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Assessment of Greenhouse Gas Emissions from Geothermal Heated Airport Pavement System

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Abstract: Geothermal heated pavement systems (GHPS), *viz.*, the use of geothermal energy to heat pavements, have been used as an efficient alternative to de-icing chemicals and mechanical snow-removal equipment. Although some previous studies on pavement-heating systems have focused on their efficiency and economic viability, up to this point none of them have systematically investigated their potential to contribute toward global warming. This study applies life cycle assessment to analyze and compare greenhouse gas (GHG) emissions resulting from the use of either GHPS or traditional snow-removal systems on airport runways and gate areas. A GHPS produces lower GHG emissions than a traditional snow-removal system in removing 2.5 cm of snow from an airport runway, and it is anticipated that the actual environmental benefits of using heated-pavement systems may become more evident at higher snowfall intensities or durations. The study also discovered that GHG emissions resulting from the use of GHPS at the airport gate area are about 100 times less in magnitude than those resulting from the use of either GHPS or traditional snow-removal strategies applied to airport runways. This indicates that the use of GHPS in selected airport areas such as airport gate areas (as opposed to runways) can result in much greater sustainability benefits, in terms of improved airport ground crew safety, cost-effectiveness, and reduced environmental impact.

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***Key words**: Geothermal; Green house gas; Heating; Pavements; Snow and ice melting.*

Introduction

Snow, ice, or slush on airfield surfaces can result in aircraft-related accidents, so snow removal is a top priority for airports [1]. De-icing and anti-icing are two major techniques for removal of snow, frost, or ice from transportation surfaces to increase traffic safety. Airports typically use mechanical snow-removal equipment such as snow plows and snow blowers to move snow from traffic areas to other locations and use chemical reagents for deicing/anti-icing for removal or preventing formation of ice on airport runways, taxi-ways, and other surface areas accessible by snow-removal equipment [2].

Heated pavement systems are being explored as efficient alternatives to mechanical and chemical de-icing techniques. Heated pavement systems refer to the idea of heating a pavement surface using either electrical means or through hydronic heating, i.e., running heated fluid through embedded pipes [3]. A geothermally-heated pavement system (GHPS) uses a ground-source heat pump (GSHP) to extract geothermal energy for warming up and circulating a hot water/glycol mixture through pipes embedded within the pavement to heat up the pavement and thereby melt the ice. A GSHP can also provide space heating by capturing heat present in the soil or groundwater using a heat exchanger [4]. Geothermal heat-exchanger systems fall into one of three types: direct-exchange, closed-loop, and open-loop. Open-loop systems are highly dependent on groundwater extraction and have relatively low efficiency; closed-loop systems require longer and larger pipes and consequently result in increased construction costs. Because of these disadvantages, this study focused on only direct-exchange-based GHPS.

A direct-exchange system uses a single loop to circulate fluid in contact with the ground to directly extract or dissipate heat. There are two kinds of piping systems, viz., horizontal systems and vertical systems. The depths of horizontal heat exchangers range from three to eight feet, while vertical heat exchangers may require depths ranging from 30 to 152 m [5]. It has been claimed that a vertical-loop system is relatively more efficient than a horizontal one because the ground temperature remains relatively constant at depths greater than 61 m [6], so only vertical direct-exchange geothermal systems will be considered in this study. Geothermal heating has been used in numerous residential and industrial applications.

Although previous studies on heated pavement systems have analyzed their snow-removal efficiency and cost–effectiveness, few if any studies have attempted to investigate in a systematic manner their environmental efficiency based on greenhouse gas (GHG) emissions of CO_2, CH_4, and N_2O. An analysis of GHG emissions from newly-developed man-made processes/techniques is essential because there is “a more than 90 percent probability” that anthropogenic GHG emissions have contributed to many of the current global-warming trends, as described in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [8]. Well-publicized global-warming effects can cause serious environmental problems such as sea-level rise, subtropical desert expansion, and even extinction of species [7-9].

To help understand GHG emissions of airport snow-removal systems, a life-cycle assessment (LCA) technique for conducting carbon footprint analysis (CFA) can be used. CFA analyzes the total

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amount of CO_2 and other GHG emissions released over the life cycle of a product or system expressed in metric tons of CO_2 equivalents or tCO_2eq. The use of a LCA and a CFA to assess the GHG emissions of both traditional and alternative airport snow-removal systems will enable airport owners or operators to consider various what-if scenarios and identify airport pavement locations where such a system is most likely to have the highest/least environmental impact.

Scope and Objectives

The overall goal of this study is to compare the energy use and carbon footprint of a GHPS with that of a traditional airport runway snow-removal system. LCA methodology will be used to estimate GHG emissions from both the snow-removal systems by defining and establishing the boundaries for the system analysis, by developing a full understanding of the amount of energy used and GHG emissions from the systems, by assessing potential environmental effects through an inventory analysis, and by evaluating the consequences of the inventory analysis and impact assessment to provide actionable insights for system operators [10].

