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Task 38

“Ground Source De-Icing and Snow Melting Systems for Infrastructure

Executive Summary of Final Report

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Task Manager ES TCP Task 38:
Bijan Adl Zarrabi
Chalmers University of Technology
Sweden

energy storage

AUTHORS

Bijan Adl-Zarrabi, Chalmers University, Sweden

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LIST OF ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger (includes the boreholes if grouted)
BTES	Borehole Thermal Energy Storage
COP	Coefficient of performance (in this study for heat pumps + heat carrier pumps)
CTES	Cavern Thermal Energy Storage
DH	District Heating
DTH	Down the hole hammer drilling
EED	Earth Energy Designer (a simulation tool for boreholes)
FEP	Foundation Energy Piles
GHG	Green House Gas
GSHP	Ground Source Heat Pump
GST	Ground Source Thermosyphon
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	Polyethylene (as in plastic pipes)
PTES	Pit Thermal Energy Storage
PEX	Cross-linked polyethylene (for hot water)
SPF	Seasonal Performance Factor
UTES	Underground Thermal Energy Storage

KEY MESSAGES AND POLICY RECOMMENDATIONS

1. Sustainable Winter Maintenance: Ground Source Hydronic Heated Pavements (HHPS) powered by geothermal energy are highly effective for snow and ice removal. They enhance safety, reduce greenhouse gas emissions, and eliminate the need for de-icing chemicals. Demonstration projects in Iceland, Japan, Germany, and Sweden have proven their efficiency, with low operational costs and broad applicability.
2. Integration with Thermal Energy Storage (TES): Coupling HHP systems with Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES) enables seasonal energy storage, optimizing and minimizing energy (electricity) use, reducing greenhouse gas emissions, and ensuring availability during peak winter demand. Solar energy harvesting integrated with UTES enhances efficiency and sustainability.
3. Proven Feasibility and Market Potential: Hydronic Heated Pavement (HHP) are widely spread in several countries and are typically heated by electricity (electric heating cables), fuel boilers, or district heating. The global market for these systems is steadily growing with an annual rate of approximately 6%, the market size expected to reach USD 7.6 billion by 2033. In a study related to payback periods for different type of HPPS, the payback time ranging from 2–8 years (report subtask 1.2), depending on system configuration and scale. So far only a limited number of applications use geothermal energy as a heat source. Projects like HERO in Sweden, HEAL in Belgium, and advanced installations in Japan and Iceland illustrate the benefits of ground source systems. In the HERO project [16] a solar heat harvesting efficiency of 42% was measured representing some 380 kWh/m2. 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. However, in that case the road had an insulating layer beneath the heat collection pipes. Thus, the energy for heating the road can be covered, which dramatically increases the efficiency of the system.
4. Technology and Regulatory Needs: Scaling up requires advancements in control systems for instance, adding a local climate station which by gathering weather condition and weather forecasting assisting to an advance controlling procedure, material durability improvements need to estimate the lifetime of the system which lead to a more accurate payback time, and supportive regulations for effective energy distribution and system longevity. Standardizing system modeling and validation processes will further enhance reliability.
5. Overcoming Barriers and Expanding Adoption: Addressing high initial costs which can be compensated with free of charge ground heat energy during operation of the system, awareness gaps, and regulatory hurdles is crucial for wider adoption. Promoting integration with existing GSHP systems and demonstration projects in various applications (e.g., pedestrian zones, sports fields, bridges) is key to building momentum.

Policy Recommendation:

1. Government Support and Partnerships: Tax incentives and foster public-private partnerships for integrating HHPS and TES technologies. Streamline permitting open-loop systems (ATES, GWHP) to unlock market potential.
2. Standards and Best Practices: Establish guidelines for design, installation, and integration with TES to ensure reliability and efficiency. Include HHPS in climate adaptation and public safety strategies in urban planning.

3. Support Innovation and R&D: Increase funding for research in durable materials, control systems, and hybrid energy configurations (combine two or more distinct power generation and/or storage technologies to improve efficiency, reliability, and stability). Encourage pilot installations to showcase feasibility and benefits across climates.
4. Climate-Adapted Infrastructure: Encourage integration of ground source systems in critical infrastructure like airports, railways, and pedestrian areas. Promote multi-use designs that combine snow melting with summer heat harvesting. Harvesting energy by hydronic system can reduce the temperature of pavement which can lead to prolongation of lifetime of a pavement. Furthermore, hydronic pavement can reduce the urban heat island in warm climate.
5. Knowledge Sharing and Capacity Building: Promote international cooperation, training, and technology transfer for widespread adoption. Establish a shared database of case studies and performance metrics to support global learning and technology scaling.

