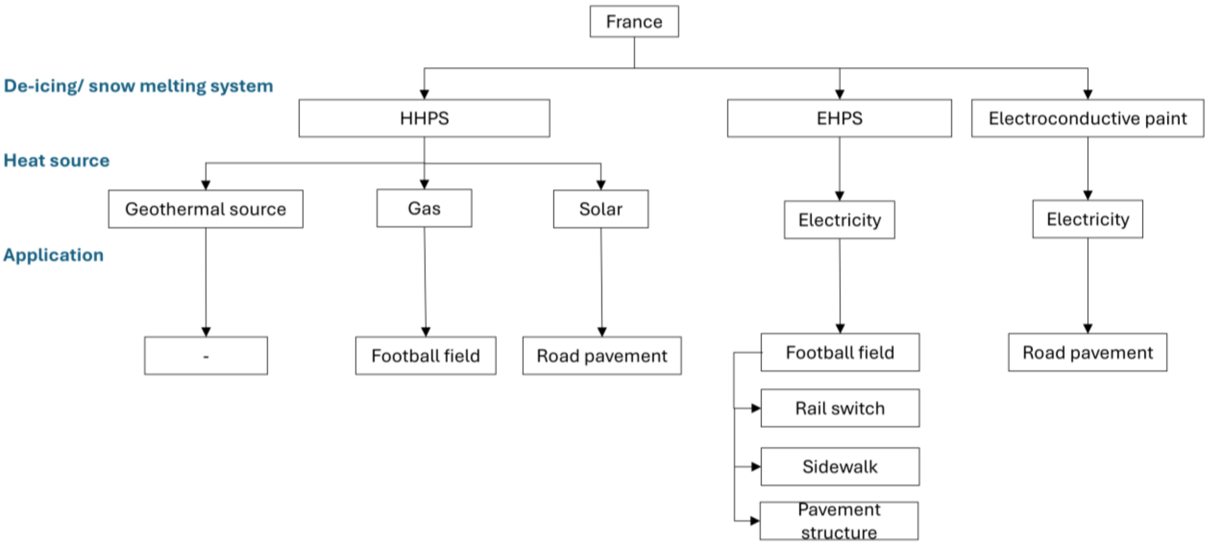

Figure 4. General mapping of de-icing and snow-melting applications in France, describing the utilized de-icing systems and the corresponding heat sources.

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 m² in France, with typical energy consumption around 300 W/m².

- 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/m².
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.

2.4 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 5 presents a general mapping of these systems, while the table in the appendix1 provides details on various projects and technologies.