There are three broad approaches to conducting a LCA: process life-cycle assessment, economic input-out life-cycle assessment, and hybrid life-cycle assessment. Although the LCA process has disadvantages, such as subjective boundary selection, lack of comprehensive data in many cases, and some uncertainty, it does provide detailed information with respect to the assessment of specific processes and is generally considered to be an effective methodology for product comparisons [11]. The LCA process considers material and energy input and GHG output within the pre-defined system boundary at every stage in the life cycle. Since the objective of this study is to do a comparative CFA and environmental impact assessment of traditional snow-removal and heated pavement systems rather than a detailed cradle-to-grave LCA of airport snow-removal systems, a partial LCA methodology has been adopted, one that excludes those phases of the life cycle that are exactly the same for both systems with respect to energy consumption and GHG emissions.

The GHGs considered in this study include CO_2, CH_4 and N_2O emissions resulting from the construction and operation phases of both snow-removal systems. The concept of global-warming potential (GWP) is typically used to express the capability of a certain GHG to trap heat in the atmosphere relative to CO_2 over a specified time horizon. Based on the Fifth Assessment Report of the IPCC [8], CO_2 has a global-warming potential (GWP) of 1 over 100 years; CH_4 has a GWP of 25 (i.e., Methane is capable of trapping 25 times more heat than CO_2 per unit weight over a 100-year time period) and N_2O has a GWP of 298.

The nature of LCA and GHG emissions from energy production and waste treatment operations is well documented in the literature, so upstream GHG emissions from power plant and end-of-life GHG emissions from waste treatment are included in this study in order to provide better understanding and highlight the differences in energy use and carbon footprints between the two types of snow-removal systems.

Carbon Footprint Analysis Methodology

Overview of Snow-removal System Life-cycle Phases

The life cycle of a snow-removal system includes several different stages in its production, implementation, and operation, beginning with the extraction of its raw materials. As the first LCA study on GHPS at airports, this study considered only life-cycle phases making significant contributions towards overall GHG emissions from both GHPS and traditional snow-removal systems. GHPS also is a relatively new technology applied to airport snow removal, and therefore detailed information needed to conduct a full-fledged LCA study related to its maintenance (frequency, energy consumption, etc.) is lacking in the literature. Thus, for the sake of simplicity, this study focused more on GHG emissions from the construction and operational phases of the traditional snow-removal system and the GHPS. The time horizon for analysis was assumed to be 20 years, ranging from construction through operation. The GHGs from wastewater treatment and incineration plants have previously been reported as being significant, so waste treatment was included separately as a life-cycle phase. Assuming that the waste released consists mostly of chemical pavement deicer (mixed with melted ice/snow slush) from the operational phase of the traditional runway snow-removal system, the wastewater treatment phase is included in the LCA of the traditional snow-removal system. However, based on reported literature, *viz.*, Life Cycle Assessment: Principle and Practice [10], landfills have not been considered as a life-cycle phase in this study

To compare the GHG emissions of both snow-removal systems under identically conditions, both are assumed to be used to remove 2.5 cm (1 in.) of snow at an ambient temperature of -21℃ (-6℉, a freezing rainy day) on identical airport runways. The runway area for analysis is assumed to be 1.67×10^5 m^2 (1,114 m × 14 m) and the runway section is assumed to consist of 30 cm thick Portland cement concrete (PCC) pavement.

Geothermally-heated Pavement System Model and Life Cycle

For the vertical direct-exchange geothermal system considered in this study it is assumed that one unit of hydronic piping (see Fig. 1 (a)) can heat an area of 0.85 m^2. A three-quarter-inch polyethylene (PE) pipe is assumed in this study to circulate a propylene glycol solution [12]; the maximum pipe length is about 91 m for a single circuit. Since one unit of hydronic piping requires 5.2 m of pipe length, there can be 18 units per circuit (see Fig. 1 (b)). In this study, 40 circuits were calculated to have been placed into one well to minimize the number of heat wells (see Fig. 1 (c)); one 152-m heat well can thus warm up to about 613 m^2 of slab area. Assuming a 3.8 liter per minute water-flow rate per circuit, the total flow rate is 2.5×10^{-3} m^3/s per heat well.

The GHPS life cycle phases include a construction materials production phase, a system construction phase, an energy production phase, and a system operation phase. There is no waste treatment phase since there is no use of deicer with heated pavements. The energy production phase also accounts for GHG

