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A critical review on large-scale research prototypes and actual projects of hydronic asphalt pavement systems

Taher Ghalandari*, Navid Hasheminejad, Wim Van den bergh, Cedric Vuye

Energy and Materials in Infrastructure and Buildings (EMIB) Research Group, Faculty of Applied Engineering,
University of Antwerp, 2020 Antwerp, Belgium

Abstract

In recent years, harvesting solar energy as a renewable and sustainable energy source has been studied extensively across engineering fields. Having reviewed more than 50 large-scale projects of Hydronic Asphalt Pavement (HAP), this paper offers a series of findings: the range of construction cost of asphalt collector varies between 25-151 €/m^2 and 1.760-3.000 €/m^2 for the heat exchanger and the total cost. The energy harvest capacity of asphalt solar collector systems (0,6-0,8 GJ/m^2/year) and the required amount of heat for snow melting projects (100-900 W/m^2) vary significantly in different projects. Using grid supports for easier pipe placement and protection of pipes against heavy loads during and after construction is recommended. Pavement solar collector systems reduced carbon dioxide emissions by 8-100% in different projects by changing their source of energy from fossil fuels to renewable and sustainable sources. Moreover, in order to further evaluate the sustainability of the HAP systems, a detailed life cycle assessment is required, including all available data related to the energy performance, pavement service life, material end-of-life recycling, etc. Finally, the paper identifies the knowledge gaps requiring further research especially in the area of energy output of the HAP systems, pavement service life and life cycle assessment.

Keywords: Energy harvesting, Solar energy, Solar collector, Pavement Solar Collector (PSC), Asphalt pavement, Asphalt solar collector

Highlights

- A comprehensive review of large-scale hydronic asphalt pavement projects is provided.
- Potential challenges in the large-scale hydronic asphalt pavement are investigated.
- Technical specifications, operational aspects and performance are explored.
- Construction cost and structural response of systems are analyzed.
- The projects' performance is evaluated based on energy output and sustainability.

Abbreviations: HAP, Hydronic Asphalt Pavement; UHI, Urban Heat Island; LCA, Life Cycle Assessment; PSC, Pavement Solar Collector; SMS, Snow Melting Systems; VOWAC, very open-graded water-bearing asphalt concrete; SERSO, Solar Energy Pilot Project; RES, Road Engineering Systems; NAU, Northern Arizona University; OSU, Oklahoma State University; FHWA, Federal Highway Administration; HEAL, Heat Exchange Asphalt Layers; OIT, Oregon Institute of Technology; AUB, American University of Beirut; HERO, Heating Road with Stored Solar Energi; UA-ERC, University of Arkansas's Engineering Research Center; GCHAP, Ground-Coupled Hydronic Asphalt Pavement; ROI, Return on Investment; LCOE, Levelized Cost of Electricity; SA, Sustainability Assessment; MCS, Monte Carlo Simulation.

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* Correspondence to: Groenenborgerlaan 171, 2020 Antwerp, Belgium.
E-mail address: taher.ghalandari@uantwerpen.be (Taher Ghalandari).

1. Introduction

Recently, interests have been directed towards renewable and sustainable energy production because of the depletion of fossil fuel sources and their destructive effect on global warming. The worldwide demand for energy production has increased due to population explosion, urbanization, and industrialization. There is widespread empirical evidence that primary energy consumption rose almost fourfold between 1965 and 2018, as the world population increased from 3,3 to 7,6 billion during the same period [1]. Statistical reports and research studies stress the need to focus on substituting renewable energy sources for fossil fuels. In many recent studies, renewable energies such as solar, wind, hydro, geothermal, and biomass have received special attention for their potential to substitute for fossil fuels [2-4]. Although clean energy production had been increasing dramatically from 4,1 to 2480 (million tones oil equivalent) between 1965 to 2018, the share of renewable energy sources was only 4% of total energy consumption in 2018 [1]. Despite the challenges for a shift from fossil fuel to clean energy, renewable sources had a 15% growth rate in energy production in 2018. In this year, the wind and solar energy contributed to more than 70% of the mentioned total energy generation by renewable sources. For this reason, harvesting solar energy has been studied extensively in different engineering fields [3, 5, 6].

Asphalt pavement, as a widely available material in road surfaces, parking lots, and airports is exposed to an extensive amount of solar radiation and therefore has been a major area of interest within the field of energy harvesting. Several technologies are developed in order to harvest energy from asphalt pavements, such as solar photovoltaic, pyroelectric modules, thermoelectric generation, and a Pavement Solar Collector (PSC) [7-10]. These technologies can be used to harvest solar radiation and then store the energy in its required form. Similar to solar panels, asphalt pavement can also extract absorbed heat energy on its surface that can reach up to 40 MJ/m^2 over a day in the summer [11]. The PSC, sometimes referred to as a Hydronic Asphalt Pavement (HAP), includes a heat exchange layer and a heat-carrying medium in its structure. The heat exchange layer can be made of porous asphalt to cool down asphalt temperature by producing airflow through this layer [12]. Alternatively, a pipe network with an appropriate fluid can be implemented in the heat exchange layer. In a HAP, circulating cooler fluid through the embedded pipes and heat exchange with heated asphalt pavement regulates the temperature of asphalt layers. While in some research, the 'PSC' is equated with 'HAP', this paper differentiates between the two. PSC systems are defined based on their ability to only harvest solar energy, while HAPs can couple other energy sources as well. Hence, all PSCs are categorized as HAPs, but not all HAPs are considered as PSCs.

The HAPs can serve several purposes such as clean energy production, increase in road safety, increase in the service life of the asphalt pavement, and mitigating the development of the Urban Heat Island (UHI) effect, as demonstrated further on in this paragraph. One of the main contributions of HAP is to harvest clean solar energy in the form of low-temperature heat to be used in residential and nearby buildings for multiple purposes. Mallick et al. [13, 14] showed that the harvested energy using PSCs can be used to heat domestic water and circulating fluid in the heating system of buildings. In addition to the domestic application, they discussed the potential of using high/low-temperature energy for industrial benefits, namely industrial cleaning (i.e., vapor degreasing process) and food processing.

HAPs can be used to increase the safety of roads to provide snow/ice-free surfaces in the wintertime by recirculation of heated fluid with the stored energy from summer. To provide a snow/ice-free asphalt surface in wintertime, several methods are available such as mechanical machinery (i.e. snowplow), chemical agents (i.e. spreading salt), and so-called Snow Melting Systems (SMS) [15]. The SMS can use different sources of energy such as electricity [16, 17], geothermal [18], fossil fuel [19], and solar energy [20]. The use of SMS, especially in bridge decks, inclined planes, and bicycle paths, has increasingly attracted the attention of studies as an alternative for the conventional snow/ice removal systems (e.g., salt spreading) that results in a safe and environmentally friendly solution (i.e., reduction in salt usage) [21, 22].

Moreover, HAP systems aim to control seasonal changes in asphalt pavement temperature to decrease the potential of pavement distresses such as top-down cracking, rutting, and fatigue cracking. As articulated by Bayat et al. [23], the compound thermal-induced and load-induced strains result in poorer performance of pavement during warm months compared to those in the cold months. Dawson et al. [8] put forward that more frequent maintenance is required for pavements subjected to higher temperature since rutting distress in asphalt pavement is a direct result of the thermal-induced strains [24]. The maximum temperature of the asphalt pavement directly impacts the service life of the pavement, which shows the notable effect of temperature gradient on the distresses formation in the asphalt pavement [13, 25, 26]. Developing higher air temperature in urban areas compared to that of in the rural areas is known as the UHI effect, which is also a result of high temperature in asphalt pavement and irradiation to the environment. Studies show the effectiveness of the PSC in reducing pavement and near-surface air temperature [13, 27].

Although considerable research has been devoted to performance analysis of HAP for de-icing or energy harvesting purposes, these research studies mainly focused on small-scale laboratory test setups [21, 28-32]. However, certain challenges arise when attempting to design and study the performance behavior of large-scale HAP systems. This paper attempts to shed light on the prevalence of these challenges concerning large scale HAPs. Throughout this paper, the term ‘large-scale’ pavement solar collector systems will refer to the projects that are constructed in situ, in an outdoor environment, and with a practical and functional area greater than 40 m^2. In this review paper, HAP systems are grouped into research prototypes and actual projects with respect to their size because these two categories differ in their objectives, manufacturing, monitoring, and technical specifications. Besides, to avoid using the terms large-scale pavement solar collectors or hydronic asphalt pavement repeatedly in the paper, HAP/PSC refers to large-scale systems unless specified.

This study, exploratory and interpretative, systematically analyzes the large-scale HAP systems aiming to present a critical review on energy harvesting technology from asphalt pavement. The importance and originality of this study are that it explores how large-scale HAP systems are different from the small/lab-scale setups in their configuration, how they are incorporated and operated in various projects, their estimated cost/m^2 and a long-term performance analysis of large-scale HAPs. The reader should bear in mind that this paper is based on the published materials in the literature and does not encompass unpublished or demo projects. All the material included in this study has been published since 1998 and comprises journal articles, conference papers, theses, and project reports.

