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Sustainability Assessment of Alternative Snow-Removal Methods for Airport Apron Paved Surfaces

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16. Abstract

Airport facilities, as entities offering public or private services, need to evaluate the energy consumption and global-warming potential of different types of snow-removal systems employed during winter operations. This study assesses the energy demands and environmental impacts of operating heated pavement systems (HPS) for airport apron snow-removal applications. Using a hybrid life-cycle assessment methodology, several systems currently used for snow removal on airport apron paved surfaces including hydronic heated pavement systems using geothermal energy, hydronic heated pavement systems using a natural gas furnace, electrically heated pavement systems, and conventional snow-removal systems (CSRS) were evaluated and compared in this study. Based on the system models assessed, HPS applications in airport paved apron areas are a viable energy and environmental option to achieve ice- and/or snow-free pavement surfaces without using mechanical or chemical methods. Conversely, this study revealed that CSRS methods typically require a relatively higher energy demand and produce relatively more greenhouse gas emissions compared to HPS during the operation phase, under the conditions and assumptions considered in this study. HPS operations were also determined to have a greater advantage during a snow event with a relatively smaller snow rate and longer snow duration.

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LIST OF SYMBOLS AND ACRONYMS

ΔT	Temperature difference
δ	Stephan-Boltzmann constant
ε_s	Emittance of wet slab
A_r	Ratio of snow-free area to total area
C	Specific heat of concrete pavement
Cp	Heat capacity of water
c_1	Conversion factor
$c_{p,snow}$	Specific heat of snow
$c_{p,water}$	Specific heat of water
D	Density of water equivalent of snow
E	Electric geothermal heat pump energy requirement
H	Total head
h_c	Convection heat transfer coefficient for turbulent flow
h_f	Heat of fusion for water
h_{fg}	Heat of evaporation at the film temperature at 33°F
h_m	Mass transfer coefficient of concrete slab
M	Mass of concrete pavement
M_f	Flow rate increase multiplier
n	Pump efficiency
P_{dry_air}	Density of dry air
Q	Flow rate
q_e	Heat of evaporation
q_h	Heat transfer by convection
q_i	Heat required for concrete pavement idling
q_m	Heat of fusion
q_o	Heat required in melting snow
q_s	Sensible heat transferred to the snow
Q_t	Total heat required for pavement idling and snow melting
s	Rate of snowfall
SG	Specific gravity of heated solution
t	Snow period
t_a	Ambient temperature
T_f	Liquid film temperature
T_{MR}	Mean radiant temperature of surroundings
t_s	Melting temperature
W_a	Humidity ratio of ambient air at 20°F
W_f	Humidity ratio of saturated air at film surface temperature at 33°F

LIST OF SYMBOLS AND ACRONYMS (Continued)

COD	Chemical oxygen demand
COP	Coefficient of performance
CSRS	Conventional snow-removal systems
ECAC	Electrically conductive asphalt concrete
ECON	Electrically conductive concrete
EHPS	Electrically heated pavement system(s)
EIA	Energy Information Administration
EIO-LCA	Economic input-output life-cycle assessment
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
GHG	Greenhouse gas
GREET®	Greenhouse gases, regulatory emissions, and energy use in transportation
GSHP	Ground-source heat pump
HPS	Heated pavement system(s)
HHPS	Hydronic heated pavement system(s)
HHPS-G	Hydronic heated pavement system(s) using geothermal energy
HHPS-NG	Hydronic heated pavement system(s) using natural gas furnace
ISO	International Organization for Standardization
LCA	Life-cycle assessment
PAN	Polyacrylonitrile
PCC	Portland cement concrete
PEX	Cross-linked polyethylene
PG	Propylene glycol
PIMA	Polyisocyanurate Insulation Manufacturers Association
Polyiso	Polyisocyanurate
SRE	Snow-removal equipment
U.S.	United States
WHP	Water horsepower

EXECUTIVE SUMMARY

Airport operations are regularly, and sometimes heavily, impacted by snow and ice during winter seasons. Considering the potential economic losses resulting from ice- and/or snow-related flight delays and airport shutdowns, there is a significant need to maintain the runways and taxiways free of snow and ice at all times. Conventional snow-removal systems (CSRS), along with snow-removal equipment (such as snow plows, snow blowers, snow brooms, and sweepers) employ deicers and anti-icers that have the potential to generate foreign object debris and can cause damage to aircraft parts and pavements. In addition, conventional snowplows and equipment have difficulty accessing critical airside operations areas, such as the apron and gate areas. A heated pavement system (HPS) is an emerging technology that either passes electric currents or circulates warm fluids through pipes in the pavement structure. This HPS technology is a promising alternative to CSRS, especially in the apron areas.