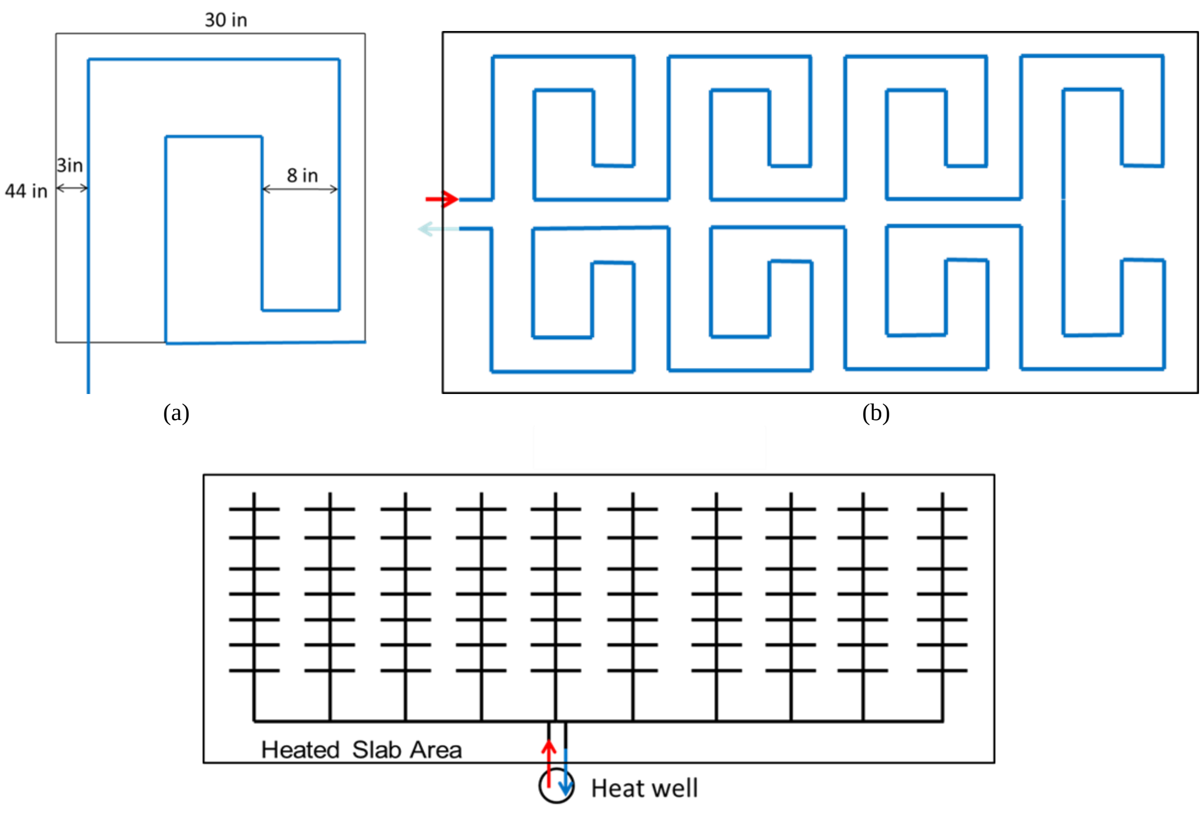

Fig. 1. Plan View of Hydronic Piping Model: (a) One Unit of Hydronic Piping, (b) One Circuit of Hydronic Piping, and (c) Hydronic Piping Model Per Heat Eell.

emissions from cradle to grid. In this study, the critical factors in the GHPS construction phase are the drilling of the heat well and the PCC pavement production. The only energy demand to run the system is assumed to be that for the pumping operation. An electric pump is selected as an example of a power-supply device for circulating the heated fluid. The system boundary of the GHPS life cycle considered in this study is shown in Fig. 2.

Because the electric pump applied in a direct-exchange geothermally-heated system consumes electrical power for circulating fluid, no GHG will be directly released from the heated system. This means that the total amount of GHG released from the construction materials production phase, the construction phase, and the energy production phase has been taken to be the total GHG emissions from the GHPS.

Construction Material Production Phase and Construction Phase

The airport runway PCC, with a 20-year design life, has an assumed composition of 12% cement, 82% aggregates, and 6% water by total volume. Using system boundaries, technical applications, fuel sources, and raw material sources described in previous studies, the GHG emission factors from concrete manufacturing, assumed to be the same as reported in those [13-17], vary from 0.10 to 0.13 tCO_2eq/t of concrete. A GHG emission factor of 0.13 tCO_2eq/t of concrete is assumed as a conservative estimate for the pavement-construction materials production phase in this study [18].

The total mass of concrete required for building a runway area of 1.67×10^5 m^2 with 30 cm thickness is estimated to be 1.35×10^5 t (density of concrete is assumed to be 2.68 t/m^3). Consequently, the GHG emissions from pavement-construction materials manufacturing is about 1.7×10^4 tCO_2eq. Based on a previous study [19], a GHG emission factor of 0.004 tCO_2eq per 30.5 m pipe is assumed for PE pipe manufacturing. Based on the geothermal-heated pavement model, about one million meters of PE pipe are needed to heat the 1.67×10^5 m^2 runway area, so the total GHG emissions from PE pipe manufacturing are estimated to be 43 tCO_2eq.

The construction phase of the GHPS includes PCC placement and heat-well drilling. Based on a previous study [14], the GHG emission factor for PCC placement taken to be 2.5×10^{-3} tCO_2eq/t concrete which is much less than 23.3×10^{-1}, the emission factor for construction-materials manufacturing. The GHG emission from PCC placement is thus 338 tCO_2eq. Heat-well drilling utilizes a driller to dig deep holes, and a driller equipped with a 1,500 kW engine and exhibiting a 39.6 m/min drilling speed is assumed in this study. Based on the geothermally-heated system model considered in this study, 263 wells are required, so the total drilling time works out to be 34 hours. To accurately determine the amount of GHG where the conversion factor for diesel fuel is taken to be 0.00268 t released from heat-well drilling, an estimation of diesel oil consumption must be included; the fuel consumption estimated as in [20] is:

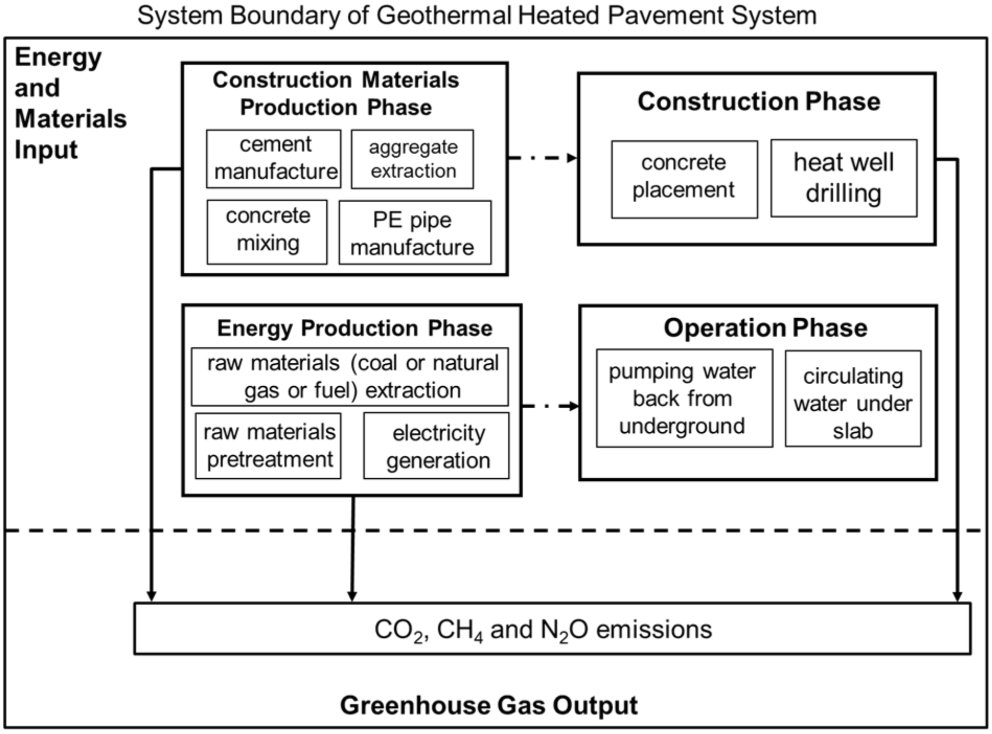

Fig. 2. System Boundary of Geothermal Heated Pavement System.

$$FC = RP \times 0.3 \times LF \tag{1}$$

where *FC* is Fuel Consumption (per h), *RP* is equipment rated power (kW), 0.3 is a unit conversion factor (per kWh), and *LF* is an engine load factor (60% assumed).

The diesel fuel CO_2 conversion factor (99% of total GHG) emission can be calculated as [20]:

$$\text{GHG emissions} = FC \times .00268 \tag{2}$$

[21]. GHG emissions from heat well drilling are estimated to be 42 tCO_2eq.

Because of lack of available data regarding energy consumption and emissions from the PEX pipe-placement operation (expected to be minimal from an overall life-cycle perspective), it is not included in this study. The resulting total GHG emissions from the construction phase are calculated to be 380 tCO_2eq. Since the time horizon of the airport runway in this study is assumed to be 20 years, the total GHG emissions from the construction material production phase and the construction phase can be calculated to be 17,423 tCO_2eq, and the resulting daily GHG emissions are 2.39 tCO_2eq.

Energy Production Phase and Operation Phase

The energy production phase GHG emissions analysis is based on previous studies [24, 27] of life-cycle assessment of electrical power production. Three different power-plant energy sources are considered in this study: coal, natural gas and distillate oil. Because coal-fired power plant GHG emissions can vary by location, a power plant located in Iowa has been assumed in this analysis. The phases of coal-fired power-plant life cycle include coal mining, coal preparation/cleaning, all necessary transportation of coal to power plant, and electrical grid power production. GHG emissions of different life phases of the assumed coal power plant are shown in Table 1.

A natural gas-fired power plant life cycle includes natural gas extraction, natural gas pretreatment, natural gas pipeline transportation, and electrical grid power production [27]. GHG emissions during different life cycle phases of a natural gas-fired power plant are shown in Table 2.

Because the distillate oil-fired power plant GHG emissions factor is highly site-specific, a reasonable value of 0.778 tCO_2eq/MWh based on a previous study [28] was assumed. To confirm the applicability and use of this factor, it was compared with the US Energy Information Administration (EIA) database [29].

In summary, a (bituminous) coal-fired power plant in Iowa has a GHG emission factor of 0.99 tCO_2eq/MWh; a natural gas-fired power plant has a GHG emission factor of 0.42 tCO_2eq/MWh, and a distillate oil (No.2) power plant GHG has an emission factor of 0.78 tCO_2eq/MWh.

To determine the amount of energy required to melt a 2.5 cm thick snow cover, the following equation for calculating the required pavement heat output (*qo*) in $Btu/h{\cdot}ft^2$ was applied [30]:

$$qo = qs + qm + Ar(qe + qh) \tag{3}$$

where *qs* = sensible heat transferred to the snow ($Btu/h{\cdot}ft^2$), *qm* = heat of fusion ($Btu/h{\cdot}ft^2$), *Ar* = ratio of snow-free area to total area (dimensionless), *qe* = heat of evaporation ($Btu/h{\cdot}ft^2$), and *qh* = heat transfer by convection ($Btu/h{\cdot}ft^2$).

The energy demand (*qo*) was estimated to be 205 $Btu/h{\cdot}ft^2$ (2.5×10^5 $J/h{\cdot}m^2$) for snow removal. Approximately 20% back and

Table 1. GHG Emissions from Coal-fired Power Plant.