The overall structure of the paper takes the form of four sections. The first section of this paper will examine the system components, purpose, and information related to certain technical characteristics. The second section is concerned with the aspects of the operational phase of the HAP. Section three begins by attempting to estimate the construction cost dimensions of the large-scale systems and looking at how these systems performed in terms of energy harvesting output, structural response, and environmental impacts. Finally, the remaining challenges and problems are dealt with in the concluding remarks.

2. Technical features of large-scale HAP systems

This section aims to describe the purpose, primary components, and geometrical aspects of the worldwide available large-scale HAP systems and critically examine the technical specifications of the projects. The main questions that will be answered in this section are:

- What is the main purpose of the constructed HAP?
- What are the primary and required components of a large-scale HAP?
- How are the projects distributed for their dimension and motive?
- What are the characteristics of the materials used in these systems (e.g. type of asphalt mixture or pipe material)?

2.1. Overview of the existing large-scale HAPs

Large-scale pavement solar collectors have received much attention in different countries. This subsection outlines the location and purpose of different HAP systems, together with primary information on the projects. The configuration of HAP systems consists of four main parts: heat exchanger, storage, control system, and data measurement devices. Depending on activating or idling each of these parts, a HAP can serve for either a single objective or combined purposes.

There exist over 50 large-scale HAP projects around the world that show these systems have been of interest to a number of investigators. The first HAP project was constructed in 1948, in Klamath Falls for de-icing of pavement to increase road safety and the project was reconstructed in 1998 [33]. Around the early 1990s, the study of large-scale PSC systems gained momentum with the introduction of projects such as the Solar Energy Pilot Project (SERSO) [34-36] and the Gaia Snow Melting System (Gaia) [37]. It was not until the late 2000s that several large-scale projects were completed in various countries, and the potential of PSC systems was proven in both energy harvesting and increasing road safety (i.e., the commercial Road Engineering Systems (RES) by the Dutch contractor Ooms) [38]. However, in recent years, the performance of large-scale HAP has been studied extensively with more control on design, construction, and detailed analysis of the measured output. Detailed information regarding the construction year of large-scale projects is given in Table 1.

Snow melting is an essential aspect of HAPs and the exclusive objective of several projects for the prevention of snow and ice accumulation on road surfaces, pedestrian sidewalks, airport aprons and bicycle paths. HAPs work as SMS in the projects of Klamath Falls [39, 40], Downtown Holland [41, 42], Tianjin pilot [43, 44], ICAX (Hiroshima project) [45] and Northern Arizona University Project (NAU project) [46]. Also, the primary aim of projects such as SERSO [34, 47], Oklahoma State University Project (OSU project) [48], Federal Highway Administration (FHWA) projects (in Nebraska, Oregon Silver Creek, and Texas) [49], and Rotterdam bridge project is de-icing of the road surface in road bends and bridge decks. Following a theoretical study in the application of HAP in the Goleniow Airport [50], several large-scale HAP projects have been constructed in airports such as EMVO airport platform Woensdrecht [51], Oslo International Airport [52], Greater Binghamton Airport [53], and Beijing New Capital International Airport [54]. These projects show the development of HAP construction in airport aprons, however, they have coupled geothermal, electrical, and conventional boilers as a heating source in order to provide sufficient heating energy for snow melting [55, 56]. Although limited to a few large-scale projects, very open-graded water-bearing asphalt concrete (VOWAC) is another alternative for a piping system inside an asphalt layer, in which water flows from the high side to the lower side due to a transversal road slope has been developed, and is implemented for energy harvesting and snow melting purposes in Cerema Clermont-Ferrand project and Solar Road project [57-59].

In distinctive projects such as Gaia [37, 60], Zonnige Kempen [61], Eurovia's Fleury-sur-Orne [62], and ICAX [45] (i.e., Howe Dell School, HM Prison Garth and Suffolk One) the goal is to harvest clean energy as well as providing safe streets and sidewalks for pedestrians and bikers. For example, Howe Dell School project uses the playground solar collector to pre-heat hot water for the school, HM Prison Garth project collects solar energy to provide hot water for cooking and washing in a nearby building, and Suffolk One project supplies heating source for the existing buildings. In addition, the collected heat from the pavement has been used in multiple or a complex of residential buildings such as social housing in the project of Eurovia Fleury-sur-Orne and Zonnige Kempen [61, 62]. So far, however, there has been little discussion about the performance and potential challenges of collective heat provision using PSC.

In other projects, the objective is also to increase the service life of the pavement. This is exemplified in the projects undertaken by RES in Westfrisia-Oost III industrial site and Wester-Koggenland building complex [34], in the Tianjin pilot, Heat Exchange Asphalt Layers (HEAL) [63-65], and AUB projects. One of the main goals of these projects is to collect heat during summer and release the collected heat in wintertime in order to reduce permanent deformation (rutting) in summer and cracking in winter in the asphalt pavement. Nevertheless, to achieve lower rutting or less cracking is not a reason for implementing PSCs since modifications in the asphalt mixture (i.e., changes in the specifications of asphalt binder, filler, and aggregates) can reduce these types of distresses with considerably lower cost.

Finally, a number of large-scale PSCs contribute to environmentally friendly outcomes, such as a decrease in CO_2 emissions, mitigating the UHI-effect, and a reduction of fuel/energy consumption in the project itself or adjacent buildings. In several projects, however, the primary aim is to achieve an energy-optimized residential, industrial, or agricultural construction, using extracted and stored energy results in an attempt to reduce the CO_2 emissions [66]. An example of this type of project is Eurovia Forez-Est, in which a PSC is implemented in a parking lot in the neighborhood of a public swimming pool. The result of using the collected solar energy for heating water of the pool reduces CO_2 emissions by 16 tons per year [67]. However, because environmentally friendly outcomes are side-benefits of PSCs rather than their primary objectives, these outcomes have received scant attention in the research literature.

One criticism on the contribution of HAP systems to the reduction of UHI and CO_2 emissions is that a comprehensive Life Cycle Analysis (LCA) is also required. Using the LCA, both HAP system and associated sections (i.e., adjacent building) need to be evaluated with respect to parameters such as energy performance, extension of pavement service life, and material recycling.

An overview of the number of large-scale HAP projects together with their geographical location is given in Figure 1.

Figure 1. Distribution of large-scale HAP systems in the world

Table 1. Description of large-scale pavement solar collector projects

No.	Project	Location	Construction period	Application/Objective	Heat Source	Project Area (m^2)
1.	Klamath Falls projects a. Esplanade Street Project b. Wall Street Bridge and Street Project c. Oregon Institute of Technology Project (OIT)	Oregon, USA	1948-2003	snow melting, de-icing	geothermal	a. 2.100 b. 960 c. 310
2.	Downtown Holland	Michigan, USA	1988	snow melting, de-icing	power plant/waste heat	55000
3.	Underground thermal energy storage snow melting systems	Japan (13 projects) a. Kochidani, Niigata b. Fukui, Fukui c. Kasiwazaki, Niigata d. Kitami, Hokkaido e. Yokotani, Hiroshima f. Muraoka, Hyogo	1989-1996	snow melting, de-icing	geothermal heat	a. 400 b. 400 c. 900 d. 100 e. 44 f. 310
4.	Solar Energy Pilot Project (SERSO)	Bern, Switzerland	1994	energy harvesting, snow melting (bridge)	solar	1.300
5.	Federal Highway Administration projects (FHWA) a. Nebraska b. Oregon Silver Creek c. I-84 Overcrossings d. Texas	USA a. Lincoln, Nebraska b. Silver Creek, Oregon c. Hood River, Oregon d. Amarillo, Texas	1994-1996	snow melting, de-icing	natural-gas-fired boiler, geothermal	a. 1.599 b. 576 c. 1.234 d. 799
6.	Gaia Snow-Melting System (Gaia)	Japan: a. Ninohe, Iwate Prefecture b. Aomori City c. Honshu (10 projects) [60]	1994-2005	energy harvesting, snow melting	Geothermal heat and solar heat	a. 266 b. 659 c. -
7.	Oslo International Airport	Gardermoen, Norway	1998	snow melting, de-icing	geothermal, electrical and fossil fuel	≈ 600 to 780
8.	Road Engineering Systems (RES) a. Wester-Koggenland building complex b. Westfrisia-Oost III industrial site c. Dordrecht Parking lot d. Rotterdam Bridge Project e. EMVO airport platform Woensdrecht f. Industrial site, ‘t Zand g. Municipality of Wester-Koggenland project h. Zonnige kempen social housing i. Ullapool office parking lot	Netherlands (NL) a. Scharwoude, NL b. Hoorn, NL c. Dordrecht, NL d. Rotterdam, NL e. Woensdrecht, NL f. ‘t Zand, NL g. Wester-Koggenland, Goorn, NL h. Zoerle-Parwijs, Belgium i. Ullapool, Scotland	1998-2006	energy harvesting, snow melting, de-icing, road service life	solar	a. 2.250 b. 3.350 c. 450 d. 10.000 e. 7.500 f. 2.200 g. 850 h. 700 i. 500
9.	Oklahoma State University Project (OSU project)	Oklahoma, USA	2000	energy harvesting, snow melting (bridge deck)	solar and geothermal	111
10.	Goleniow Airport (theoretical study)	Poland	2002	snow melting, de-icing	geothermal	-
11.	Solar Road projects	Netherlands	2003	energy harvesting, road service life	solar	