MAIN RESULTS IN A NUTSHELL (1–2 PAGES)

Introduction:

The international collaboration under IEA ES Task 38 "Ground Source De-Icing and Snow Melting Systems for Infrastructure" has yielded significant advancements in utilizing ground source energy for sustainable winter maintenance. Spanning across demonstration projects in Sweden, Belgium, Japan, and other participating nations, Task 38 has explored innovative designs, market potential, and technological breakthroughs for hydronic heated pavements (HHP) powered by geothermal energy and thermal energy storage (TES).

Key Findings:

Ground Source Hydronic Heated Pavements (HHPS) Effectiveness:

- HHPS systems using geothermal energy provide efficient snow and ice removal, enhancing safety, increasing accessibility, reducing single fall accidents in urban areas and reducing greenhouse gas emissions. Furthermore, a HHPS system can be used in warm climate for reducing the effect of the urban heat islands. Demonstration projects, such as those in Iceland, Sweden, and Japan, showcased increase mobility, expected to reduced maintenance costs and reduce environmental footprint by minimized chemical runoff.

- Harvesting energy by pavement and seasonal energy storage through Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES) optimizes energy utilization during winter months, with significant greenhouse gas reductions compared to electric or chemical-based methods.

Integration of Solar Energy Harvesting and Thermal Storage:

- The combination of hydronic heated pavements (harvesting solar energy by the surface) and underground thermal energy storage (UTES) has proven to be a sustainable solution for urban infrastructure.

- In pilot project Östersund, the total accumulated energy during 15 May and ended on the of August was 17 200 kWh, which is equivalent to 245 kWh/m2, whereas the total amount of incoming solar radiation was 614 kWh/m2. Furthermore, the surface temperature of the pavement was 7-10 C lower than reference pavement. Pilot projects demonstrated that solar energy collected during the summer can be stored in UTES systems and used efficiently for snow melting in winter, significantly lowering operational costs and environmental impact.

Technological Innovations and System Design Improvements:

- Advances in heat exchanger design, control systems, and predictive modelling have improved the efficiency and reliability of HHPS.

- Design guidelines for optimal pipe spacing, material choice, and heat source integration were established, enhancing the performance and durability of pavement heating systems.

- Numerical modelling efforts have contributed to optimizing geothermal heat flux, fluid circulation patterns, and the calibration of real-world applications, ensuring accurate performance predictions.

Demonstration Projects and Market Insights:

- The HERO project in Sweden and HEAL in Belgium demonstrated the effectiveness of HHPS in urban and rural infrastructure, with significant energy savings and enhanced safety.

- Mapping existing installations across Europe identified successful hydronic heated system projects in pedestrian walkways (600000 m^2, Sweden, mainly heated by district heating), ramps (2200 m^2 , Germany, geothermal energy), sports 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). Transition of other energy sources to ground source energy/renew able system is technically possible by utilization of hydronic heated pavement system.

- Market analysis highlighted a growing interest in energy-harvesting pavements and solar-assisted de-icing technologies, driven by urban resilience strategies and smart city initiatives.

Conclusion:

The work conducted within Task 38 underscores the feasibility and market potential of geothermal-based hydronic heated pavements for sustainable winter maintenance. 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. Utilization of hydronic heated pavement in urban areas reduces the fall accidents which reduce society cost for health care. Integration with TES systems and solar energy harvesting by surface of a pavement presents a robust pathway towards climate-resilient urban infrastructure which includes also mitigation of urban heat island.

Thermal storage facilities are essential to fully utilize the potential of the hydronic heated pavements. It is well known that the larger storage, the lower CPAX. It is necessary to find more economically feasible storage for smaller systems.

Future efforts should focus on standardizing design practices, enhancing real-time control mechanisms. Almost all infrastructures such as roads, streets, bicycle paths, airports, etc. administered by public sector and the payoff time för the infrastructures are already too long thus, fostering public-private partnerships is necessary to scale these technologies across broader applications in Europe and beyond.

EXECUTIVE SUMMARY

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.

1.1 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.

1.2 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

1.3 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

1.4 Duration of Task

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

1.5 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)

1.6 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 Summary of Subtasks

2.1 Task 1: Market potential and State-of-the-Art

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.

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

The report summarizes the state-of-the-art technologies, market conditions, and applications of ground source de-icing and snow melting systems across participating countries (Belgium, France, Germany, Italy, Sweden, Türkiye) and selected non-participating countries.

Technology Overview: The primary system discussed is the Hydronic Heated Pavement System (HHPS), which uses embedded piping beneath surfaces to circulate heated fluid. These systems can be powered by: Ground Source Heat Pumps (GSHP), Underground Thermal Energy Storage (UTES) such as Borehole (BTES) or Aquifer (ATES), Solar heat harvesting, High-temperature geothermal water (in regions like Iceland and Japan).