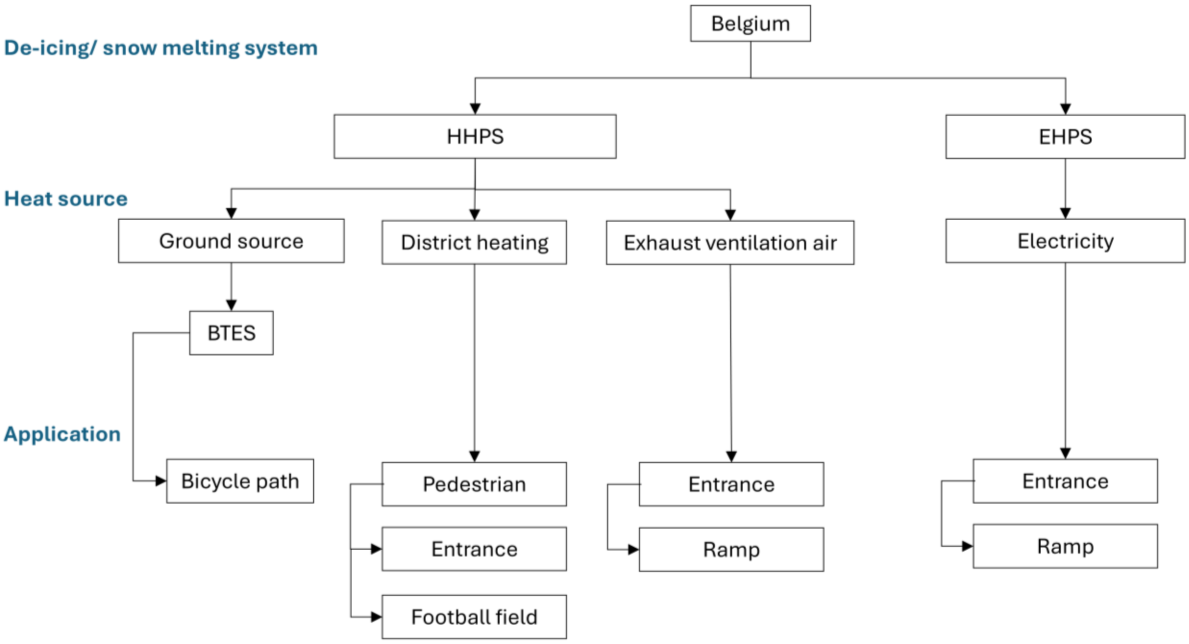

Figure 5. General mapping of de-icing and snow-melting applications in Belgium, describing the utilized de-icing systems and the corresponding heat sources.

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.

2.5 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 6 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.

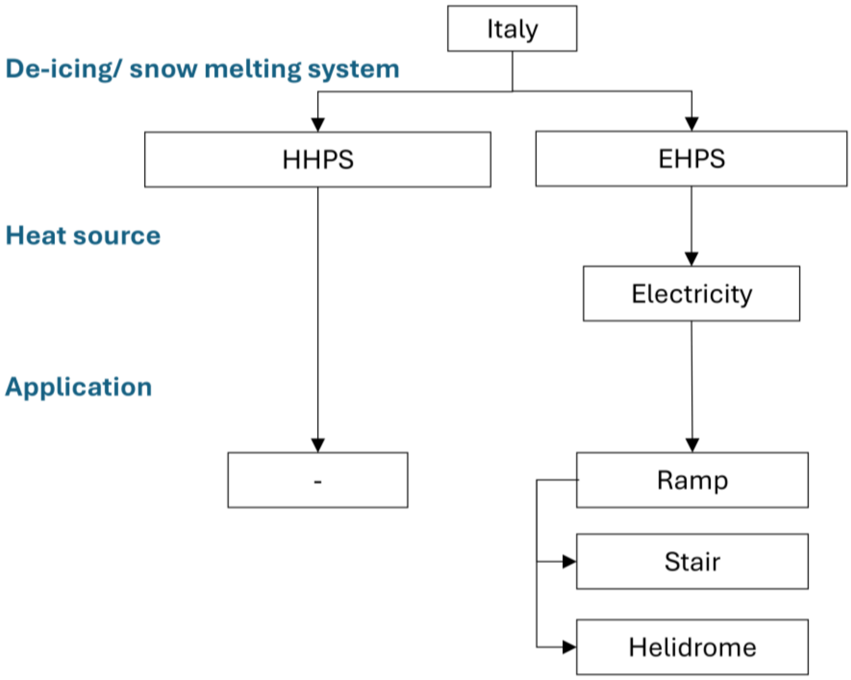

Figure 6. General mapping of de-icing and snow-melting applications in Italy, describing the utilized de-icing systems and the corresponding heat sources.

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.

2.6 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 7 presents a general mapping of these systems and their associated heat sources, while Table 4 summarizes typical power and energy demands.