	a. parking lot of Visser & Smit Hanab's b. business park of 'De Compagnie'	• Papendrecht • Middelharnis				a.625 b.32.000
12.	Train Platform	Harz, Germany	2005	heat collection, snow melting	geothermal	375
13.	Stockholm Arlanda Airport	Stockholm, Sweden	2006	snow melting, de-icing,	geothermal	1700
14.	ICAX a. Hiroshima b. TRL c. Howe Dell School d. HM Prison Garth e. Suffolk One	a. Hiroshima, Japan b. Toddington, England c. Hatfield, England d. Lancashire, England e. Ipswich, England	2006-2012	a. snow melting b. energy harvesting, snow melting, road service life c. pre-heat hot water for school d. pre-heat hot water for cooking and washing e. heating source for exciting buildings	solar and geothermal	a. -- b. 300 c. 550 d. 420 e. 1.560
15.	Greater Binghamton Airport	Johnson City, New York	2009	snow melting, de-icing	geothermal	297
16.	Tianjin pilot	Tianjin, China	2012	snow melting, de-icing road service life	solar	80
17.	Northern Arizona University (NAU projects)	Arizona, USA	2012	snow melting, de-icing	central heating plant	91
18.	Power Road® Projects a. Vermot TP b. Saint Arnoult D1 c. The Pontarlier Project d. Eurovia, Forez-Est e. Eurovia, Fleury-sur-Orne	a. Gilley (Doubs), France b. Saint-Arnoult-en-Yvelines,Fr c. Pontarlier, France d. Forez-Est (Loire) e. Fleury-sur-Orne (Calvados)	2013-2019	energy harvesting, snow melting, de-icing	solar	a. -- b. 500 c. 3.500 d. -- e. 1.420
19.	CyPaTs Project, Heat Exchange Asphalt Layers (HEAL)	Antwerp, Belgium	2015-2020	energy harvesting, snow melting, de-icing, road service life	solar	65
20.	Cerema Clermont-Ferrand project	Égletons, France	2015	snow melting, de-icing	solar	200
21.	Beijing New Capital International Airport (Beijing Airport project)	Beijing, China	2016	snow melting, de-icing	solar	90
22.	American University of Beirut project (AUB project)	Beirut, Lebanon	2016-2019	snow melting, de-icing road service life	solar and geothermal	144
23.	NordFoU project, Heating Road with Stored Solar Energi (HERO)	Östersund, Sweden	2015-2019	energy harvesting, snow melting, de-icing	solar	70
24.	University of Arkansas's Engineering Research Center (UA-ERC)	Arkansas, USA	2019	snow melting, de-icing	solar	44

2.2. HAP system components and configuration

Asphalt solar collectors are composed of four main parts in their configuration: heat exchanger, heat storage, control system, and data measurement devices. In this subsection, first, different components of the HAP system are defined and discussed, followed by how the application of a HAP can change with respect to activating or deactivating a component in its configuration.

Figure 2 shows a schematic diagram of a HAP system. Although it is not imperative for a HAP, geothermal or other sources can provide auxiliary heat for the system. The heat exchanger section can either be used for both heat collection and rejection or solely for heat rejection. Projects of Klamath Falls, Downtown Holland, NAU, and FHWA benefit only from the heat rejection aspect to heat pavement for snow melting or de-icing purposes [33, 39, 41, 46, 49]. These large-scale projects use heat from a power plant, waste heat, geothermal, or central heating plant to keep road surface ice/snow-free. On the other hand, several projects such as SERSO, Gaia, RES, OSU project, ICAX, Power Road, HERO, HEAL, etc. harvest heat energy from solar radiation, store and use it for the project itself and maybe other purposes [35, 38, 62, 64, 68, 69].

In the latter group of projects, heat storage is essential to store the harvested heat in summertime until its application during the cold months. There are both horizontal and vertical seasonal heat storage systems [70]. In the case of space availability in large-scale projects, either of the two heat storages can be constructed. The projects of TRL and AUB are a good illustration of implementing a horizontal ground heat exchanger into HAP [34, 36, 71, 72]. In the AUB project, a horizontal pipe network is embedded at three meters below ground to construct the ground-coupled heat exchanger. Hence, the Ground-Coupled Hydronic Asphalt Pavement (GCHAP) is connected to heat storage to keep the inlet temperature of the circulating fluid constant, bringing about temperature balance between pavement and the fluid [72]. Moreover, vertical ground loop heat exchangers consist of a single borehole or a group of boreholes, in which the borehole is grouted to prevent contamination of the groundwater and increase the thermal contact between components [73].

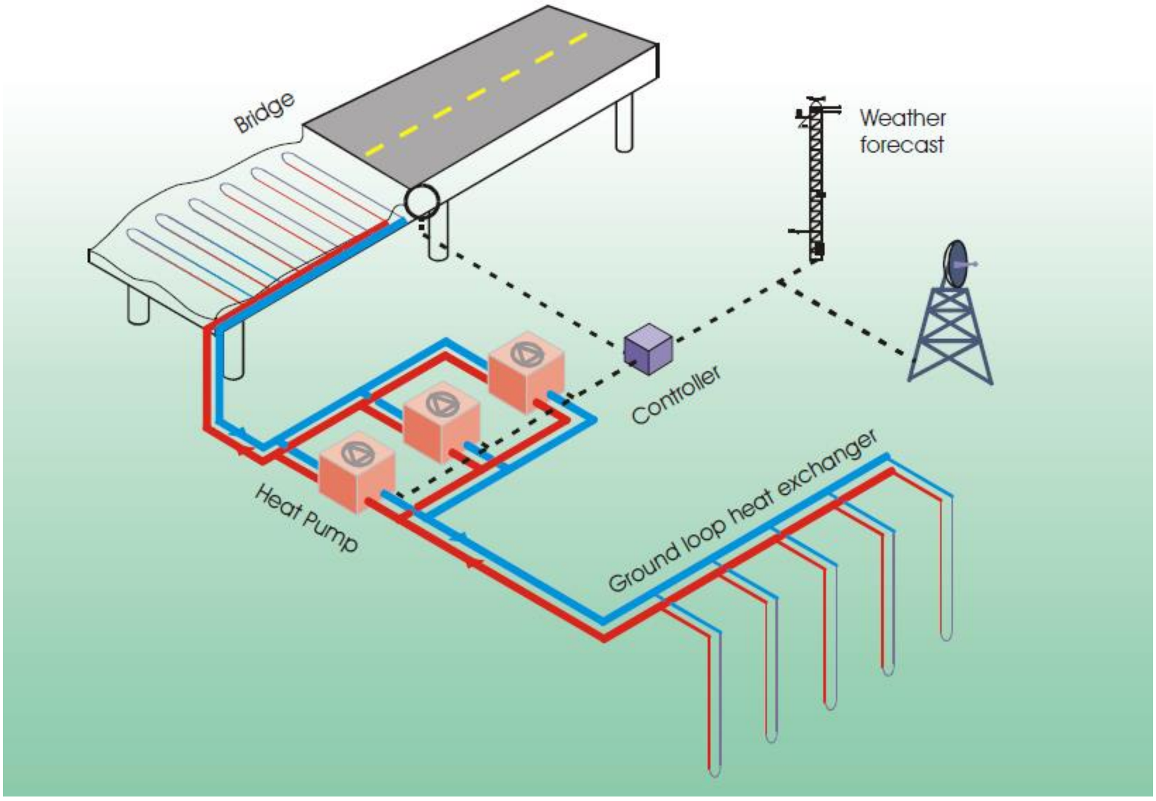

Figure 2. Schematic of a hydronic snow melting system in a bridge [73]

The performance of large-scale HAP projects is monitored and controlled by means of the control section. As shown in Figure 2, the control system aims to synchronize different sections in a HAP for optimum performance. In addition to the monitoring system, the control system is connected to a water pump, heat pump, control valves, and mixing tanks [47]. The importance of using a heat pump in the Gaia project is described along with suggestions for using a more efficient heat pump [37]. However, due to a simple configuration of small- or laboratory-scale solar collectors, the control system is not an integral part of such systems.

Furthermore, measurement devices were installed to measure weather parameters, asphalt temperature, fluid pressure, flow rate and fluid temperature. Several large-scale research prototypes installed a stand-alone weather station to measure solar irradiation, rainfall, humidity, temperature, wind speed and direction to monitor and control the system effectively [43, 48, 57, 68, 71, 73]. Also, measurement sensors are embedded in order to collect experimental data from large-scale HAP for real-time monitoring and operation or post-processing performance analysis. Although instrumentation such as temperature sensors (thermistors or thermocouples) and flow meters are implemented in both large- and small-scale prototypes, they are identically used in large-scale projects for heat loss and heat flow measurement of storage and heat pump power consumption [43, 48, 71, 72].