Life Cycles of Coal Power Plant		GHG Emission Factor (tCO_2eq/MWh)	Percentage (%)
Surface Mining[1]		7.0×10^{-3}	0.70
Coal Washing[2]		1.0×10^{-4}	0.01
Coal Transportation	Shipping[3]	1.0×10^{-1}	10.1
	Railway[4]	2.6×10^{-4}	0.03
Grid Electricity Production[5]		8.8×10^{-1}	89.2
Whole Life Cycle		9.9×10^{-1}	100

[1] Illinois No. 6 coal as an example; electricity demand: 0.0143 MWh/t of coal; diesel oil demand: 269 m^3/MMT of coal; transportation of diesel oil GHG emission: 2.7 $kgCO_2eq/L$; 0.54 kg coal/kWh electricity produced [22-24].

[2] Jig washing is the technique used in this LCA [22].

[3] Distance from mining to power plant: 434 km; GHG emission: 0.43 $kgCO_2eq/t{\cdot}km$ [25].

[4] Distance from mining to power plant: 48 km; GHG emission: 0.01 $kgCO_2eq/t{\cdot}km$ [25].

[5] Data from US Energy Information Administration EIA-1605 is used [26]

Table 2. GHG Emissions from Natural Gas-fired Power Plant.

Life Cycles of Coal Power Plant	GHG Emission Factor (tCO_2eq/MWh)	Percentage (%)
Natural Gas Extraction[1]	4.3×10^{-3}	1.01
Natural Gas Pretreatment and Transportation[2, 3]	9.9×10^{-5}	0.03
Grid Electricity Production[4]	4.2×10^{-1}	99.0
Whole Life Cycle	4.2×10^{-1}	100

[1] Natural gas density: 0.7 kg/m^3; 2-phases 95%-efficiency compressor is applied, power demand: 4.9×10^{-3} kw/m^3 of natural gas [27].

[2] Total distance: 482 km by pipeline transportation [25].

[3] Specific volume of natural gas: 1.49 m^3/kg; auxiliary boiler natural gas consumption: 0.16 kg/MWh [27].

edge losses [31] were assumed in the heat output calculations. Because the total area for one runway is 1.67×10^5 m^2, the total energy demand to melt 2.5 cm snow is estimated to be 452 million kJ. Using the geothermally-heated pavement model discussed above, there is a demand of 263 heat wells and each heat well is 152 m deep. The energy supplied by the geothermal vertical loop can be calculated using the following equation [32]:

$$E = 0.00095 \times P \times m \times cp \times (\Delta T) \tag{4}$$

where E = energy supply (J/h), m = mass flow rate of water (9.200 t/h), cp = specific heat of water (4.18 J/g·°C), ΔT = outlet water temperature - inlet water temperature (10℃ assumed), P = energy loss from PE (cross-linked polyethylene) pipes, soil, and concrete slab (80% assumed).

Therefore, 263 heat wells can supply about 8.1×10^7 kJ/h. The energy required to melt 2.5 cm of snow on a 1.67×10^5 m^2 runway section is 4.5×10^8 kJ with an operational time of 5.56 hours. To pump 2.5×10^{-3} m^3/s of water through a 152 m deep heat well, the pump power requirement can be calculated as:

$$Hp = Q \times H \quad 3960 \tag{5}$$

where Hp = horse power of each pump, Q = flow rate (151 liter/h), and H = depth of heat well (152 m).

The horsepower demand for each pump is 5.05 Hp, or 3,768 watts. Because 263 heat wells would require 263 pumps, the required energy is 5,522 kWh to melt 1.67×10^5 m^2 of 2.5 cm-depth snow in 5.56 hours. The GHG emissions resulting from the use of electricity produced by a coal-fired power plant, a natural gas-fired power plant, and a distillate oil-fired power plant are 5.43 tCO_2eq, 2.32 tCO_2eq, and 4.30 tCO_2eq, respectively.

Traditional Snow-removal System Model and Life Cycle

Based on the FAA snow-removal standard [1], snow-clearing time for each runway at a commercial service airport whose annual airplane operations exceed 40,000 in number should be limited to 0.5 hours. Snow plows, snow brooms, snow blowers and chemical deicer trucks are the assumed snow removal equipment units to be used in removing 2.5 cm of snow from a runway in this study. Snow-removal equipment is assumed to operate at a speed of 32 km/h, and the traditional snow-removal strategy assumed in this study is as follows: a snow-plow is run to move the snow to the side (it is assumed that 6 snow plows and 6 snow brooms with a 8,600 kW total engine power will be employed), followed by two snow blowers with a total engine power of 1,640 kW and two chemical sprayers with a total engine power of 1,200 kW to spray deicer on the runway to prevent snow formation.

One of the major differences in life cycle phases between the GHPS and a traditional snow-removal system is the waste-treatment phase required during the traditional snow-removal system life-cycle phase. Because chemical deicer is used in snow equipment application, the resulting polluted water must be treated in a wastewater treatment plant, contributing considerable GHG emissions to the system life cycle. It is assumed that the traditional snow-removal system is operated over a conventional PCC pavement, and that diesel oil is used for snow-removal equipment operation. The system boundary for the traditional snow-removal system operation life cycle considered in this study is shown in Fig. 3.

