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Hydronic pavement heating for sustainable ice-free roads

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Abstract

Hydronic pavement is an alternative method for de-icing of roads. A hydronic pavement (HP) could be more environmental friendly than traditional de-icing methods such as salting. The HP system consists of embedded pipes in the pavement structure, with a fluid as energy carrier. The performance of a HP system strongly depends on a number of parameters e.g. the location of the pipes, the thermal properties of pavement structure and the temperature level of the heat storage system. In this paper initial results related to the designing of a HP system are presented.

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Keywords: Melting of Ice and Snow; Hydronic Pavement Heating; thermal properties of pavement; asphalt; seasonal energy storage

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1. Introduction

Driving on a slippery road pavement could be unsafe and dangerous. The situation might get even harsher in some particular sections of the road like slopes, curves and bridges. To mitigate the slippery conditions, a well-known method is to spread out salt and sand on a road surfaces. A negative effect of spreading salt and sand is the polluting effect of the surrounding environment along the road. In 2014, the consumption of salt and sand used for

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winter maintenance of roads was around 0.6 and 1.7 million ton in Scandinavia, respectively (Knudsen et al., 2014). Considering the undesired environmental effect as well as the costs related to corrosion of the road infrastructures caused by spreading salt, it is necessary to apply an alternative method with less negative effects.

An alternative method of spreading sand and salt on the slippery road surfaces could be Hydronic Pavement (HP) system using renewable energy. The HP is a system with embedded pipes inside road pavements in which a fluid like brine, oils or glycol-water circulates (ASHRAE, 2003). During sunny days with high solar gains the road surface temperature is high and the fluid gets warm. The energy of the warm fluid is saved in thermal energy storages to be utilized during cold periods for de-icing of a road surface.

Melting snow/ice via embedded pipes is not a new method. In 1948, the earliest system was installed in Klamath Falls, Oregon, USA by Oregon Highway Department which used geothermal energy (Pan et al., 2015). Nevertheless, the innovation of this study is to use renewable energies such as solar energy as the source of energy. The idea to use renewable energies for safe and ice-free road infrastructures was introduced in the paper which was about sustainability assessment of infrastructure elements with integrated energy harvesting technologies (Bijan Adl-Zarrabi et al., 2014,; Sundberg and Lidén, 2014).

In this paper, three different parameters involved in designing of a HP system, the thermal properties of pavement materials, the design of a HP system and seasonal thermal energy storage (STES) were investigated.

2. Measuring Thermal Properties of Asphalt Pavement by Transient Plane Source method

Thermal diffusivity of a pavement is one of important parameter that influence the efficiency of a HP system e.g. a low thermal diffusivity leads to a longer time to achieve a certain temperature level on the surface of the road. Furthermore, a high specific heat capacity will influence the desired amount of energy in a thermal energy storage. Thus, accurate determination of thermal properties of involved materials are essential in a HP system. There are several methods to measure thermal properties of materials at ambient conditions (Adl-Zarrabi et al., 2006; Mamlouk et al., 2005). One of the methods which have become common for measuring thermal properties of materials is transient plane source (TPS). Gustafsson (1991) described the TPS method for thermal conductivity and thermal diffusivity measurements of solid materials. The measurement method is described in ISO22007-2 (International Organization for Standardization, 2015). Furthermore, Pan et al. (2014) used TPS method to investigate influence of graphite on the thermal properties and anti-ageing properties of asphalt binder. In this paper, the suitability of using the TPS method for measuring thermal properties of asphalt was investigated by using different sensor sizes. Furthermore, the assumption whether or not an asphalt sample is an isotropic material was investigated by measuring thermal properties of the sample in different positions and in different depths of the sample.

2.1. Sample preparation results

A cylindrical sample with the radius of 100 mm and thickness of 60 mm was arbitrary selected. The TPS method needs two specimens thus the sample was divided into two specimen with a thickness of 30 mm. Furthermore, the specimens were divided into two new specimens to measure the thermal properties in different depths. The samples were conditioned in the laboratory. Temperature and relative humidity in the laboratory were 22℃ and around 50%. Fig 1 shows the surface of the sample and position of the sensor. Different sensor sizes were used in order to investigate the most proper size of the sensor related to aggregate size. The sample used in these measurements was arbitrary selected; thus, the information about binder and aggregate is missed. However, largest size of aggregate on the surface is measured to 11 mm.