2.3. Size and geometrical specifications

The geometrical structure and specifications of large-scale HAP projects are explained in this subsection. The design procedure of HAP starts with the main question about the heating capacity of the system and thus deciding on the geometrical variables of the HAP. In the early studies on geothermally coupled SMS, lack of experience resulted in complexities in both the design and application of HAPs [40]. Recent studies suggest that circulating fluid temperature, flow regime, flow rate, thermophysical properties of asphalt, and geometrical specifications are key points of an optimum HAP system [74, 75].

Existing research recognizes the critical role played by geometrical specifications (pipe spacing, depth, etc.) of HAPs in their output efficiency. It is widely accepted for large-scale installations to use a simulation tool for the final system layout prior to construction [35]. Experimental and numerical studies illustrate that parameters such as the size of HAP, pipe arrangement, spacing, diameter and embedment depth have a distinct impact on the energy harvesting and snow melting performance of HAPs [76]. However, these geometrical specifications do not have the same effect on the HAP system performance. A recent systematic parametric study concluded that pipe spacing, embedment depth and pipe diameter are the most influential parameters in HAP efficiency, respectively [72]. It should be noted that the size of the collector and pipe arrangement were kept identical in this parametric study.

The large-scale HAPs are constructed in different sizes depending on their application and area to cover. The Downtown Holland project in Michigan is undoubtedly the largest snow melting system that has been constructed with 55.000 m^2 coverage area [42]. This project is not capable of collecting heat and only distributes waste heat from a nearby power plant for snow melting and de-icing of the pavement. Another example of a large PSC project was constructed at the car park of the 'De Compagnie' business park in Middelharnis, Netherlands, with a size of 32.000 m^2 using VOWAC [58]. However, most of the large-scale HAP projects have an area between 65-10.000 m^2, with a median of 550 m^2 which shows the high potential of implementing HAP in projects with different sizes. The median size of the research prototypes and actual projects is 90 m^2 and 740 m^2, respectively. Figure 3 gives an overview of the HAPs regarding their size.

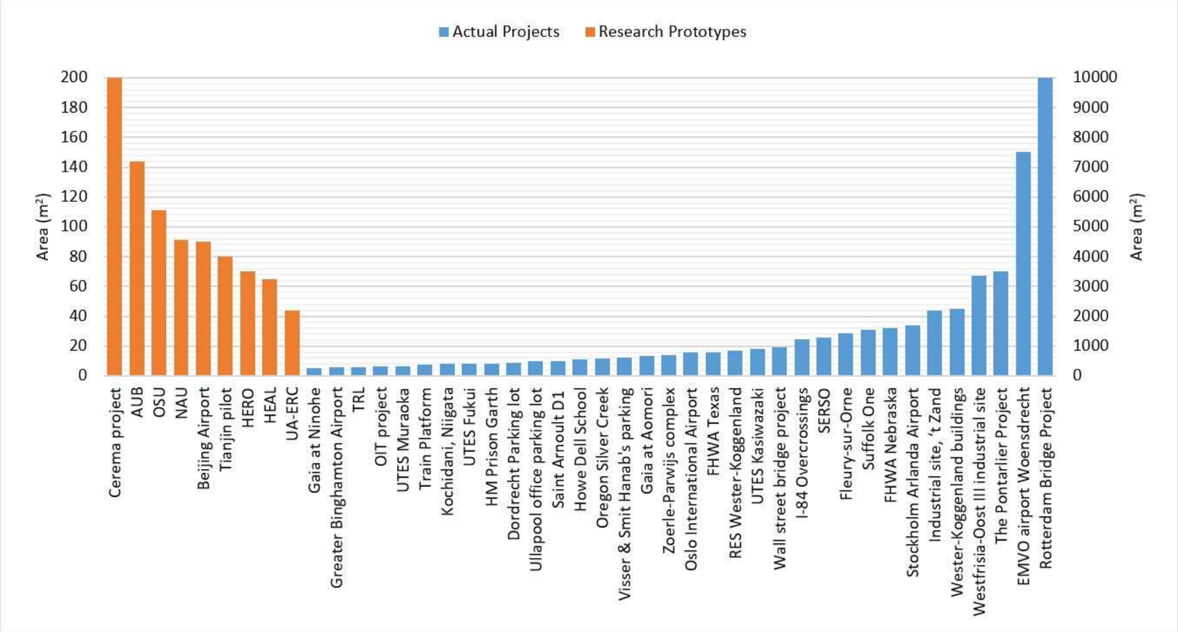

Figure 3. Size of different large-scale asphalt solar collectors (less than 10.000 m^2)

In the large-scale HAP systems, pipe spacing varies between 5 and 40 cm [33, 66, 68]. The calculated average pipe spacing for the large-scale HAP systems in Table 1 (if available) is 18,91 cm, with a standard deviation of 8,46 cm. The histogram of the pipe spacing given in Figure 4 shows that pipe distance between 10-20 cm is preferred more than other pipe spacing values. In specific projects, for upcoming projects or reconstructions, it was decided to shorten the pipe spacing in order to achieve higher efficiency in the thermal performance of HAP [33, 37]. In snow melting projects on bridges, minimum pipe spacing is reported 11,4 cm (i.e., Nebraska and Oregon) [49]. The small pipe spacing (5-10 cm) brings up a question whether this distance is enough for good quality compaction of the asphalt between the pipes because insufficient compaction may result in an unexpected reduction in the service life and a decrease in the heat transfer between pipe and asphalt.

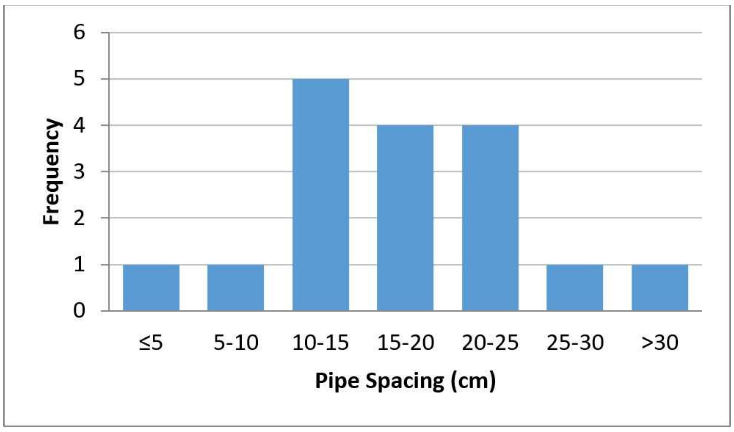

Figure 4. Pipe spacing histogram

Another important geometrical specification in HAP efficiency is pipe embedment depth. The challenge to achieve the optimum pipe embedment depth is to make a balance between harvesting maximum solar energy and preventing pipe damage due to wheel track passes. The heat extraction efficiency increases, the closer the pipe is placed to the surface. However, due to practical limitations and circumstances in large-scale projects (i.e., maximum aggregate size and compaction load), it is suggested to place pipes deep enough in order to resist potential structural failures. In addition, rehabilitation and maintenance of the surface layer should be possible without damaging the HAP layer. Embedment depth changes between a minimum of 5 cm (RES projects) to a maximum of 12 cm (TRL project) in different projects. A histogram of the embedment depth for the studied projects in Table 1 is given in Figure 5. The average embedment depth is 7,67 cm, and pipes are placed between 5-9 cm in most of the large-scale projects.

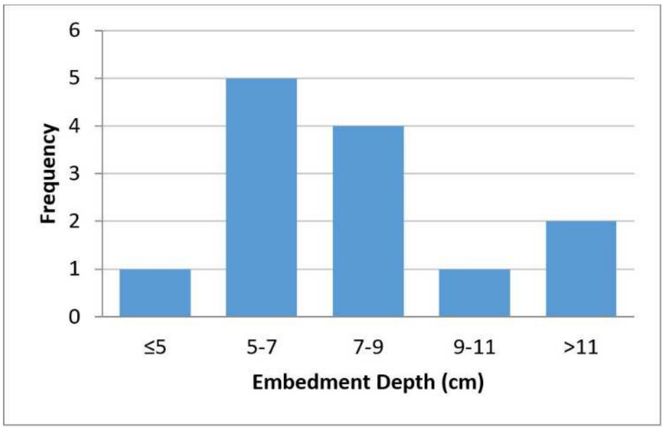

Figure 5. Embedment depth histogram

2.4. Material characteristics

The following subsection presents a brief description of the material characteristics used in large-scale HAP systems. Also, this subsection aims to look at different pipe materials since a trade-off between heat transfer, resistance to ‘medium temperatures’ during compaction, and their cost needs to be fulfilled. Embedded pipes in HAP are mostly made from metal or plastic. In the earliest HAP system in Klamath Falls (Esplanade Street Project), wrought iron pipes were placed in the bridge deck. As a result of corrosion, leakage was observed, and the de-icing system stopped providing service [39]. However, during the reconstruction of the project, the high-density polyethylene (cross-linked polyethylene) pipes were replaced with malfunctioning iron tubes [33]. Besides, Yoshitake et al. [77] proved that pop-outs of the concrete pavement in the large-scale pipe heating system were caused by the water leakage from the pipe joints. Although implementing metal pipes in the HAP is not common in large-scale projects, lab-scale experiments [11, 25] and a recently constructed HAP system [54] have used copper and cross-linked stainless steel pipes. Polyethylene pipes are used in projects of RES [66], TRL [34, 71], HERO [68], (UA-ERC) [78], FHWA (Nebraska Lincoln and Oregon Silver Creek) [49]. Also, in order to increase the thermal conductivity, the polybutene pipe was replaced by polyethylene in the Gaia system [37, 60]. It can be concluded that the plastic pipe, such as polyethylene or cross-linked polyethylene is the most suitable and preferred option concerning their lower cost and resistance against corrosion [55, 72]. A histogram of the pipe materials used in large-scale HAPs is given in Figure 6. The information of pipe material in the projects from the same company (i.e., RES) is counted as one in the histogram.