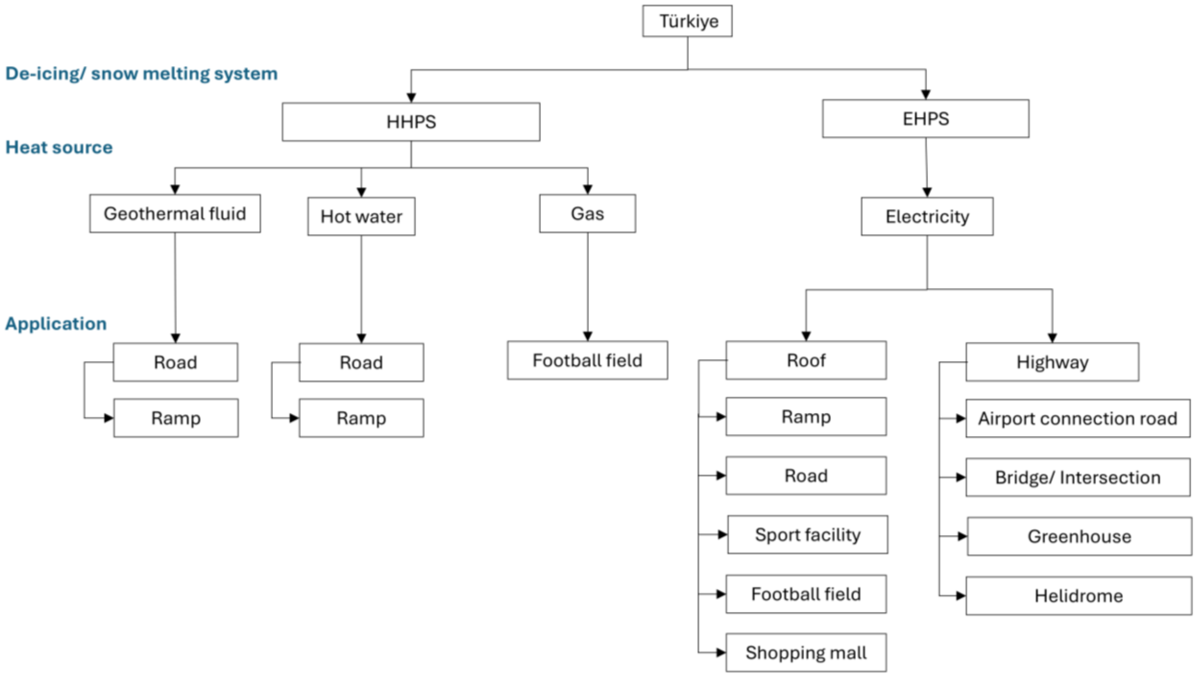

Figure 7. General mapping of de-icing and snow-melting applications in Türkiye, describing the utilized de-icing systems and the corresponding heat sources.

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.

2.7 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.