Key design parameters include: The heat load is in the rang 200–350 W/m². The heat load demand depends on the desired application, namely deicing or snow melting. Supply temperature varies between 10 to 35°C which depends on if the system is a low temperature system or the system utilizes the return pipe temperature in a district heating system. Heat carrier fluid is water with antifreeze (glycol or ethanol).

Applications: Ground source de-icing systems are used for following applications:

Roads, ramps, bridge decks, Sidewalks and pedestrian zones, Railway switches and platforms, Sports fields (e.g., soccer pitches), Airport gates and helicopter pads

Environmental and Social Benefits: Ground source de-icing systems emit significantly less CO_2 than electric or fossil-fuel systems, eliminate de-icing chemicals, prevent corrosion and environmental contamination. Furthermore, it improves safety, reduces pedestrian falls and traffic accidents, . enhanced accessibility and supports mobility for vulnerable populations. Finally, extend infrastructure lifespan by preventing freeze-thaw damage.

Economic Considerations: While initial investment costs are high, operational and maintenance costs are low. Cost-effectiveness improves when systems are integrated with existing GSHP installations.

BTES systems show strong economic viability, while ATES and GWHP systems depend on site-specific conditions and permitting.

Global Status
Iceland and Japan lead global adoption, Germany and USA have multiple full-scale installations. Sweden uses district heating extensively, with emerging GSHP applications. Belgium, France, Türkiye, and Italy show potential but limited implementation.

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

This report evaluates the market potential of using shallow geothermal energy as a heat source for Hydronic Heated Pavement (HHP) systems, which are used for de-icing and snow melting in infrastructure. It builds on the previous state-of-the-art report (D1.1) and includes technical evaluations, scenario analyses, and environmental impact assessments.

Ranking of potential for Ground source heating: 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 commercial on the heating and cooling market.
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 1 of D1.2. The result of the ranking is shown in Table 1 followed by a description of factors used for the ranking.

Table 1. Ranking potential ground source systems as a heat source for HHP applications (+ = low; +++++ = high), SPF is Seasonal Performance Factor.

System Type	SPF Range	Market Potential	Notes
GSHP (with space heating)	3–4	★★★★★	Low investment, high synergy
BTES	8–13	★★★★☆	High efficiency, long lifespan
HT-BTES	20+	★★★★☆	Uses surplus heat, no heat pump needed
GWHP	8–14	★★★☆☆	High efficiency, limited geological availability
ATES	10–15	★★★☆☆	Excellent performance, permit challenges

Scenario analyses: A scenario analysis was performed to estimate the payback time, investment and seasonal performance factor. The results of the analysis are presented in Table 2.

Table 2. SPF and payback time for Different applications and systems

Scenario	**Application**	**SPF**	**Payback Time**	**Investment (€)**	**Annual Savings (€)**
1	GSHP + HHP (200 m²) for minor systems	3.0	1.9 years	15,000	8,000
2	GWHP for shopping center (4,000 m²)	12.5	4.6 years	275,000	62,700
3	BTES for city walkways (10,000 m²)	9.1	7.8 years	2,710,000	351,000
4	HT-BTES with surplus heat, Pedestrian streets	20.0	5.0 years	1,900,000	380,000
5	BTES for slippery road (1,000 m²)	12.5	7.2 years	320,000	44,500
6	ATES for road section	13.9	6.1 years	260,000	42,500
7	BTES for sports arena	11.4	7.6 years	1,360,000	178,000

Environmental analyses: 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, however, shallow geothermal borehole systems cause some CO2 emissions by drilling of boreholes, drilling equipment and components. 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.

Table 3. 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

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

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 modeling 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.

2.2.1 Deliverable 2.1: The State of the Art in System Modelling and Design Load Assessment

The objective is to evaluate and compare modeling approaches for HHPS using geothermal energy. Over 20 case studies were analyzed, covering numerical simulations, laboratory experiments, and full-scale prototypes. A database was created to extract technical parameters and modeling strategies.

Figure 1. Location of case studies analyzed

System Components and Modeling: 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. HHPS systems typically include a heated pavement surface, a geothermal heat source (e.g., GSHP, BTES, ATES), and a control system. Modeling these systems requires accounting for climatic conditions, heat flux requirements, and geothermal resource characteristics.

Modeling Approaches: Modeling HHPS involves complex heat and mass transfer mechanisms, dynamic weather conditions, and system control strategies. Approaches range from 1D steady-state models to 3D transient simulations using tools like COMSOL Multiphysics. Key performance indicators include heat flux requirements, surface temperature maintenance, and system efficiency. 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, for instance, Heat and mass transfer mechanisms of the snow-melting process involves complex phase change phenomena or 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, furthermore, dynamic weather conditions i.e. 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.