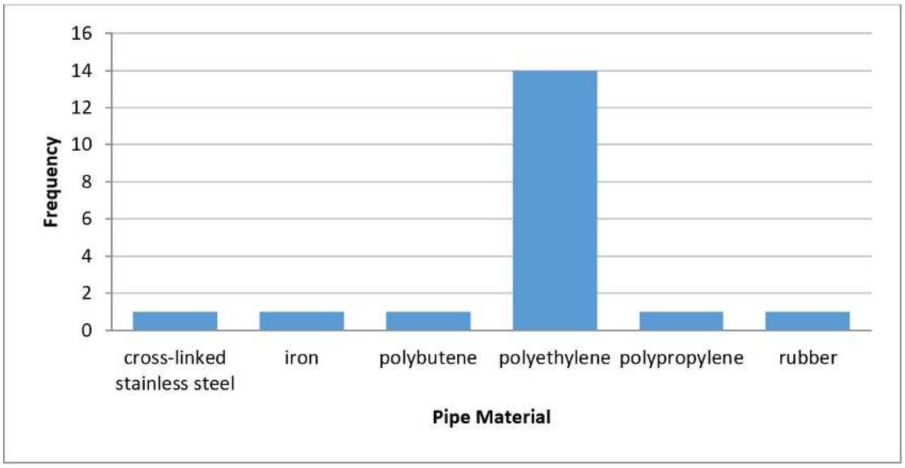

Figure 6. Pipe material histogram

Thermophysical properties of asphalt mixtures, such as thermal conductivity and absorptivity, have been studied by many researchers in small/lab-scale experiments. An interested reader may refer to [75, 76] for more detailed information, as it is outside the scope of this review paper. A few large-scale projects also investigated the thermophysical properties of asphalt mixture concerning the thermal performance, for instance, the Gaia systems used quartzite to increase the thermal conductivity and heat transfer in HAP. While the type of asphalt mixture is not as much important per se, the composition of the mixture in the heat exchange layer (i.e., binder percentage, air voids content, and type of aggregates) affects its thermophysical properties. Furthermore, a polymer-modified bitumen with higher resistance against cracking is used to achieve a soft mixture in the RES projects, so, the asphalt can be applied at a lower compaction temperature (130°C) [34, 51, 66]. During the pavement placement, water is circulated through the pipes to cool them as much as possible in order to avoid potential pipe deformations.

In the case of VOWAC solar collectors, pavement slope and porosity of the VOWAC layer are prominent features of the collector. Previous large-scale VOWAC collectors (Solar Road [58] and Cerema Clermont-Ferrand [57, 79] projects) were constructed with a road slope of about 2% in order to have water flow through the VOWAC layer. While a laboratory experiment manufactured the

VOWAC layer with 23% and 27% voids [80], the Cerema Clermont-Ferrand project paved used a porous layer with a porosity of only 20% [57].

3. Operational aspects

The objectives of this section are to investigate the integration of geothermal heat as a renewable energy source into HAP systems and different modes of operation in the asphalt solar collectors. To date, there are few studies that have investigated the association between geothermal heat and HAP. Besides, researchers have not treated different operation modes of HAP in much detail. The following two subsections highlight the importance of a functioning HAP with hybrid energy sources and alternative operation modes (see Table 1 for detailed information).

3.1. Hybrid geothermally coupled systems

The geothermal heat source coupling within HAP is discussed in the following subsection. As described in § 2.2, geothermal heat can be used in HAP systems as the heat source for snow melting or de-icing application. Geothermal energy is a sustainable, clean, and renewable source of energy that has been studied extensively in recent years and showed great potential to be used as a direct-use energy supply [81-84]. Although a low-temperature resource, geothermal heat extraction and utilization have been widely investigated in HAP due to its low-cost and availability in many countries all over the world [85-89]. Geothermal energy can provide the required heat for large-scale SMS by means of ground source heat pumps either exclusively or in combination with other heat sources such as electric heaters or fuel boilers [90, 91].

Geothermal heat is the main heat source of the Gaia snow melting projects, FHWA projects in the US (in Texas, Colorado and Nebraska), Klamath Falls projects, and 25 snow melting systems in Honshu Island [33, 39, 40, 90, 92, 93]. Besides, the OSU project implemented ground source heat pumps in a hydronic snow melting system to increase the energy efficiency of the system by harvesting heat and recharging the heat sink in the summertime [48, 73]. However, these projects use solar radiation as the auxiliary heat source to extract energy and store it in the heat sink [37, 73].

Moreover, the study by Iwamoto et al. [94] investigated the large-scale SMS using underground thermal energy storage in Japan. In the study by Iwamoto et al., they draw our attention to the broad popularity of using geothermal energy in snow melting projects, in which only electric power from an external source is required for the pump operation [94]. In another project, Yoshitake et al. [95] developed a geothermal energy-based snow melting system for bridge decks where groundwater is used as a circulating fluid in pipes. In addition to promising results in terms of economic (i.e., around 50% less expensive than a similar project with a borehole heat exchange system) and snow melting performance of this system, using groundwater in the system prevents ground subsidence that is highly potential in the sprinkler snow melting systems that use a mixture of groundwater and salt to spray it on the road surface [94, 95].

As indicated previously, GCHAP systems are constructed to heat airport aprons and aircraft parking in Greater Binghamton Airport [53], Oslo International Airport [52, 96], and Stockholm Arlanda Airport [78, 97] (see an example in Figure 7). In Greater Binghamton Airport, HAP is coupled together with twenty vertical (around 150 m) and two horizontal (around 40 m) geothermal storages to heat aprons in winter and cool down the terminal in the summer [19, 55, 78]. However, in the Oslo International Airport, HAP is coupled with an aquifer thermal energy storage system to heat aircraft parking stands [52, 98]. Similarly, the hydronic system is able to heat and cool the terminal buildings as well [99, 100].

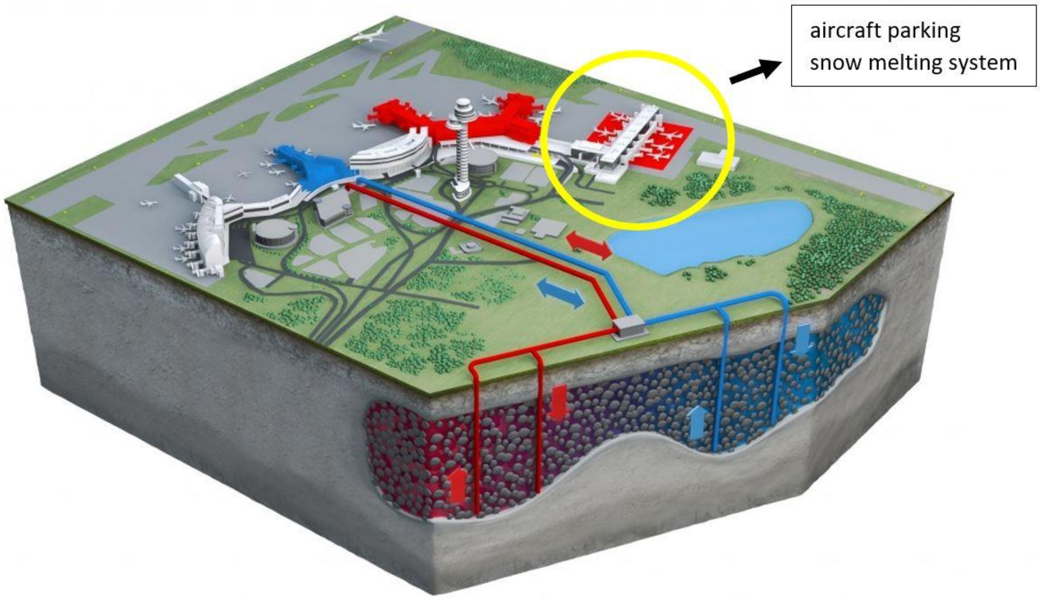

Figure 7. Aquifer thermal energy storage system coupled with HAP in Stockholm Arlanda airport (annotated from [101])

3.2. Modes of operation

Each large-scale HAP is programmed to operate in certain conditions of air temperature, asphalt surface temperature, etc. What follows is an account of various operation modes in different large-scale systems along with a critical review of their performance results. As explained earlier (§ 2.1), a large group of HAP systems is designed for snow melting or de-icing purpose on roads, bridge decks and pedestrian sidewalks. Obviously, the efficient operation of these systems during the wintertime is of paramount importance.