2.2. Measurement results

2.2.1. Sensor size

The results of measured thermal properties of the asphalt pavement sample using different sensor sizes are presented in Table 1. As it is seen from the results, measuring thermal properties of the pavement samples using different sensor sizes offers different results. However, the variation of the results was expected. Small sensor sizes (small diameter) do not cover proper amount of binder and aggregates in the pavement surface; thus, will lead to inaccurate results e.g. the measured thermal conductivity of the sample using the sensor design of 5465 with the diameter of 6.36 mm is about 50% lower than the measured thermal conductivity by the sensor 5501 with a diameter of 12.8mm. The reason for this large deviation is that the sensor design of 5464 covered mostly binder part of the sample.

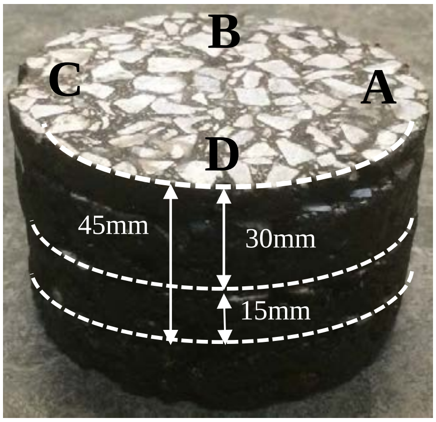

Fig. 1. Measuring positions A-D on the surface and two different depths of the Asphalt specimen.

Table 1. Measuring thermal properties of the asphalt pavement sample with different sensor sizes.

Sensor Design	Sensor diameter (*mm*)	Conductivity (*W/m.K*)	Diffusivity (mm^2/s)	Volumetric heat capacity (MJ/m^3K)
5465	6.36	1.19	1.60	0.74
5501	12.8	2.33	1.34	1.73
8563	19.7	2.38	1.39	1.71
4922	29.2	2.62	1.28	2.04

Furthermore, if the sensor covers only an aggregate, the thermal properties of the aggregate will be measured. As it mentioned, the maximum size of aggregate is 11 mm. The diameters of the other sensor used in this study are larger than the maximum aggregate size in the sample; therefore, they could measure the thermal properties of the sample more accurately. The larger sensor the more accurate results. For further studies, it is possible to find a ratio between sensor size and maximum aggregate size. This study will be completed by using sensor sizes with diameter larger than 29.3 mm in order to insure the accuracy of the measured values.

2.2.2. Evaluation of isotropic assumption

In this study, it is assumed that asphalt pavement is an isotropic material. To investigate this assumption, two different measurement setup were used. In the first setup, the sensor position was changed over the surface of the sample, see Fig 1. In the second setup, the sensor is placed in different depth from the surface i.e. 45 mm from the sample surface. The sensor design 8563 is used in this measurement. The reason of selecting this sensor is that according to recommendation for performing TPS measurements the thickness of samples under investigation should be at least equal to radius of the sensor. Thus, in order to not jeopardizing the accuracy of this measurement the sensor design 8563 is selected instead of sensor design 4922. The results are presented in Table 2 and 3.

The thermal properties of the sample in three positions A, B and D are in the same range with a maximum deviation of 2% Furthermore, the diffusivity of the sample in positions A-D are in the same range with a deviation of 5%. However, the thermal conductivity and volumetric heat capacity of the sample in the position C in comparison with other positions deviates by 10% and 20% respectively. A reason for the deviation might be the inconsistent distribution of the aggregates in the asphalt sample. However, if the size of the sensor was large enough, the deviation in the position C would be eliminated and the sample could be assumed to be isotropic at the surface of the sample.

Table 2. Thermal properties of the asphalt pavement: different positions on the surface using sensor design of 8563.

Position	Conductivity (W/m.K)	Diffusivity (mm2/s)	Volumetric heat capacity (MJ/m3K)
A	2.38	1.39	1.71
B	2.39	1.38	1.73
C	2.67	1.28	2.07
D	2.43	1.32	1.84

Table 3. Measuring thermal properties of the asphalt pavement in different depths using sensor design of 8563.