Although the efficiency and economic benefits of HPS in snow and ice removal have been assessed by previous studies, their environmental impact is not well known. Airport facilities that offer public or private services need to evaluate the energy consumption and global-warming potential of different types of snow-removal systems. Using the hybrid life-cycle assessment methodology, this study evaluated and compared several snow-removal systems, including hydronic heated pavement systems that use geothermal energy (HHPS-G), hydronic heated pavement systems that use a natural gas furnace (HHPS-NG), electrically heated pavement systems, and CSRSs. Based on the system models assessed in this study, the use of HPS applications in airport paved apron areas was determined to be a viable option, in terms of energy consumption and environmental impact, to achieve ice- and/or snow-free pavement surfaces, without using mechanical or chemical methods. It was also determined that the use of mechanical or chemical methods requires more energy and produces greenhouse gas emissions over the CSRS's operation life cycle. Compared to CSRS, HPS operations have a greater advantage during a snow event with a small snow rate and a long snow period. In particular, the HHPS-G and HHPS-NG show potential as sustainable options.

1. INTRODUCTION.

This section provides a brief introduction, including background information and the research objectives and approach used in this report.

1.1 BACKGROUND.

United States (U.S.) commercial airports play an important role in economic growth by providing a worldwide transportation network for people and goods [1]. Consequently, it is essential for commercial airports to maintain continuous operation to avoid detrimental economic impacts. This can be difficult during extreme weather conditions in winter, when snow, ice, and slush hinder operations, causing a significant economic effect. For example, as stated in the report “The Economic Impact of Commercial Airports in 2013,” 485 U.S. commercial airports support 9.6 million jobs and produce $1.1 trillion annually [1]. Commercial airports also provide significant contributions to local economies. According to the Norfolk International Airport 2014 Economic Impact Study, airports produced an additional income of $68 million and 2134 jobs to the local economy of Virginia [2]. The challenges of winter weather conditions (i.e., snow, ice, or slush on airfield pavements including runways, taxiways, etc.) could lead to serious situations resulting in delays and adverse incidents. Snow removal is therefore a top priority for U.S. commercial airports [3].

1.1.1 Snow-Removal Systems.

To maintain continuous operation during extreme weather in winter, airports generally use mechanical snow-removal equipment (SRE), such as snowplows and snow blowers, to remove contaminants from transportation surfaces, and use chemical agents, such as potassium acetate, sodium acetate, and propylene glycol (PG), to prevent the reformation of snow, ice, or slush on airport surfaces [4]. However, SRE is usually designed for large areas, such as runways, and it is sometimes difficult to operate in narrow spaces, such as airport aprons. Likewise, chemical deicers are expensive and can lead to potential environmental pollution problems. Many techniques, such as heated pavement systems (HPS), superhydrophobic coating, and phase change materials, have been suggested for removing snow from airport aprons in place of mechanic equipment or chemical reagents. Superhydrophobic coating and phase-change materials are still under development at a pilot scale, but their longevities are not yet well understood. However, HPS, also known as snowmelt systems, are considered to offer an alternative strategy for effectively mitigating the effects of winter contaminants by melting snow and preventing bonding to the pavement surface [5].

HPSs fall into two types based on different heat sources: electric radiant heat or hydronic heat from a fossil-fuel boiler/heater combustion or geothermal source [6]. Although this is a relatively new technology used in airport snow-removal applications, there are many studies available that focus on the design and the mechanical or thermal behavior of different types of HPS; however, very few have analyzed the environmental impact of such systems.

1.1.2 Practices in Airport Sustainability.

Based on the environmental programs of the Federal Aviation Administration (FAA), sustainability is considered a core rather than a secondary objective in the airport planning process [7]. The Airport Sustainability Planning program provides support to 44 airports. The program provides comprehensive sustainable initiation of reduction in environmental impact, assistance to airport companies in maintaining high and stable economic growth, while ensuring that local community needs and values can be achieved [7]. Specifically, this program provides benefits to help airports reduce energy consumption, reduce noise impact, reduce hazardous and solid waste generation, reduce greenhouse gas (GHG) emissions, improve water quality, and increase cost savings [8].