Construction Materials Production Phase and Construction Phase

The PCC pavement construction materials production phase includes only the pavement construction materials manufacturing process. In this study, PCC pavement concrete applied in a traditional snow-removal system runway is assumed to be identical to the concrete used in GHPS, so the GHG emissions are estimated to be 1.7×10^4 tCO_2eq. The GHG emissions from the PCC pavement construction phase are estimated to be 338 tCO_2eq, similar to the construction phase estimate for the GHPS.

Energy Production Phase and Operational Phase

Diesel fuel is assumed to be the only energy source used for snow-removal equipment. The emission factor for fuel extraction is 0.022 tCO_2eq/MWh, and for petroleum is 3.35 kWh/L, so the GHG emission factor is 0.0737 t/m^3. Since fuel consumption is 231.06 L, the total GHG emissions from the fuel extraction phase of the traditional snow-removal system life-cycle are estimated to be 0.017 tCO_2eq. To calculate the amount of diesel fuel used by snow-removal equipment in removing 2.5 cm of snow and thereby estimate the GHG emissions, Eqs. (1) and (2) were used to calculate GHG emissions from heat-well drilling, so removal of a 2.5 cm deep snow layer in 0.5 h from about 1.67×10^5 m^2 of runway area requires six snow plows, six snow brooms, two snow blowers and two chemical sprayers; the GHG emissions resulting from snow removal operations are thus 0.62 tCO_2eq/day.

Waste-treatment Phase

At an ambient temperature of -21℃ on a freezing rainy day, the potassium acetate deicer demand is approximately 11 liters per 93 m^2 runway for melting 2.5 cm of snow [34]. The total potassium acetate demand is about 20,000 liters, and 90% of the de-icing wastewater is assumed captured [33]. The concentration of the 50% potassium acetate component is 7.8×10^{-4} t/L [34], so the Chemical Oxygen Demand (COD) content of potassium acetate deicer can be calculated as:

$$\begin{aligned} COD(lbs) &= Chemtcal\ (lbs) \\ &\times Chemical\ Molecular\ Weight\ (mole/g) \\ &\times ThOD \times O_2 Molecular\ Weight\ (g/mole) \end{aligned} \tag{6}$$

where the ThOD (Theoretical Oxygen Demand) of potassium acetate is 0.92 mole/g, the Potassium acetate molecular weight is 0.01 mole/g, and the O_2 molecular weight is 32 g/mole [35].

The total wastewater COD is 4.2 t. The airport runway wastewater is assumed to be treated by the nearest city wastewater treatment plant that uses an aerobic biological treatment, and a value of 1×10^{-3} kWh electricity demand per t COD is assumed for such treatment [36]. Therefore, the total electricity demand for deicer wastewater treatment will be about 4,202 kWh. With respect to the GHG emission factors of the power plant, the GHG emissions of wastewater treatment are estimated to be 5.83 tCO_2eq from coal-fired plants, 2.85 from natural gas-fired plants, and 4.74 from distillate-oil-fired power plants.

Comparison of Results and Discussion

The GHG emissions from both snow-removal systems to remove 2.5 cm of snow on a freezing rainy day are summarized in Table 3 and Table 4, respectively. Energy production and construction materials production are two phases that release more GHG emissions than other life-cycle phases in both snow-removal systems. The GHG emissions from the operational phase are not included in Table 3 since they are already accounted for in the energy production phase (electrical power is consumed during the

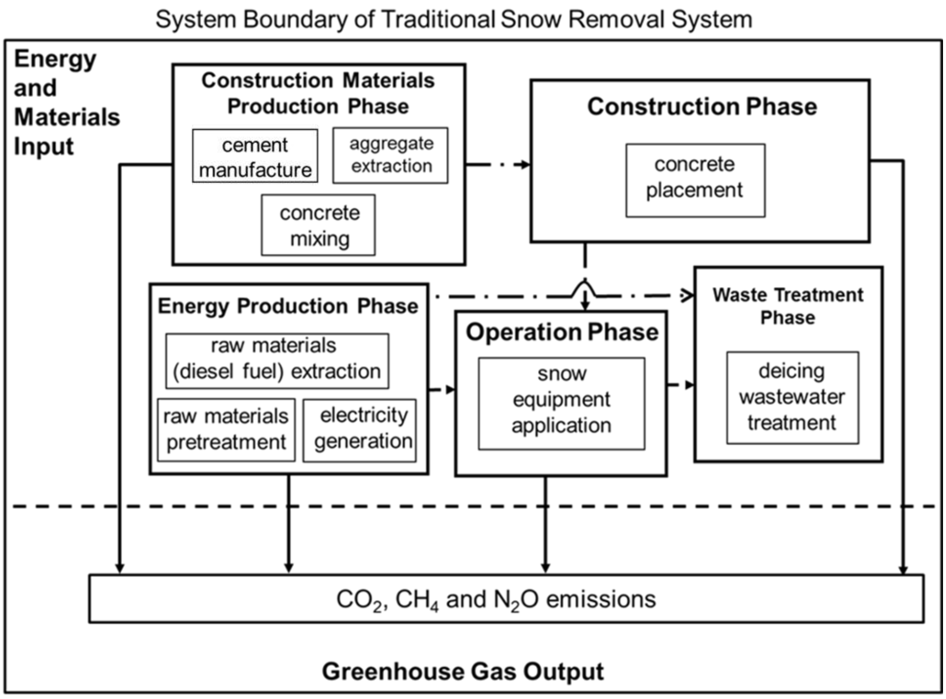

Fig. 3. System Boundary of Traditional Snow Removal System.

operation of the GHPS). Similarly, GHG emissions from the waste-treatment phase are not included in Table 4 since they are already accounted for in the energy production phase (electricity is consumed during deicer wastewater treatment). However, operational-phase GHG emissions are separately presented in Table 4 since diesel fuel is consumed during the operation of snow-removal equipment and this has not been accounted for in other life cycle phases of the traditional snow-removal system.