Position	Depth (mm)	Conductivity (W/m.K)	Diffusivity (mm2/s)	Volumetric heat capacity (MJ/m3K)
A	30	2.38	1.39	1.71
	45	2.49	1.45	1.71
B	30	2.39	1.38	1.73
	45	2.54	1.49	1.70
C	30	2.67	1.28	2.07
	45	2.66	1.49	1.78
D	30	2.43	1.32	1.84
	45	2.57	1.21	2.13

The variations of measured thermal properties in two different depths of 30 mm and 45 mm from the sample surface for conductivity, diffusivity and volumetric heat capacity are about 6%, 14% and 14%, respectively. The deviation of the thermal properties in two different depth might happen because of two main reasons, different aggregate distribution and also the different compaction pressures. These variations can be used in a sensitivity analysis related to efficiency of a HP system. Further investigation is needed in order to finalize the suitable set up for determination of thermal properties.

3. Hydronic Pavement Design

The pipes positions, their buried depth from pavement surface (D) and the pipes distance from each other (S), are parameters that influence the efficiency of snow melting process. A numerical model was made in COMSOL Multiphysics to investigate the influence of the pipe positions on snow melting performance. A scheme of the pipe positions in a HP system is shown in Fig 2.

To simulate the snow melting model, it was assumed that the snow layer is homogenous and porous. The heat supplied from the embedded pipes will melt the ice crystals in the snow and also increase the temperature of the snow. Furthermore, it was assumed that all melting process is done on the pavement surface and the pavement is ideally drained. According to Liu et al. (2007), two snow melting assumptions are considered which divide the snow melting process in two steps. First, the height of the accumulated snow on the pavement surface is higher than the capillarity height in snow and second the height of accumulated snow is lower than the capillarity height. In the first assumption, the part of the snow which is above the capillarity height is considered as a heat insulator; hence, in this step, the effect of ambient condition on the snow-melting will be low. While, in the second assumption, there is no insulating layer on the snow and so both convection and evaporation will affect the snow melting process.

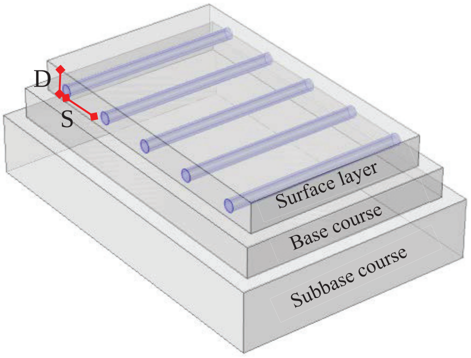

Fig. 2. A scheme of the pipe positions in a HP system(D is the distance from the center of a pipe to the pavement surface and S is the space between two successive pipes).

A three courses asphalt pavement was considered, see Fig 2. The pavement system includes asphalt layer, base and subbase courses and the pipes which are buried in the asphalt course. The thermal properties of the different layers and the pipe are given in Table 4.

Table 4. Thermal Properties of materials associated with the simulated model (Theodore L. Bergman et al., 2011).

Course	Thickness (*mm*)	Thermal Conductivity (*W/m.K*)	Density (*kg/m3*)	Heat Capacity of Constant pressure (*J/kg.K*)
Surface Layer (Asphalt Concrete)	150	2.5	2300	1000
Base	250	1.1	2000	1000
Subbase	250	0.7	1700	900
Pipe* (PEX[1])	1.5	0.42	1100	1465

*Pipe outside radius is 10 mm.

3.1. Modelling, material properties and boundary conditions

The main goal of the simulation, in this paper, is to investigate the effects of the pipe positions (D and S) on the snow-melting process. To give an example how the simulation works, a boundary conditions including constant weather conditions, and constant fluid temperature inside the pipe were assumed. The boundary conditions and the pipe positions is given in Table 5.

3.2. Simulation results

Considering the given boundary conditions, the required time to remove all snow from the road surface with different pipe positions is presented in Fig 3. The influence of altering S and D affects the snow-melting differently. An example is given here to explain how different positions might influence the melting process. Let assume that the initial pipe position S is equal to 190 mm and D is equal to 95 mm. The required melting time for this positon is 16 hours with given conditions. 16 hours includes 1 hours for preheating, 10 hours for melting during snowfall and 5 hours for melting remaining snow and ice on the road. To know the influence of pipe positions, both variables (S and D) are increased in steps of 15% and 30% and then the required time to melt snow for new positions is measured. The results is presented in Table 6.