The operation mode of snow melting systems is divided into continuous and intermittent types. The control module of such systems is developed to automatically operate when certain criteria are met. For example, Downtown Holland and NAU projects are simple in their control system and are activated when it starts snowing, or weather temperature outside reaches 3,3°C [41, 46]. Although air temperature is taken as a salient parameter to activate snow melting systems, ice/snow formation depends upon the relative humidity and the dew point temperature [71]. Hence, projects of Gaia and FHWA (Nebraska) are operated according to more complex commands associated with road surface temperature, water presence on the road surface, precipitation, condensation of water in the air on the road surface and combination of several weather parameters [37, 49, 102].

In terms of operating continuity, Klamath Falls projects (in Oregon, USA) are rare projects that run continuously during the winter season [39, 40]. Evidently, the uninterrupted geothermal heat source of Klamath Falls explains the continuous operation of the project in wintertime [73]. However, in the intermittent mode, the snow melting system is controlled with a binary ON-OFF strategy [48, 103]. In this operation mode, the system automatically starts up and continues running until the system reaches a certain condition (i.e., pavement surface temperature) [73]. There have been no controlled studies that compare the performance of snow melting systems working in different modes. While research argues that continuous system operation requires less heat flux, this approach is limited in practice due to energy cost implications [35, 73]. Data from several studies suggest that applying moderate heat in-advance to harsh weather conditions results in better efficiency with respect to preventing ice/snow formation than distributing higher heat rates to defrost or melt snow [44, 73, 100, 104].

It can be concluded that the intermittent mode of operation saves both cost and energy compared to the continuous strategy. The future HAP projects can also benefit from a pre-heating strategy to ensure higher snow melting performance. Since the seasonal changes in asphalt pavement temperature result in pavement distress, omitting the gradient temperature can result in the prolonged service life of the pavement. However, there have been no controlled studies which compare differences in the service life extension of intermittent and continuous operation modes.

4. Performance evaluation

This section presents the findings of research on large-scale HAPs, focusing on the five key themes of construction cost, energy harvesting output, structural behavior, environmental impacts, and overall sustainability of these systems. The goal of the current section is to seek for inadequacies in previous research which will help to address the research gaps.

4.1. Cost of construction and payback period

To provide a comprehensive outline of Return on Investment (ROI) and payback period for HAP systems, this subsection analyses the cost of HAP construction in different projects. The cost of HAP systems strongly depends on parameters such as type of project (bridge deck or road pavement), size of solar collector, storage capacity, and coupling the HAP with geothermal heat supply. The limitations on finding detailed information on these key parameters remain a major challenge for researchers to pursue HAP cost/benefit analysis in different large-scale HAP projects. In this part, the cost values are converted and presented in euro currency for consistent and comparable analysis [105]. Besides, an online inflation calculator platform is implemented to calculate the present value of the HAP projects in 2020, where the USD to EUR exchange rate is taken equal to 0,92 [106].

The snow melting system of Wall Street Bridge project was constructed for €265.000 (around 289 €/m^2), and the older Esplanade Street project from 1948 required an additional €630.000 for reconstruction and operating cost [39]. In SERSO, the initial cost of the project, including research, development and supervision, was approximately €5,7 million. Although the installation costs of the SERSO prototype were high (around 3.000 €/m^2), it was argued that a follow-up system could be constructed at almost half-price [47]. In one of the NAU projects, the total cost of HAP system construction was approximately €162.000 (1.760 €/m^2), including primary research and design. Road Engineering System (RES) constructed a series of large-scale PSC during 1998-2006 to show that the cost per square meter of an asphalt collector is relatively low, compared to other solar thermal collectors. For example, it was demonstrated that a simple flat roof collector and a flatbed collector cost approximately 209 €/m^2 and 895 €/m^2 [107]. However, the total cost for one square meter of asphalt collector was reported about 151 €/m^2 [34]. Although in the projects of RES details of costs, investment, and comparisons with other systems are given, it remains unclear what is included in the project cost and what is not [38]. A recent study reported the following cost of different asphalt solar collectors: asphalt concrete (25-52 €/m^2), asphalt pavement (52 €/m^2), and VOWAC (41 €/m^2) [108]. In this study, the reported total cost of asphalt collector includes heat exchanger, but not the other parts such as electromechanical devices (i.e., heat pump), heat storage and control section since their cost can vary significantly from one project to another (i.e., €103.000 to €411.000 for the collector projects involving VOWAC).

In the preliminary studies of the AUB project, the cost of implementing PSC in a road section (including installation costs) was evaluated €1.408 for a two-lane 10-m section road (approximately 23,5 €/m², assuming the road area equal to 60 m^2). This construction cost is not in close agreement with the findings of the Wall Street Bridge and Street project, in which the cost of the piping was reported between 50-140 €/m^2 [39]. Moreover, a seminal study in the bridge heating systems illustrated that the construction cost of de-icing systems on the bridge deck varies from 287 €/m^2 to 1.094 €/m^2 [49]. Apart from construction costs, operational and maintenance costs vary widely depending on the heat source and climatic conditions [49].

In the HAP projects with a geothermal heat source, the cost of a project is directly affected by activating solar collectors or not. In certain projects that only use geothermal heat for de-icing, the major part of costs is due to drilling vertical boreholes, which costs approximately €80-120 per meter in depth [90, 109]. In Greater Binghamton Airport and Oslo International Airport, the pavement is equipped with airfield heated pavement systems using a geothermal heat source and their construction cost is €1.310.000 (3.520 €/m^2) and €320.000 (for each parking stand, and around 457 €/m^2) respectively [19, 78].

A systematic understanding of how economic analysis contributes to the payback period of HAP is still lacking. In projects of RES, researchers concluded that the return on capital investment is within 8 - 12 years [38, 108]. However, another study estimated the payback period of about five years for the project [25]. This variation in payback years of different projects stems from the items that are associated with the economic analysis. In [25], for example, the experimental setup used a configuration without a heat pump and complex control section.

The findings of this subsection have a number of important implications concerning the construction cost of HAP systems. First, implementing PSC in asphalt pavement is more cost-effective than other solar collector systems. Second, drawing a solid conclusion on the construction cost of different HAP projects is a challenge since their value differs in a large amount depending on project specifications (i.e., size and configuration). One possible reason for dramatic differences in the cost of HAP constructions can also be the selected location for the projects, knowing that in the countries with a cheap workforce, the project can be completed with competitive cost. The range of construction cost of asphalt collector for the heat exchanger section is between 25-151 €/m^2. This range is between 1.760-3.000 €/m^2 for the total cost, including the installation costs, research and design. The wide range of construction costs for the HAPs causes complexities in drawing a conclusion concerning system cost. In [7], Wang et al. compared the Levelized Cost of Electricity (LCOE) (i.e., total system costs divided by total electrical energy produced) for different energy harvesting technologies in the roadway. The comparison is based on the evaluated electrical energy output and the total cost of the systems. They concluded that PSC systems have better LCOE (4,21 \$/kWh) compared to thermoelectric (95,74 \$/kWh), electromagnetic (278,95 \$/kWh), and piezoelectric systems (106,38 \$/kWh). However, photovoltaic and geothermal technologies provide better LCOE than PSCs with 0,45 and 0,15 \$/kWh, respectively. Although assessment of the ROI and payback period in HAP systems demands in-depth analyses on energy output, construction cost, operational expenses, and savings in expenditure, there has been limited information published in the literature.

4.2. Energy harvesting output of PSC systems

It has previously been observed that PSC systems are capable of harvesting 50% of the solar radiation from the road surface [43]. However, other studies suggest a more conservative value (20%-30%) for the energy harvesting efficiency of PSCs [47, 100]. Although PSCs are proved as effective energy harvesting systems (up to 0,67 GJ/m² in the heat collection season), the debates are ongoing about heat loss from storage and quality of the harvested energy [34, 60, 100, 110]. In the SERSO project, around 150.000 kWh of solar heat (20% of incident solar radiation) is collected during summer and only 65% of that energy is available in winter due to the accumulated heat losses [47].

The energy harvesting capacity of the PSC depends on the project geographical location, storage capacity (seasonal energy extraction), and size of the collector. The collected heat can be used for power generation of the PSC system itself or external usage. In the Zonnige Kempen project, 20% of the extracted heat was used for de-icing, and the remaining 80% of harvested heat was used as a heating source for adjacent buildings [111]. In several other projects, internal and external use of collected heat is reported 20%–30% and 70%–80%, respectively [43, 64, 112].