Based on the assumptions made in this study, the total GHG emissions from GHPS appear to be less than the GHG emissions using a traditional snow-removal system to remove 2.5 cm of snow from an airport runway on a freezing rainy day. High GHG emission from a traditional snow-removal system is caused mainly by the deicer wastewater treatment. An increase in snowfall, of course, requires more deicers for the same area. GHPS can solve the problem caused by using a deicer to remove snow from the runway.

The GHG emissions from both types of snow-removal systems are slightly higher if coal and distillate oil are used as power-plant energy sources; the GHG emissions, however, are reduced when electrical power to operate the GHPS and the deicer wastewater treatment of a traditional snow-removal system is obtained from a natural gas-fired power plant.

Some Implications for Practice: Use of GHPS in Airport Gate Areas

The use of GHPS on airport gate areas, compared to use on runways/taxiways, has gained more attention from airport authorities such as the U.S. Federal Aviation Administration (FAA), especially because traditional snow-removal equipment has difficulty in accessing such areas when a flight remains at a gate; in such a situation, before performing snow-removal operations, some on-ground maneuvering of the aircraft is required because of the presence of snow-clearing crews. This type of operation on slippery pavement surfaces has the potential to cause accidents involving the snow-clearing crew (such incidents have been reported by some airports) as well as economic penalties. Considering the potential benefits of using GHPS in airport gate areas, an environmental impact assessment study focusing on the use of GHPS in airport gate area was carried out.

GHG emissions from the use of GHPS in airport gate areas were estimated using procedures and assumptions similar to those used in estimating GHG emissions from airport runaway areas. Table 5 summarizes the GHG emission estimates for each life-cycle phase considered in this study for the use of GHPS in airport gate areas. Assuming about 1,700 m^2 of gate area, about 95 times less than that of the runway area, about 0.025 tCO_2eq/day of GHG emissions can be estimated from pavement construction materials manufacturing, about 6×10^{-5} tCO_2eq/day of GHG emissions from PE pipe manufacturing, and less than 1×10^{-3} tCO_2eq/day of GHG emission for the construction phase. To melt 2.5 cm of snow on a 1,700 m^2 gate area, 4.9×10^{6} kJ of energy is required to operate15 well pumps in 15 bore holes. To produce this energy requirement, the estimated GHGs are 0.057 tCO_2eq/day from a coal-powered plant, 0.024 tCO_2eq/day from a natural gas-powered plant, or 0.045 tCO_2eq/day from an oil-powered plant.

Based on GHG emission estimates for each life-cycle phase in the use of GHPS in the airport gate area, the estimated total GHG emissions are:

Table 3. GHG Emissions from Geothermal Heated Pavement System.

Life Cycle Phases		GHG Emissions (tCO_2eq/day)
Construction Materials Production	Pavement Construction Materials Manufacturing	23.3×10^{-1}
	PE Pipe Manufacturing	5.9×10^{-3}
Construction	Concrete Placement	4.6×10^{-2}
	Heat Well Drilling	5.8×10^{-3}
Energy Production	Coal Power Plant	54.6×10^{-1}
	Natural Gas Power Plant	23.2×10^{-1}
	Distillate Oil Power Plant	43.0×10^{-1}
Total	Case 1: Energy Generated by Coal Power Plant	78.5×10^{-1}
	Case 2: Energy Generated by Natural Gas Power Plant	47.1×10^{-1}
	Case 3: Energy Generated by Distillate Oil Power Plant	66.9×10^{-1}

Table 4. GHG Emissions from Traditional Snow Removal System.

Life Cycle Phases (20 Year Time Frame)			GHG Emissions (tCO_2eq/day)
Construction Materials Production	Pavement Construction Materials ManuFacturing		23.3×10^{-1}
Construction	Concrete Placement		4.6×10^{-2}
Energy Production	Diesel Fuel Manufacture		1.7×10^{-2}
	Electricity for Wastewater Treatment	Coal Power Plant	58.3×10^{-1}
		Natural Gas Power Plant	28.5×10^{-1}
		Distillate Oil Power Plant	47.4×10^{-1}
Operation	Snow Equipment Application		6.2×10^{-2}
Total	Case 1: Energy Generated by Coal Power Plant		8.2×10^{-2}
	Case 2: Energy Generated by Natural Gas Power Plant		5.2×10^{-2}
	Case 3: Energy Generated by Distillate Oil Power Plant		7.1×10^{-2}

Table 5. GHG Emissions from Geothermal Heated Pavement System Applied in Gate Area.