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[1] Cross-linked polyethylene

Table 5. The boundary conditions used to simulate the snow-melting process.

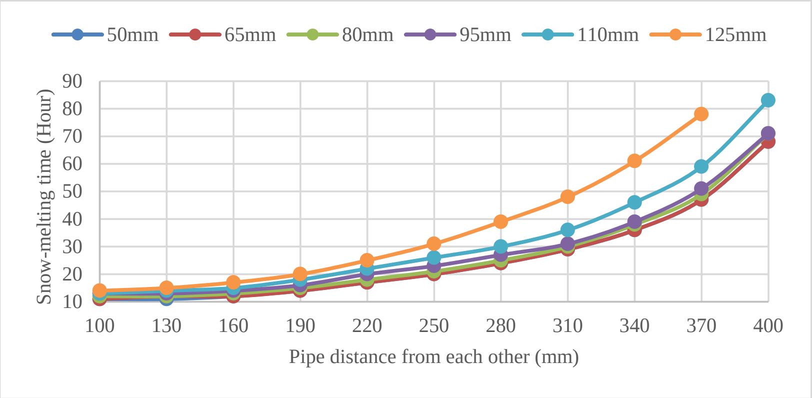
Condition	Value
Fluid temperature inside the pipes	15℃
Ambient temperature	-2℃
Humidity	80 %
Wind Speed	$5\ \mathrm{m/s}$
Snowfall rate	$20\,{}^{mm}/_{hr.m^2}$
Snowfall duration	10 hours
Density of snow	$117\,{}^{Kg}/_{m^2}$
Capillarity Height	25mm
Distance between two pipes	$100-400$mm
Buried depth of pipes	$50-125$mm
Temperature in the bottom of subbase course	1℃
Preheating (idling)	1 hour

The required time for the initial S of 190 mm and increasing D by 15% and 30% will increase around 13% and 25% respectively. However, for the initial D of 95 mm and increasing S by 15% and 30% increases the required time will increase around 25% and 44%respectively. The results shows that the altering pipe distance (S) in comparison with the buried depth (D) has more influence on the snow-melting process.

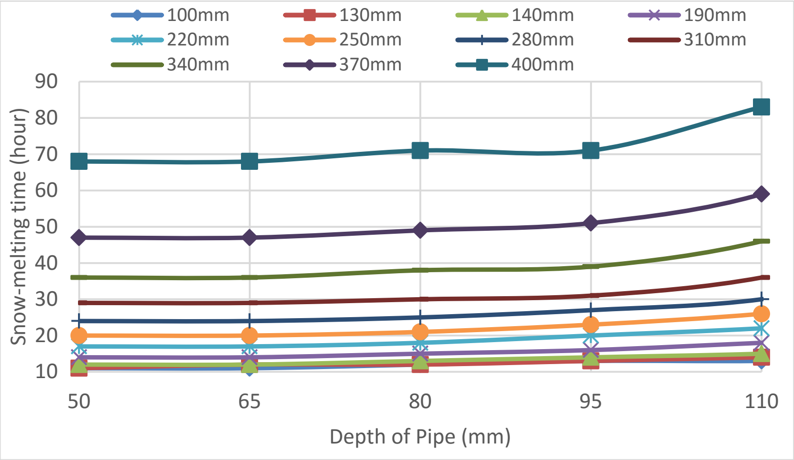
Table 6. Required time to remove all snow form the pavement surface with different positions.

S(mm) D (mm)	190	220	250
95	16hr	20hr	23hr
110	18hr	22hr	26hr
125	20hr	25hr	31hr

As it is seen from see Fig 3a, if the distance between pipes (S) is longer than 200 mm, the required time to melt snow will increase rapidly; therefore, it is advisable to install pipes in a position that their distance from each other is less than 200 mm. Moreover, the effect of the buried depth on the snow-melting process will be negligible if the buried depth of pipes is shallower than 100 mm, see Fig 3b.



(a). different buried depth



(b). different pipe distance

Fig. 3. The required time to remove all snow from the pavement surface with different pipe positions.