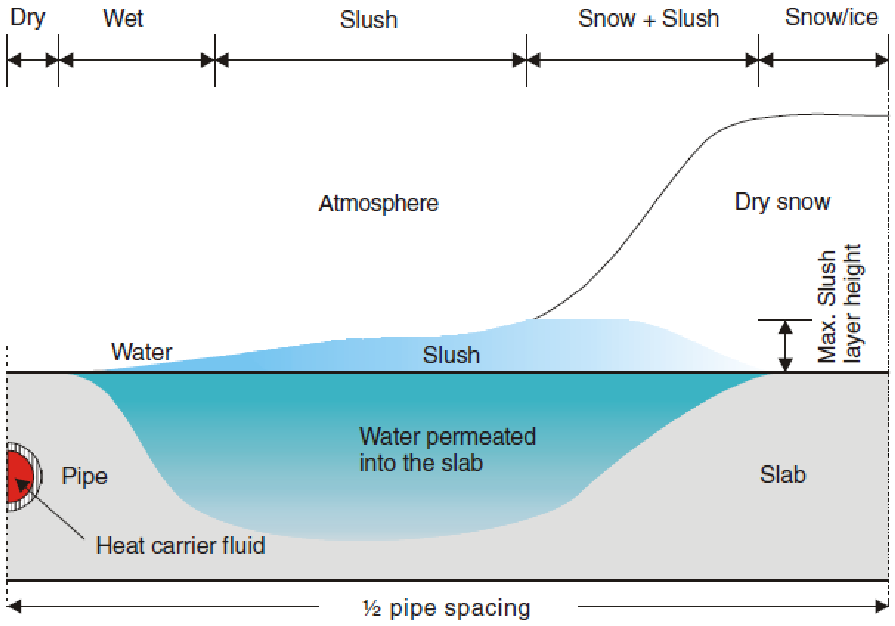

Figure 2. Variation of surface condition on a heated pavement slab during the snow melting process

Operational strategy: Three operational strategies were identified: low-power continuous heating for sports fields, high-power intermittent heating for urban environments, and continuous high-power heating for airports. The choice of strategy significantly affects energy consumption and system efficiency.

Case studies from China, the United States, and Europe demonstrated the effectiveness of various modeling approaches. COMSOL Multiphysics was frequently used for 3D simulations, while steady-state and transient models helped define heat flux requirements. The SERSO system in Switzerland and the Gaia system in Japan exemplify successful integration of solar and geothermal energy for snow melting.

2.2.2 Deliverable 2.2: Assessment of Model Capabilities and Validation Processes

The report analyzes numerical models simulating thermal and mechanical performance of de-icing systems by reviewing four case studies, each employing different modeling approaches and validation techniques.

The reviewed models demonstrated strong alignment with experimental data, particularly in steady-state conditions. However, calculation of transient conditions was less aligned with the experimental data due to strong variation of outdoor conditions.

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 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 modeling of climate condition.

The report underscores the effectiveness of integrating experimental and numerical approaches for optimizing HHPS systems. Future research should focus on field-scale validation, multi-physical coupling, and long-term performance analysis to enhance the reliability and sustainability of geothermal de-icing technologies.

2.3 Task 3: Development of system components for selected applications

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 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.

2.3.1 Deliverable 3.1&2: Thermal design of the heating surfaces & Mechanical requirements of the surface heating system when required

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.

Classification of loading: one of the major concerns of engineers is the structural behavior of a pavement with embedded pipes in the pavement. 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).

Hydronic heated pavement: The configuration of HHPS incorporates three primary components: the HHP, Borehole Heat Exchanger (BHE), and control system. The HPP includes the piping network, and the pavement material i.e. asphalt, concrete and stone. Definition of HHP components and sub-components, outlining their characteristics and material specifications were performed. −Evaluation of the mechanical response of HHPs, addressing provisions for the construction phase and necessary post-construction measures.

Figure 3. Post-failure resistance behavior of reference and HHP specimens in ITS test

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

Sensitivity analysis: Sensitivity analysis of key parameters affecting thermal performance, focusing on geometrical specifications, thermophysical properties, and operational conditions were performed by reviewing the papers and reports concerning different HHPS. The results of a study related to location (depth and spacing) of the pipes in a pavement is shown in figure 5. The supply temperature in this study was 25-35°C.