Airport Sustainability Planning includes five sections: plan preparation, sustainability categories, baseline assessments, sustainability goals and objectives, and outreach and stakeholder engagement. It encourages decision makers and participants in airport activity to coordinate with airport management and staff by involvement and support of sustainability plans. It also encourages airport planners to increase engagement in sustainable design during new project planning. An airport plan can maintain a proper focus on sustainability by following the program guidelines. Although the most sustainable solution may not be possible in all cases, sustainability plans give airport personnel a more informed view with respect to decision making [9]. An airport's sustainability categories are not limited to environmental impact issues, but may also include inventories such as socioeconomics, airport facilities and procedures, land use, etc. [8].

1.2 RESEARCH OBJECTIVES AND APPROACH.

Airports, as facilities that must increasingly focus on environmental impact and sustainability of their product or system as environmental awareness increases, have tried different approaches to evaluate and decrease their environmental impact. One approach, a life-cycle assessment (LCA), has been commonly used by industries or businesses to evaluate behavior or environmental impact of their own products or systems [10]. This study is intended to develop a sustainability assessment framework using an LCA that focused on the operation of airfield heated pavements. An LCA was used to estimate the environmental impact of HPSs compared to conventional snow-removal systems (CSRS) for removing snow from airport apron areas under different snow-rate conditions. This study focuses on the operation of three types of HPS.

- Hydronic heated pavement system using geothermal heat pump (HHPS-G)
- Hydronic heated pavement system using natural gas furnace (HHPS-NG)
- Electrically heated pavement system (EHPS)

The study considers the current topics of energy crisis, global warming, and climate change, and evaluates energy consumption and GHG emissions produced by snow removal systems as significant indicators of sustainability. The study is intended to provide airport decision makers or HPS operators with a better understanding of the global-warming potential of different HPSs to help them choose more sustainable snow-removal strategies.

2. REVIEW OF LCA.

This section summarizes literature review results focusing on the structure and variants of LCA and the previous LCA studies on conventional snow removal.

2.1 STRUCTURES OF LCA.

LCAs provide a macroscopic view for studying the environmental impacts of products, techniques, processes, and systems. Because an LCA identifies the relationships among media (e.g., energy consumption and GHG emissions) and/or among life-cycle stages (e.g., product manufacture stage and use stage), it has the capabilities to do the following [11]:

- Evaluate the impacts associated with a given product or system in a systematic way
- Compare with one or multiple alternatives to have a better/more informed selection
- Quantify the environmental emissions associated to each life-cycle stages
- Identify the most significant contributor in the life cycle of a product or system
- Assess and compare the human and ecological impacts of a selected product or system
- Identify impacts to one or more environmental areas of concern

LCA has been applied to analyze both energy consumptions and GHG emissions associated with various industries or businesses [10]. LCA is regarded as a cradle-to-grave approach for assessment of production processes or industrial systems. Cradle-to-grave implies that a system analysis begins with the raw-material extraction stage and extends through the use of a product or the operation of a system, including the end-of-life stage [12]. In other words, LCA enables the estimation of cumulative impacts from all stages of a product or system life cycle, where life cycle refers to the stages in a product's or system's life span ranging from raw-material extraction, manufacture, use, and maintenance, to final disposal of its waste.

As a systematic and comprehensive model, the LCA has four components: goal and scope definition, inventory analysis, impact assessment, and interpretation, as illustrated in figure 1 [13].

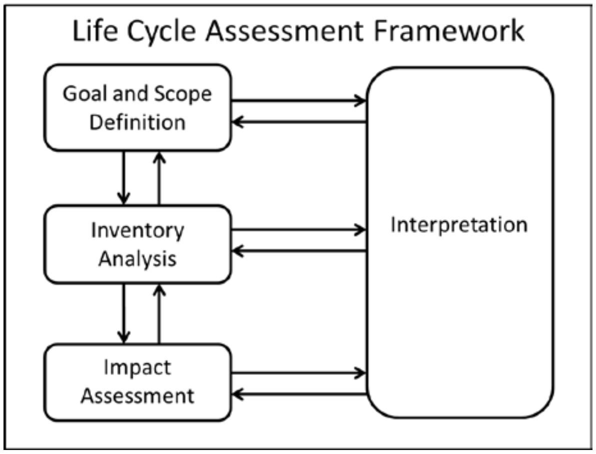


Figure 1. Components of an LCA

- Goal and scope definition: define the product, process, or system; establish a purpose or objective; and identify the system boundary and functional unit.

- Inventory analysis: identify the value of energy, material inputs, and environmental outputs (e.g., GHG emissions, solid waste disposal, and wastewater discharge).

- Impact assessment: assess the significance of potential impacts on the environment associated with energy, raw-material input, and environmental outputs.