4. Seasonal Thermal Energy Storage

One of the challenges using a seasonal thermal energy storage (STES) to store solar energy meant for an ice-free road is the temperature level of the storage in the end of heating season. Since, there could be very cold nights in the end of the heating season which require a high level of heat extraction i.e. the need for a high temperature level. However, the temperature in the STES tends to be at its lowest level by the end of the heating season. There are different alternatives for achieving the desired temperature level e.g. supplementary energy source such as using electricity for heating, adding solar panels or increasing the depth and the number of boreholes in the STES.

The aim of this study is to investigate if it is a feasible solution to combine a short-term thermal energy storage using solar panels with a STES. The combined system would be a hybrid system. This study aims at investigating if it would be possible to harvest the solar radiation in early spring, store the energy and use it during night time, thereby decreasing the size of the STES. If the size of the STES could be reduced, it would decrease the initial construction cost of STES and the hybrid system.

4.1. Methodology

To investigate a hybrid system, a number of numerical simulations were performed on two suggested systems in the transient simulation tool TRNSYS, which is a well-established software for investigating system combining solar energy and energy storage. Two systems were compared by varying essential parameters. System A is made of a STES connected to a cooling unit, the cooling unit simulated the energy demand to maintain a road ice free, and system B consists of system A, but with the addition of a thermal storage tank and solar collectors. The simulation results can be used for optimization of the numbers of boreholes used in an STES.

4.1.1. System Description

In the first system, system A, the fluid is heated in the STES and then pumped to the cooler which removes a constant amount of energy during operation. In the second system, system B, the heated fluid leaves the STES and enters the storage tank where the temperature increases by mixing with the water in the storage tank. The two systems are shown in Fig. 4 and Fig 5. The input data for the simulations is presented in Table 7. Furthermore, a climate file supplied by Meteonorm, a commercial software for generating climate data, for Stockholm with a yearly average air temperature of about 6 °C was used for the simulations.

Table 7. Major parameters for the different systems.

Parameter	System A	System B	Unit
STES size	80000	80000	m^3
Depth borehole	220	220	m
Fluid flow Pump 1 – F1	4,6-10	4,6-10	kg/s
Storage tank size	-	10-20	m^3
Number of boreholes	25-105	25-65	-
Solar collector area	-	100	m^2

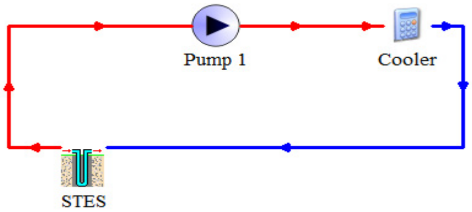


Fig 4. System A, STES with a cooler of 100 kW.

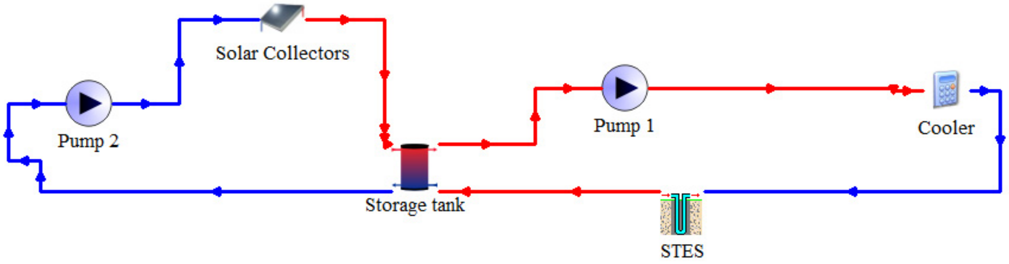


Fig 5. System B with short time thermal energy storage connected to STES.

4.2. Results and analysis

The temperature level of a STES is closely connected to the maximum power that the STES could supply as well as the amount of usable stored energy in the STES. Thus, the temperature level of the STES in the beginning of the heating season is of great importance for the operation of a HP system. The results from the simulations indicated that for a STES which has a low mean temperature in the beginning of the heating season would benefit more from having a hybrid system like the system B than the STES which has a higher mean temperature. This means that low initial mean temperatures makes the system more sensitive. As the temperature in the STES declines, the heat extraction rate decreases. Moreover, by adding extra heat from the solar panels, the system could still deliver the required power. This means that solar panels and a short time storage could be good to add to a STES that has been designed poorly or when the temperatures in the STES is too low in the start of the heating period.