Life Cycle Phases (20 Year Time Frame)		GHG Emissions (tCO_2eq/day)
Construction Materials Production	Pavement Construction Materials Manufacturing	2.5×10^{-2}
	PE Pipe Manufacturing	6.2×10^{-4}
Construction	Concrete Placement	4.9×10^{-4}
	Heat Well Drilling	6.1×10^{-5}
Energy Production	Coal Power Plant	5.7×10^{-2}
	Natural Gas Power Plant	2.4×10^{-2}
	Distillate Oil Power Plant	4.5×10^{-2}
Total	Case 1: Energy Generated by Coal Power Plant	8.3×10^{-2}
	Case 2: Energy Generated by Natural Gas Power Plant	5.0×10^{-2}
	Case 3: Energy Generated by Distillate Oil Power Plant	7.1×10^{-2}

- Case 1: 0.083 tCO_2eq/day for energy generated by a coal-powered plant,
- Case 2: 0.05 tCO_2eq/day for energy generated by a natural gas-powered plant, and
- Case 3: 0.071 tCO_2eq/day for energy generated by a distillate oil-powered plant.

All these GHG emission estimates for GHPS in the airport gate area are about 100 times less than those for GHPS (See Table 3) and traditional snow-removal strategies (See Table 4) in airport-runway applications. These results indicate that the use of GHPS in selected airport areas such as airport gate areas (as opposed to runways) offer far greater sustainability benefits, in terms of improved airport ground crew safety, cost-effectiveness, and reduced environmental impact.

The efficiency of geothermal energy could be defined as a coefficient of performance (COP) of geothermal heat pump, a ratio of heat energy provided to electrical energy consumed. Thus, geothermal heat pumps with lower COPs consume more energy than the ones with higher COPs. The COP of geothermal heat pump utilized in this study is 1. In order to give airport managers a more informed evaluation of geothermal heated pavement system applied in different geothermal energy locations, a sensitivity analysis of COP of geothermal heat pump was conducted and summarized in Table 6. The COP values investigated in the sensitivity analysis are 1, 1.5, 2, 2.5, 3, and 3.5. A GHPS with a COP of 1.0 can produce about twice as much GHG as a GHPS with a COP of 3.5. These results demonstrate that by improving the efficiency of geothermal energy, it may be possible to achieve reduced GHG emissions.

Table 6. Sensitivity Analysis of GHG Emissions from Geothermal Heated Pavement System with Various Coefficient of Performance (COP) Values

COP of Geothermal Heat Pump	Energy Source of Power Plant	GHG Emissions (tCO_2eq/day)
1.0	Coal	8.3×10^{-2}
	Natural Gas	5.0×10^{-2}
	Distillate Oil	7.1×10^{-2}
1.5	Coal	6.4×10^{-2}
	Natural Gas	4.2×10^{-2}
	Distillate Oil	5.6×10^{-2}
2.0	Coal	5.5×10^{-2}
	Natural Gas	3.8×10^{-2}
	Distillate Oil	4.9×10^{-2}
2.5	Coal	4.9×10^{-2}
	Natural Gas	3.6×10^{-2}
	Distillate Oil	4.4×10^{-2}
3.0	Coal	4.5×10^{-2}
	Natural Gas	3.4×10^{-2}
	Distillate Oil	4.1×10^{-2}
3.5	Coal	4.2×10^{-2}
	Natural Gas	3.3×10^{-2}
	Distillate Oil	3.9×10^{-2}

Conclusions and Recommendations

This study was carried out to assess and compare GHG emissions from GHPS and traditional snow-removal systems. A partial process-based LCA approach was adopted in this study with the specific goal of carrying out a comparative assessment of the GHG emissions from GHPS and traditional snow-removal systems. Several simplifying assumptions were necessary because of lack of publicly available data. Overall findings (subject to the scope and specific assumptions made in this study) and future recommendations are summarized below.

Findings

- A GHPS produces lower GHG emissions than a traditional snow-removal system in removing 2.5cm of snow from an airport runway.
- An LCA of GHPS in an airport-runway application demonstrates that most of the associated GHG emissions are released during the energy production and construction materials production phases.
- A relatively high amount of GHG emissions result from the large amount of energy required to extract sufficient geothermal energy for melting snow from large runway areas (1.67×10^5 m^2 in this study). Therefore, if the efficiency of geothermal energy extraction were to be improved, a geothermally-heated pavement system could reduce GHG emissions and result in improved viability from an environmental perspective.
- The independent LCA carried out for the airport gate area shows that the GHG emission from GHPS is about 100 times less than the emission from a similar system used on a runway, so the use of a geothermally-heated pavement system in an

airport gate area not only has less environmental impact, but also overcomes a number of problems associated with removing snow from gate areas using mechanical equipment, environmental pollution caused by use of chemicals, and safety issues involving snow-clearing ground crews on cold winter days.
- The deicer wastewater treatment phase accounts for the majority of GHG emissions when using a traditional snow-removal system.

Recommendations

- Based on assumptions and calculations for a geothermally-heated pavement heated pavement system, most of the GHG releases occur during the operational phase, so system equipment sizing and choice of energy source can be critical in enabling geothermally-heated pavement systems to be more environmental-friendly.
- Since the use of GHPS in airport paved surfaces represents a relatively new application, a there exists only a sparse amount of data for conducting a full-fledged LCA. As more data becomes available, a detailed LCA could be conducted to gain further insight into sustainability benefits and other impacts associated with the use of GHPS.
- Future studies should focus on differences in weather conditions, snow-removal equipment and strategies, and other potential factors that might influence GHG emissions produced by both systems.

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