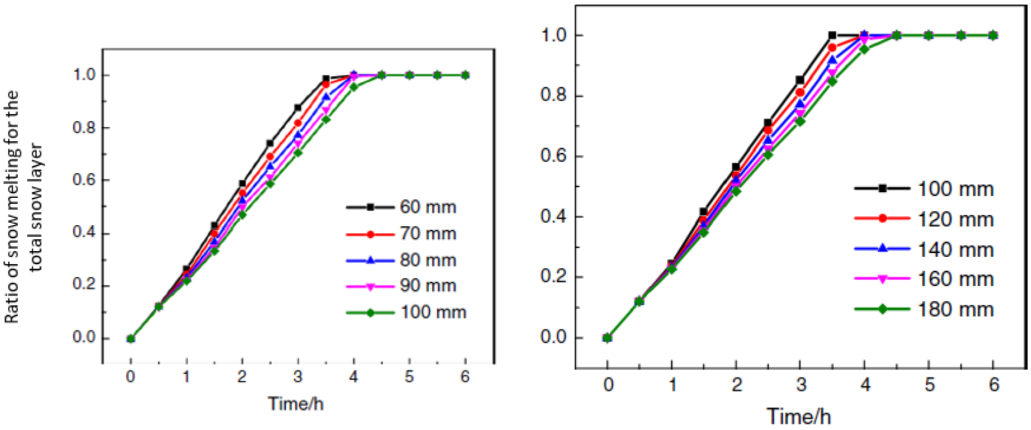

Figure 5. Melting ratio of snow at different (left) embedded pipe depths (right) pipe spacings

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.

Key Findings:

- Pipe material selection and placement significantly affect thermal distribution, mechanical stability, and pavement performance. Polyethylene pipes are preferred for their cost-effectiveness and corrosion resistance.

- Control systems integrate heat pumps, buffer storage, sensors, and weather stations to regulate fluid temperature and flow. Real-time monitoring enhances system efficiency and reliability.

- Geothermal energy and seasonal heat storage systems are viable sources for HHPs, reducing reliance on conventional energy.

- Experimental and numerical studies show that pipe spacing, depth, diameter, and fluid temperature are critical parameters influencing snow melting efficiency and heat harvesting capacity.

- Mechanical challenges include cracking due to stiffness differences, inadequate compaction, and rutting. Innovative construction techniques and material selection help mitigate these issues.

- Recommendations include using elastomer-modified bitumen for pipe coating, optimizing aggregate size for compaction, and ensuring minimum asphalt thickness above pipes.

2.3.2 Deliverable 3.3: Materials for geothermal heating systems

The report D3.3: '*Thermal vs. structural performance - Suggestions to facilitate system development for further applications*' explores the interplay between thermal and structural aspects, analyzing 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.

- **Evaluated the heat harvesting**: 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 influence the amount of the harvested energy. The influence of pipe length and embedded pipe depth is presented in figures 6-7.

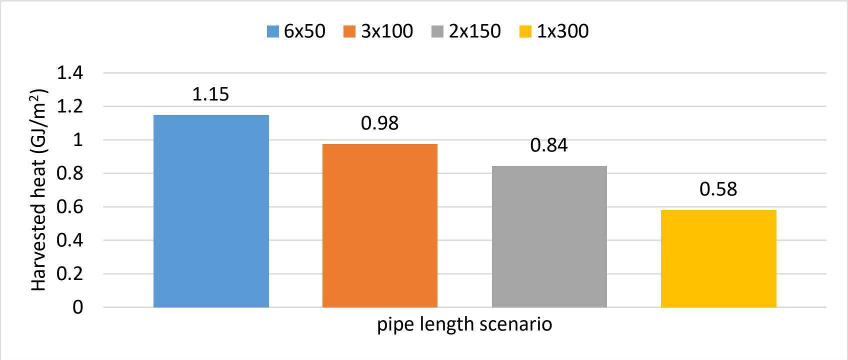

Figure 6. Total yearly heat harvesting capacity for various pipe section length for the following design parameters: flow rate 180 l/hour, embedded pipe depth 7.5 cm, and water inlet temperature 12 °C

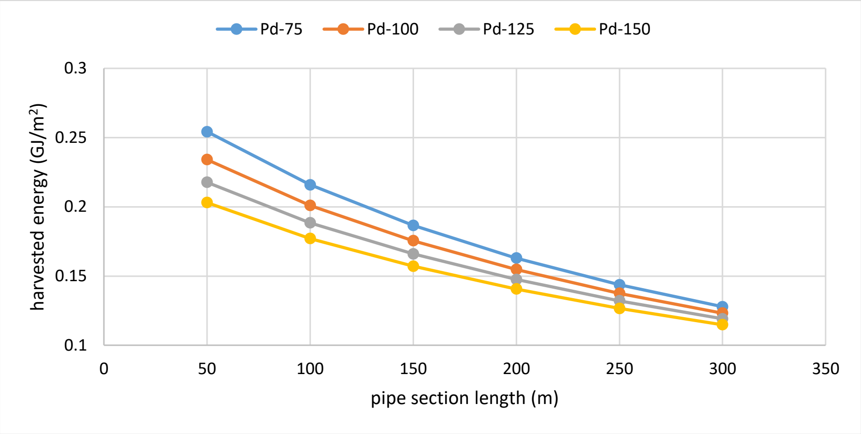

Figure 7. Harvested monthly energy vs. embedment depth for various pipe section lengths for June 2020 with the following design parameters: flow rate 180 l/hour and water inlet temperature 12 °C