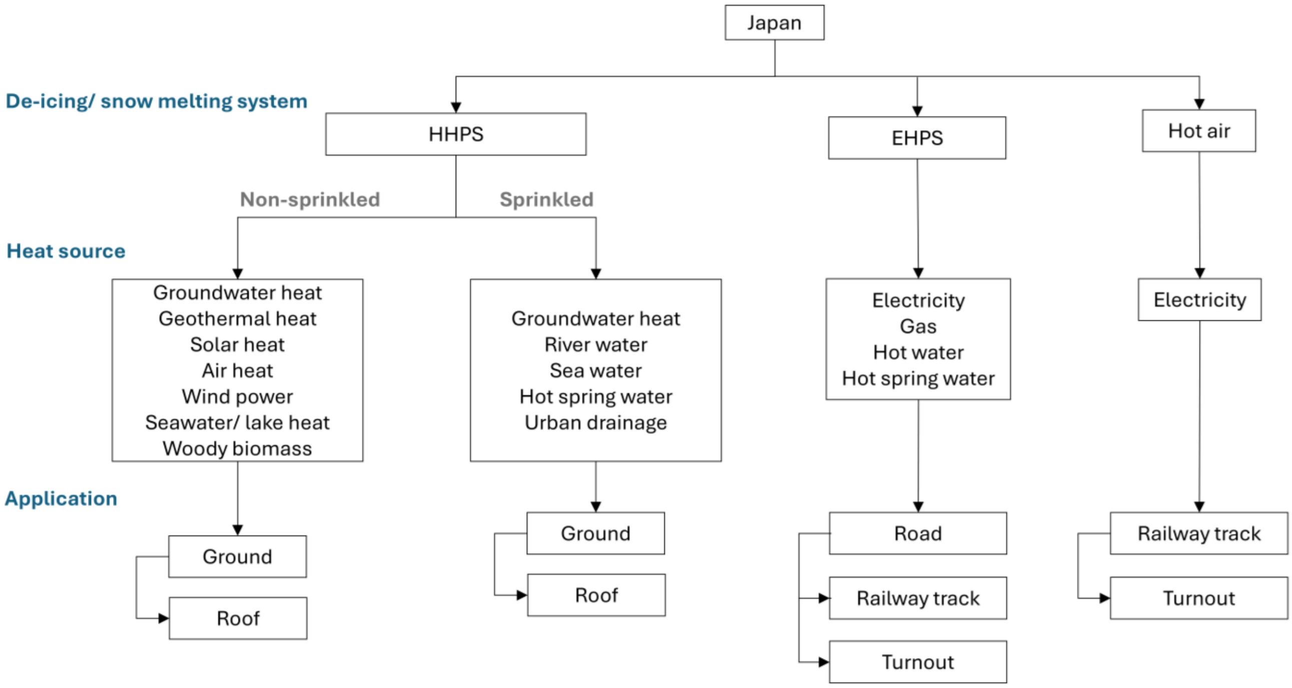

Figure 8. General mapping of de-icing and snow-melting applications in Japan, describing the utilized de-icing systems and the corresponding heat sources.

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.

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.

3.1 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

3.1.1 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.

3.1.2 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.

3.1.3 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.

3.1.4 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.

3.1.5 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.

3.1.6 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.

3.1.7 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.

3.1.8 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.

3.2 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:

3.2.1 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.

3.2.2 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.

3.2.3 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.

3.2.4 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.

3.2.5 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.

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.

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APPENDIX 1

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/m²)	Temperature and Humidity sensors, de-icing activates when below 3 °C	180 m²
4	Metro Station Therese-GiEHPSe-Allee Munich	Multiple solutions: pumped system, Two-phase CO2-thermosyphon system, EHPS	Ground Water/Electric Resistance	250 W/m²	Temperature and Humidity control	200 m², heating medium temperature: 30 °C
5	Canal Bridge Berkenthin	HHPS	Geothermal Wells/ ground water	Two stage heat pump: First stage: 65 kW (110 W/m²), Second stage: 135 kW (225 W/m²)	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 m²
7	Garage Ramps at Audi in Ingolstadt	Mastic Asphalt System	Geothermal Energy	-	-	2200 m², 20,000 m of tubes
8	Exit ramp: Fire Department Access in Bad Waldsee	CO_2-Thermosyphon System	BTES			165 m²
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/m²	-	-
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):	HHPS	BTES	-	-	600 m², Expected lifetime: at least 10 years, BHs: 9x200 m

	Triple.S-Systeme Platform Heating System technology					
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/m²	Automatic control systems available	Total installation cost: €50-100/m²; 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 m², Connected to the city DH, Construction cost: 250000 €

Country	Application	De-icing/ Snow-melting system	Heat source	Required power/energy	Control system/ Operation scheme	Additional information
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 m², Electrical: 71,400 m², Design parameters: outdoor temperature -10 °C, 50°C supply, 34°C return
4	Stadiums, Shopping Malls, Ramps/Parking Areas, Highways, Airport Connection Roads, Bridges/Intersections, Greenhouses, Helipads	EHPS	Electricity	Heat output: 18-30 W/m or 300-375 W/m^2 for the cities of Ankara, Istanbul and Erzurum	Air and humidity sensors	
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 ℃
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