The heat output of the system is a fundamental property of HAP in terms of thermal energy performance. The required heat energy for snow melting asphalt surface strongly depends on the weather parameters of the cold season. It is now well established from a variety of studies that large-scale HAP systems use 100 up to 900 W/m^2, again a large variation, of collected heat to provide ice/snow-free surfaces [33-35, 39, 43, 46, 47, 100]. For example, projects of Klamath Falls, SERSO, Gaia, Tianjin pilot and Power Road require 100-200 W/m^2 heat to maintain their snow melting serviceability. On the other hand, the NAU project, which is supplied by a central heating plant, has a heat output of between 700 and 920 W/m^2 in different months of the year. In a study investigating HAP energy harvesting potential, it is reported that the efficiency of the VOWAC solar collectors is 0,8 GJ/m^2/year [108]. According to this study, VOWAC systems have a higher energy harvesting efficiency in comparison with HAP systems (approximate efficiency of 0,6 GJ/m^2/year).

Despite the importance of energy harvesting from PSC, there remains a paucity of evidence on the amount of harvested solar heat in order to provide clean energy for external usage. Besides, a much-debated question is related to the definition of the ratio for internal and external use of the extracted heat due to the different size and specifications of various PSC projects.

4.3. Structural response of large-scale HAP systems

The following part of this paper describes the structural behavior of HAP with respect to stress distribution around pipes and pavement distresses due to temperature changes. As explained earlier in the introduction to this paper, one of the primary objectives of HAP systems could be to tune temperature changes in asphalt pavement in order to avoid pavement distresses such as top-down cracking, rutting and fatigue cracking. In previous studies on rutting damage in asphalt pavement, it was demonstrated that the service life of the HAP can increase between 3-5 years depending on traffic load, weather conditions, mixture material, etc. [13, 25]. SERSO [35], RES [34, 38], HERO [20, 113], Tianjin pilot [43], and AUB projects [72, 114] claimed to prevent permanent deformation of the pavement by implementing HAP systems. In a research conducted by Sullivan et al. [38] they have suggested using a relatively soft mixture in PSC heat exchangers, where bitumen should have a reduced viscosity, and good low and high-temperature performance to be able to resist cracking and rutting. However, a systematic understanding of how controlling temperature changes of asphalt pavement throughout different seasons prevents pavement distresses formation in such large-scale HAPs is still lacking to the knowledge of the authors.

As regards the introduction of heat exchange layer in HAP, structural performance of the pavement is expected to vary due to high stresses developing around the pipes, challenges in the construction stage (i.e., laying and compaction of the heat exchange layer), cracking resistance, differences in the thermal expansion coefficient of asphalt and pipe, improper adhesion between asphalt and pipe, and moisture damage [66, 72]. Van Bijsterveld et al. [66] performed a series of experiments using the commercial RES system to predict the failure mechanism and to obtain insight into the stress distribution in HAP systems. As a result, they showed that crack initiation starts from pipe vicinity, which affects the durability of the HAP structure negatively. To tackle the stress concentration around pipes, studies encourage using grid supports to fix and protect the embedded pipes (Figure 8). The grid support has been successfully implemented in projects of RES [38, 66] (EMVO airport platform Woensdrecht, Rotterdam Bridge, Ullapool office parking lot, and Wester-Koggenland building complex) and the CyPaTs project [64, 65, 69] at the University of Antwerp (Figure 9). The grid also provides a solid layout for precise placement of pipes, enhances confining and arching actions to reduce asphalt thickness, and takes the loading during construction partially (i.e., paving and compaction machinery). Lastly, the need for a grid was confirmed as several large-scale HAP projects reported potential difficulties due to lack of grid in the heat exchange layer [49, 71].

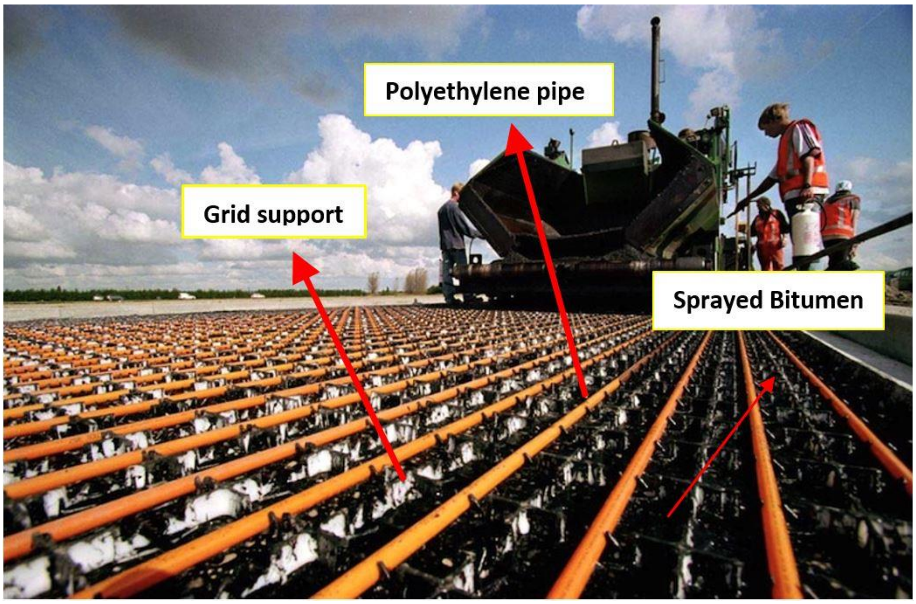

Figure 8. Details of the heat exchange layer in a PSC (annotated from [38])

Figure 9. Spraying bitumen on the support grid and pipes before the asphalt placement [65]

The structural performance of HAP systems is highlighted in projects concerning heavy traffic and loading (i.e., airport). To evaluate the structural performance of asphalt in Power Road projects, a pavement fatigue carrousel simulates the equivalent of 3 to 5 million heavy trucks [62]. In order to improve heat transfer, adhesion between the pipe surface and the surrounding asphalt mixture, and allowable movements due to differences in coefficients of thermal expansion between pipe and asphalt, grid and pipes are sprayed with 1,5 mm bitumen (high-quality elastomer modified bitumen) before the asphalt paving stage [66].

Even though several recent projects have not implemented grid supports, it proved to be an essential protection element in the construction of HAP systems.

Figure 10 and Figure 11 show the construction stage of projects with and without grid support.

Figure 10. The construction stage of PSC with grid support in a RES project [115]

Figure 11. The construction stage of PSC without grid support (left) Power Road where the tubes are placed in grooves in the previously installed layer [67], (right) ICAX TRL project where the pipe network is connected to a steel square mesh using metal pins [45]

4.4. Contribution to the reduction of UHI and CO_2 emissions

A more detailed account of the contribution of large-scale HAP systems regarding UHI, CO_2 emissions, and fossil fuel consumption is given in the following subsection. HAP systems with renewable energy sources are proved to have less carbon footprint than conventional vehicle-operated salt spreading systems for snow melting purposes [36]. As a result of harvesting solar radiation from asphalt, upper layers get cooler, and consequently, the sensible heat flux to the atmosphere reduces, which mitigates the effects of UHI [12, 13, 59, 62]. Although Dakessian et al. [25] showed that HAP significantly decreases pavement surface temperature using small-scale and simulation experiments, Saleh et al. [72] observed that both the HAP and GCHAP systems are not effective in reducing the surface temperature of the pavement sufficiently. Therefore, the findings of the impact of HAP systems on UHI effect are inconclusive.

PSC systems have demonstrated great potential in reducing carbon dioxide emissions due to the use of sustainable heating and cooling energy. For example, the annual decrease of CO_2 emissions in the ongoing Eurovia Forez-Est project is 16 tons by harvesting heat from a parking lot and using it for water heating in a public swimming pool. Besides, large-scale systems assessed the reduction in CO_2 emissions by means of replacing fossil fuels with renewable energy sources. The CO_2 emissions was diminished in projects of Gaia by 80% [37], Eurovia Fleury-sur-Orne 75% [67], RES (Wester-Koggenland building complex 45% [38] and Zonnige kempen social housing 8-50%) [61, 111], TRL 33-45% [109], and Howe Dell School (zero-carbon) [45]. It is noteworthy mentioning that the presented results are related to the theoretical and operational stages of systems since no information regarding the life cycle studies of the projects has been reported.

4.5. Sustainability assessment

The sustainability of the HAP systems with regards to economic feasibility, snow melting performance, and environmental effects are explained in this part. Sustainability Assessment (SA) is an important aspect of large-scale HAP systems [99, 116]. Studies have emphasized to investigate the SA of HAP systems utilizing LCA and life cycle cost analysis [64, 65, 113, 117, 118]. Sustainability of HAP should be assessed from various points of view, such as economic viability (i.e., return on investment), pavement service life, performance feasibility, safety increase (less car accidents) and environmental impacts. Although a limited number of studies have attempted to evaluate the sustainability of the large-scale HAP systems [119-123], they present a useful framework for future SA analysis by providing valuable information regarding governing parameters.