Energy demand during Wintertime: using advanced control mechanisms, including adaptive temperature modulation and real-time monitoring, optimize energy demand of the system during wintertime. Furthermore, pre-heating strategies to keep pavement surfaces above freezing before snow events will reduce overall energy demand.

Material improvement: 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. 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.

Key Findings:

- Thermal efficiency of HHPs in harvesting mode ranges between 20% and 30%, with some studies reporting up to 50%.
- Pipe spacing, flow rate, inlet temperature, and embedment depth significantly affect performance of the system.

- Solar absorptivity of pavement surfaces declines over time, reducing heat harvesting capacity.
- Pre-heating strategies and adaptive control systems improve operational efficiency.

The D3.3 report underscores the importance of balancing thermal and structural performance in HHPs. By addressing design, material, and operational challenges, HHP technology can be scaled to diverse infrastructure applications, enhancing safety, sustainability, and cost-effectiveness.

2.4 Task 4: Planning, construction, and monitoring

The objective of subtask 4 was to gather experience and knowledge from Subtask 1-3 in order to provide recommendations on how ground source thermal energy should be used for de-icing and snow melting systems.

2.4.1 Mapping of demonstration and existing plants

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). An example of mapping is presented in figure 9.

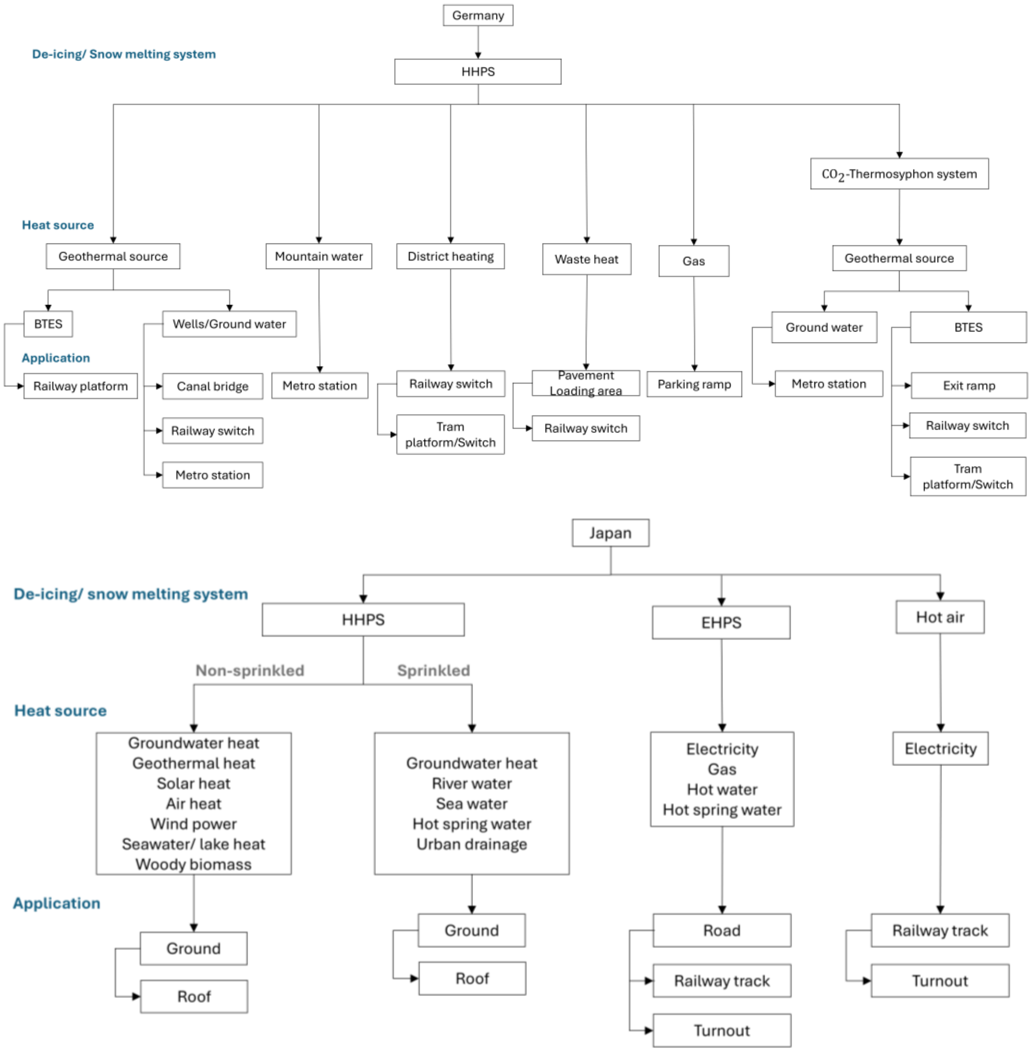

Figure 9. General mapping of de-icing and snow-melting applications in Germany utilizing hydronic heated pavement system, and the corresponding heat sources.

The results pf the mapping reveals that most 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.

The subtask report 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 subtask 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.

2.4.2 Best practices for design, construction, operation, and maintenance

Key recommendations include site-specific planning, optimal pipe spacing, and efficient zoning to enhance energy efficiency and snow-melting performance. Construction guidelines emphasize proper embedding of pipes, insulation to minimize heat loss, and integration with underground thermal energy storage (UTES) systems like Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES) for seasonal energy utilization. Operational strategies highlight real-time monitoring and predictive control to maintain surface temperatures effectively while minimizing energy consumption. Regular maintenance, fluid checks, and thermal performance monitoring are crucial for system reliability and longevity.

Design: Design of hydronic de-icing systems involves careful planning of pipe layout. Generally, pipe spacing in the range 100–300 mm, and embedment depth in the range of 50–70 mm is used. Reverse-return pipe orientation ensures uniform heating.

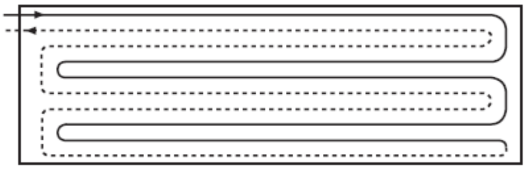