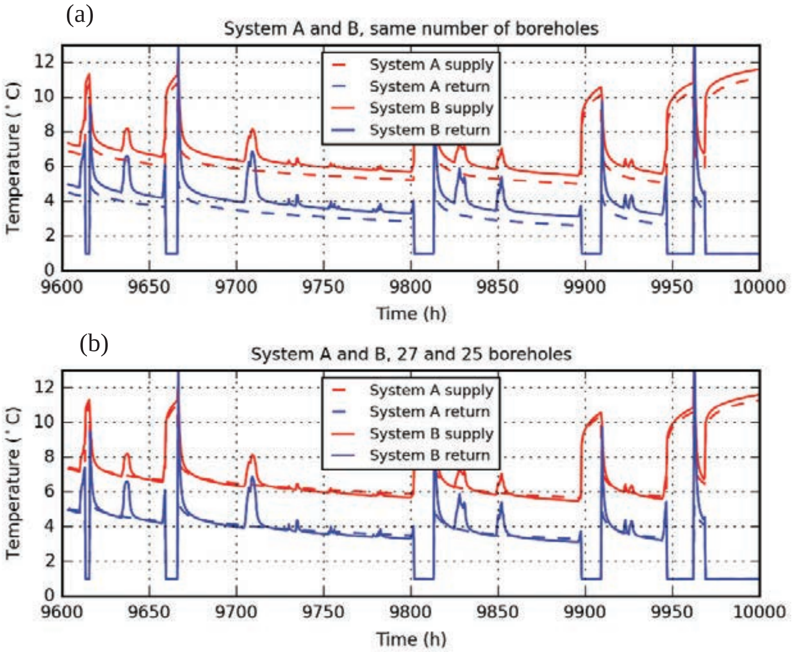


Fig 6. Simulations results from TRNSYS revealing the supply and return temperature to the pavement from STES for system A and B with different configurations.

Comparing System A and B with the same number of boreholes in the STES, it was found that there is a temperature difference between the two systems, supply and return flows that comes from the hydronic pavement, see Fig 6a. The difference was almost 0.7 °C, this difference seams low; however, it corresponds to an increased supply temperature of about 10 % for system B compared to system A. It was also investigated how many more boreholes that System B would need to have the same temperature performance as system A. From Fig 6b it is seen that when system A has 27 boreholes, it is equivalent to system B with 25 boreholes since there is almost no difference in the fluid temperatures. The difference between the two systems in this case is two boreholes. This small difference of two extra boreholes for system A to achieve the same performance as system B shows that adding the solar panels are unjustifiable due to the added system complexity and extra maintenance costs due to the solar panels and pumps etc.

5. Conclusions

Ice and snow have always been a challenge for road administrators in cold climates. Increasing demands on accessibility and safety in rural roads can lead to a costly winter maintenance. The common way of handling ice and snow on a road is to use snow-ploughs and de-icing salt. Salting creates technical and environmental issues such as decreased durability of different types of pavement material and soil saltification along roads. An alternative method for de-icing is to use the HP system using renewable energy. Using HP systems to create sustainable ice free roads could decrease traditional road maintenance costs for instance salting and snow-ploughs as well as increasing the lifetime of the transport infrastructure. In this paper, three different parameters that have major influence on efficiency of a HP system were investigated: thermal properties of an asphalt sample, buried pipe positions in the pavement and seasonal energy storage. The thermal properties of an asphalt pavement were measured by transient plane source method. The results of measurements indicated that the thermal properties varied around 6-14% in the different depths of an asphalt pavement. Furthermore, numerical simulations were performed for geometrical design of the embedded pipes. The results of the calculation indicated that the space between the pipes have a larger influence on the system performance than the depth at which the pipe were buried. Finally, in order to decrease the energy loses and size of the seasonal energy storage, solar panels were added and the system performance is evaluated. The results of numerical simulations related to STES indicates that adding solar panels is not justifiable because additional system complexity and costs. This conclusion can be even valid for other additional renewable energy as wind power. More investigations are required to find a sustainable backup system for a hydronic pavement system. Additionally, the systems needs to be optimized regarding different parameters like water flow, size of the pipes, available harvested solar energy.

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