In [119], Habibzadeh-Bigdarvish et al. carried out a life cycle cost-benefit analysis on a GCHAP and showed their economic feasibility in comparison with conventional snow/ice removal systems. In addition to the high initial investment of GCHAP systems, the operation and maintenance cost was recognized as an important cost factor through the life cycle of the project [119]. Moreover, they performed a sensitivity analysis of the input variables on output results utilizing Monte Carlo Simulation (MCS), in which an increase in the traffic flow recognized as the most dominant variable. Nahvi et al. [121] confirmed that HAP systems are economically feasible, however, they argued the high dependency of benefit-cost ratio to project-specific features (i.e., in this case specifically the number of airplane operations and HAP project area) by employing MCS in a sensitivity analysis of input variables.

With respect to global warming, studies analyzed greenhouse gas emission in the conventional (mechanical machinery) and HAP snow/ice melting systems using life cycle assessment and concluded that HAP systems produce less greenhouse gas [122, 123]. Shen et al. [122] performed LCA on different snow and ice removal systems in airports (i.e., HAP) using a well-to-gate assessment to evaluate energy consumption and environmental impact aspects. The study aims to facilitate the decision-making process of the airport authorities and concludes that geothermally coupled HAP systems consume less energy and have lower greenhouse gas emissions than traditional snow and ice removal methods. A comparison of greenhouse gas emission (kgCO2 equivalent) between HAP and mechanical snow removing systems shows that traditional snow and ice removal systems reach around 6.000 (kgCO2 equivalent) after 12 hours of snow, while a HAP system could decrease the greenhouse gas emission up to around 55%. However, the results show that the snow rate affects greenhouse gas emission, especially at higher snow rates (e.g., 50,8 mm/h), and HAP systems with a lower coefficient of performance will produce almost the same amount (around 6.000 kgCO2 equivalent) of greenhouse gas as traditional snow and ice removal systems. In [123], a partial LCA assessment has been performed to exclude the same life cycle phases for snow/ice melting systems subjected to comparison. Due to the limited information on data and cost of the subjected projects, the LCA of HAP systems is concentrated on the partial phases such as the operation phase [122] and construction and operation phase [123]. The service life of the airport concrete pavement in the HAP, including construction and operation, was assumed as 20 years [122, 123].

5. Current challenges and future developments

This section presents current challenges in the design and construction of large-scale HAPs as well as future developments that need further investigation.

There has been limited discussion about the performance and potential challenges of collective heat provision using PSC. A further study could assess the distribution of the extracted surplus heat for district heating.

In terms of construction challenges, the small pipe spacing (e.g., 5-10 cm) can result in low-quality compaction of the asphalt between the pipes and grid (if any). Further experimental and numerical modelling is needed to understand the compaction quality around the pipes since insufficient compaction may create an insulation layer of air voids and decrease the heat transfer between pipe and asphalt. Another drawback of inadequate compaction is that the service life of the asphalt pavement could shorten due to an increase in rutting.

Embedment depth of pipe should be carefully considered to balance energy harvesting and prevent structural damage on the pipe due to wheel track passes. It is suggested to conduct combined numerical and experimental investigations to evaluate the sensitivity of pipe depth on the structural and thermal performance. An optimum solution is to achieve maximum solar energy extraction and minimum pipe damage, while the rehabilitation and maintenance of the surface layer should also be possible without damaging the pipe and grid.

Further research might explore the impact of intermittent and continuous operation modes on the snow melting ability and service life extension of asphalt pavement. Besides, future HAP projects can use a pre-heating protocol to achieve higher snow melting performance.

Finally, research on the LCA of HAP systems has been mostly restricted to limited comparisons of operation and construction phases rather than complete life cycle analysis. It can be argued that installing a HAP incorporates an increase in the CO_2 emission during the initial phase. Furthermore, since the polyethylene pipes (and grid) are embedded in the asphalt pavement, milling and reclaiming the top layer is challenging. In case of practical issues in the pavement milling and recycling of polyethylene and asphalt material, it might eliminate expected environmental benefits and result in an unfavorable scenario. Hence, further research should be carried out to establish the claim that the environmental benefits of HAP systems outweigh their adverse impacts.

6. Conclusions

The pavement solar collectors can extract solar radiation during summertime and deposit the heat in storage for cold months. Also, hydronic asphalt pavements (i.e., PSC) are an alternative for conventional snow melting systems. Based on the definition in this study, PSC systems are defined based on their ability to only harvest solar energy, while HAPs can couple other energy sources as well. This paper reviewed the constructed large-scale HAP to evaluate different aspects of these infrastructures. The present research aimed to investigate potential challenges that arise in large-scale HAPs and are less present in small- or lab-scale systems. This study has identified several findings that are summarized as follows:

There are only about 50 large-scale HAP systems around the world that are used for different reasons such as sustainable energy production, increase in road safety and extend of pavement service life. This limited number of large-scale HAP systems can be due to high initial cost, insufficient data on ROI and payback period for long-term investment, and inadequate research on the performance (e.g., high dependency on geographical location) and sustainability assessment of such systems. The area of a great number of large-scale projects changes between 65-10.000 m^2, with a median of 550 m^2. The median size for the research prototypes and actual projects is 90 m^2 and 740 m^2. In the HAP systems, pipe spacing changes between 5 and 40 cm, with an average and standard deviation of 18,91 cm and 8,46 cm, respectively. Most of the projects place the pipes with a pipe distance between 10-20 cm. However, there is a high risk of insufficient compaction in case of small pipe spacing that can cause a reduction in the service life. Embedment depth of pipe varies between 5-12 cm, with an average of 7,67 cm and highest frequency between 5-9 cm in different large-scale HAP projects. A trade-off in heat extraction efficiency, protecting the pipes from the forces during compaction and traffic(avoiding failure due to possible damages), and allowing the possibility of renewing the pavement surface layer is necessary for the embedment depth selection. The polyethylene pipe is the most widely used material in HAP systems owing to its cost-effectiveness and resistance against corrosion.

Hydronic asphalt pavements can be coupled with other heat sources such as geothermal, electric heaters, and fuel-based boilers to satisfy the required heat capacity of snow melting systems. The intermittent operation mode provides a more optimized operational strategy than the continuous mode in terms of saving cost and energy. A comparison between long term performance of intermittent and continuous operation modes seems necessary to evaluate their impact on the potential increase of the pavement service life.

PSCs are proven to be an economical alternative to the other solar collector systems. The construction cost of asphalt collector varies between 25-151 €/m^2 for heat exchanger section and 1.760-3.000 €/m^2 for their total cost. The wide range of cost for both cases reveals an uncertainty related to the variables concerning system cost. In terms of LCOE, PSCs (4,21 $/kWh) are a better alternative than thermoelectric (95,74 $/kWh), electromagnetic (278,95 $/kWh), and piezoelectric (106,38 $/kWh) technologies, while photovoltaic (0,45 $/kWh) and geothermal (0,15 $/kWh) technologies are more effective in LCOE than PSC systems. The return on capital investment for large-scale PSC systems are reported between 8-12 years. Since a large number of items are involved in a comprehensive economic analysis of the HAP systems, an accurate calculation of payback period needs more extended research. The energy harvest capacity of large-scale PSCs varies between 20%-50%, which depends on several parameters such as project geographical location, storage capacity, and size of the collector. Hydronic snow melting systems consume 100-900 W/m^2 of heat from storage to provide ice/snow-free surfaces. Both energy harvest capacity and heat requirement for snow melting show a great variation in different projects. Using grid supports is recommended to have better alignment of pipes and protection against heavy loads during and after construction. Even though several recent projects have not implemented grid supports, it can also provide a solid layout to enhance confining and arching actions to reduce asphalt thickness.

Based on the reviewed studies, the impact of PSC systems on the pavement surface temperature reduction is unclear. Consequently, PSCs do not necessarily mitigate the UHI effect. Further research should focus on the impact of large-scale HAP systems on the surrounding air temperature in the urban areas rather than limiting the scope of studies to temperature variation of the pavement surface. HAPs can decrease the release of CO_2 considerably by substituting fossil fuels with the geothermal or solar energy. However, a comprehensive LCA is required to evaluate the system from different points of view, such as energy performance, an extension of pavement service life, and material recycling. The LCA of HAP systems is limited to the operation and construction phase since not much information is available on data and cost of the large-scale projects.

This review paper has brought to notice several challenges and problems in need of further investigation. The extracted heat is a low-quality energy type, and storage of this heat with efficient insulation until wintertime is a major concern. The construction time of HAP systems needs to be as short as possible in order to be practical to be applied in the existing road pavements (interfering with the road users). Embedment depth of pipe should be carefully considered in order to improve the efficiency of both the heat collection and winter maintenance while also tackling durability issues in asphalt pavement. The large-scale HAP systems should be monitored in the long-term to enable researchers to provide an assessment of the thermal and structural performance of these systems.

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