Figure 10: Revers return layout

Insulation under pipes is recommended to reduce energy losses to ground which leads to reduction of energy demand and zoning the pavement allows flexible and efficient operation.

Control systems should be based on embedded sensors and weather-responsive controls.

Renewable energy sources like ground source heating and solar-assisted heating are preferred. Thermal storage options include ATES and BTES, selected based on site specific conditions recommends.

Design should follow a structured process: pre-feasibility, feasibility, predesign, and detailed design, with environmental and economic risk analyses.

Construction: Construction involves installing pipes using wire mesh or insulated panels depending on load conditions. To ensure tightness of the piping system a pressure testing (4–5 bar for 24 hours) is required before pavement laying. Sensors for snow and ice detection must be embedded and tested prior to casting.

Fluid quality is critical—treated water with propylene glycol and pH value between 9–10 is recommended. Drainage systems should be heated to prevent refreezing.

For ATES, certified drillers and documented geological observations are essential. BTES systems require leakage and flow tests. Coupling of HHP to storage includes pumps, heat exchangers, valves, and control modules. GSHPs may be needed if storage temperature is insufficient.

Operation: Effective operation requires monitoring inlet/outlet temperatures, flow rates, pressure, surface temperature, and climate data.

Set points should be optimized to minimize energy use and zoning allows targeted heating. Weather forecasting helps anticipate snowfall and reduce time lag. In summer mode, supply temperature should be kept low to optimize heat storage.

Maintenance: Seasonal checks are essential before and after winter to inspect leaks, antifreeze concentration, and damages.

ATES systems require monitoring of flow rate, drawdown, and injection pressure to detect clogging. BTES systems need minimal maintenance if properly designed; monitor inlet temperatures and pressure drops. Two-phase thermosiphon systems require regular pressure checks; leaks are visible during operation, and no control system is needed.

2.4.3 Recommendations on market and technology development

Deliverable 4.3 synthesizes the findings from Subtasks 4.1 and 4.2 and translates them into strategic recommendations for broader adoption. Subtask 4.1 maps all the systems which have been utilized in different countries. The goal of following recommendation is to scale up these systems from pilot projects to mainstream infrastructure, contributing to smart cities and climate-resilient urban planning.

Market Strategies:

I) The payback time of a HPPS is between 2-8 years depending on system configuration. Thus, it is feasible to invest in these systems for transition of existing electricity-based systems.

II) **A**wareness Campaigns: Educate stakeholders about the benefits of ground source heated hydronic and energy-harvesting pavements through public awareness campaigns and educational programs.

III) **I**ncentives: Government incentives and subsidies can help offset initial investment costs and encourage adoption.

IV) **P**artnerships: Collaborate with urban planners, construction companies, and policymakers to integrate these systems into new projects and urban development plans.

Technological Advancements:

V) **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.
VI) **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.
VII) **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.
VIII) **C**ontrol system: Develop accurate weather forecasting programs to increase the efficiency of the hydronic system.
IX) **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.
X) **C**onduct life cycle assessments to ensure that the systems are environmentally friendly and have a positive environmental impact.

Policy and Regulation:

XI) **S**tandards Development: Establish industry standards for the installation, performance, and maintenance of ground source systems coupled with hydronic heated and energy-harvesting pavements.
XII) **R**egulatory Support: Advocate for policies that support using renewable energy sources and provide regulatory support for technology adoption.
XIII) Variable electricity tariffs that reflect current fluctuations in the stock market should become mandatory for all consumers. This helps to replace consumers who are unfavourable to the power grid.

3 Comprehensive Results and Recommendations for Deployment

The findings of IEA ES Task 38 demonstrate the feasibility, sustainability, and economic benefits of ground source hydronic heated pavement systems (HHPS) for de-icing and snow melting in critical infrastructure. Through a series of demonstration projects across Europe, Japan, and North America, the effectiveness of geothermal energy for winter maintenance was validated, offering a reliable alternative to traditional electric and chemical-based de-icing methods. Furthermore, the integration of thermal energy storage (TES), including Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES), optimizes seasonal energy use, reduces greenhouse gas emissions, and minimizes operational costs. The presented results and targeted recommendations aim to accelerate the deployment of sustainable de-icing and snow-melting solutions, contributing to resilient urban infrastructure and climate adaptation across Europe and beyond.

3.1 Main Results:

- Energy Efficiency and Sustainability:
    - Ground source HHPS provides efficient and sustainable snow melting, significantly reducing carbon emissions compared to electric or fossil fuel-based systems.
    - Demonstration projects showed a 40–60% reduction in energy consumption when coupled with TES technologies, allowing seasonal storage of thermal energy harvested from solar or geothermal sources.
    - Optimized control systems improved energy distribution, with predictive algorithms responding to real-time weather conditions, enhancing efficiency and safety.
- Technological Advancements and Design Optimization:
    - Innovative heat exchanger designs, optimal pipe spacing, and material enhancements have increased the efficiency and durability of HHPS.
    - Integration with solar harvesting and UTES systems enables year-round energy cycling, reducing peak energy demands during winter months.
    - Numerical modelling and simulation tools developed in Subtasks 2.1 and 2.2 have refined system designs and informed best practices for site-specific installations.
- Market Potential and Deployment Opportunities:
    - Mapping of installations across Europe, Japan, and North America identified high-potential markets, particularly in urban centers, airports, sports fields, and pedestrian walkways.
    - Policy-driven incentives and urban resilience strategies are accelerating adoption, with projected market growth of 6% annually.
    - Public awareness and government support are crucial for overcoming barriers, including high upfront costs and regulatory challenges.
- Demonstration Projects and Best Practices:
    - Successful installations such as the HERO project in Sweden and HEAL in Belgium validated design guidelines for efficient snow melting and energy savings.
    - Best practices include careful planning, optimal zoning, and effective thermal storage integration, enhancing energy efficiency and cost-effectiveness.

3.2 Recommendations for Deployment

- Policy Support and Incentives:
  - Generally, infrastructures is own by public sector, thus governments/municipalities should provide targeted subsidies, tax incentives, and streamlined permitting for ground source de-icing and snow-melting systems.
  - Integrating HHPS into climate adaptation policies and urban planning strategies can accelerate deployment.

- Development of Industry Standards:
  - Establishing design and construction standards for HHPS and TES technologies will ensure consistency, reliability, and scalability.
  - Guidelines should include specifications for pipe spacing, material choices, and integration with TES systems.

- Enhanced R&D and Innovation:
  - Continued research on advanced materials, heat exchangers, and real-time monitoring systems is essential to improve efficiency and cost-effectiveness.
  - Pilot projects should be expanded to various climates and infrastructure types to validate performance under diverse conditions.

- Market Expansion and Awareness:
  - Public awareness campaigns and demonstration projects can drive market acceptance and highlight economic, social and environmental benefits.
  - Partnerships with urban developers, municipalities, and energy providers are critical for scaling installations.

- Long-Term Monitoring and Optimization:
  - Deployment strategies should include long-term monitoring of installations to assess performance, durability, and environmental impact.
  - Data collection and analysis will support continuous optimization and adaptation to changing climate conditions.

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