- Interpretation: report the results in the most informative way possible and evaluate the need and opportunities to reduce the impact of the product(s) or service(s) on the environment.

According to the Environmental Protection Agency (EPA), the first step to carry on LCA is to develop a flow diagram and a data collection plan for the processes being evaluated [14 and 15]. The inventory data collection and evaluation follows. The final step is reporting of results.

The process of defining the goal and scope of an LCA is critical, because it determines the system boundary and time frame of the study and identifies meaningful inventories [13]. An LCA can be conducted to deliver a broad environmental assessment because the LCA not only studies the product or the system itself, but also analyzes environmental burdens resulting from associated processes [13]. LCAs can also be used to choose the best product, process, and system with the least undesirable environmental impacts and human-health effects, or to help develop and enhance the technology, process, and system to require less energy and reduced emissions [12]. Because an LCA provides detailed information about each step in the whole-system life cycle, the step representing the greatest environmental emissions and energy/material input would be identified during an inventory collection [13]. An LCA has the capability to provide direction to a decision maker seeking to discover the step that contributes the greatest pollution prevention, resource conservation, and emission minimization during a system's or product's life cycle.

2.2 VARIANTS OF LCA.

LCA can be used to analyze a wide variety of production processes or systems under different system boundaries or time frames, thus analysis may be relatively simple or much more complex. There are multiple approaches to performing a LCA to achieve the defined objectives. The three most commonly used methods are (1) process-based, (2) economic input-output, and (3) hybrid LCAs [16].

2.2.1 Process-Based LCA.

The process-based LCA approach has been used more commonly than the other two approaches for analyzing existing material-processing models and energy flows [17]. As summarized in the International Organization for Standardization (ISO) Standard 14040, when performing a process-based LCA, the processes of a product or a system are first identified, followed by a cradle-to-grave (i.e., life cycle from raw-material extraction to waste disposal) or a cradle-to-gate (i.e., life cycle from raw-material extraction to factory gate) analysis, usually performed at the system boundary determination [16]. All data required for energy or material input inventories and environmental impact outputs under different processes in each stage of the system life cycle are collected from available sources (e.g., system operators, product manufacturers, process technicians, previous studies, et al.). Generally, processed-based LCA uses a process flow diagram to estimate impact at each step and summarizes them to find the total impact produced by a production or system process. It also demonstrates all quantified inventories and possible paths at the identified system boundary. It can effectively illustrate the complexity and variety of a production or system process.

Although a process-based LCA can be relatively simple to do when each of the process inventories of a production or a system are assessable, collecting the complete inventory data for a comprehensively process-based LCA can be challenging. For example, to collect process-specific data in the LCA for a product-manufacture life cycle is difficult because there is an infinite possibility of supply chain paths, which makes it difficult to analyze all inventories from all production supply chain paths [18].

There are two ways to solve this problem in conducting a process-based LCA. The first is to make assumptions regarding the missing inventories and the second is to perform a partial process-based LCA neglecting some parts of the system. However, assumptions regarding cutoff system boundary selections are usually subjective and could create uncertainties producing misleading or inaccurate results. For example, water delivery through a pipeline was assumed to have no impact in a natural gas extraction LCA study without any further justification [19]. However, in reality, water requires natural gas extraction for pumping during pipeline delivery; and this will have a certain amount of impact. Some studies have also found that a cutoff approach has about a 20% impact for many impact categories [20] but may have a considerably larger impact at the raw-material extraction stage in some product-processing life cycles [21]. Taking a biofuel production life cycle as an example, 23% of total carbon dioxide equivalent (CO_2eq) was attributed to biofuel upstream emissions that were normally excluded from the process-based life cycle [22].

2.2.2 Economic Input-Output LCA.

In contrast to a process-based LCA, an economic input-output LCA (EIO-LCA) does not require analysis of every inventory or sector at each life-cycle stage. An EIO-LCA quantifies each sector in an economic system interconnected to an environmental and energy analysis [2]. Because of this, an EIO-LCA has the capability to identify direct and indirect economic, energy, or environmental outputs resulting from economic inputs of purchases. Carnegie Mellon University developed an online tool EIO-LCA model theorized by economist Wassily Leontief in the 1970s [21]. The EIO-LCA online tool developed by Carnegie Mellon University reports relative impacts of different material production processes, services, or system processes with respect to resource use and emissions throughout the supply chain. Since the EIO-LCA online tool uses the entire national economy and import data, summarizing different possible supply chain paths, the cutoff problem can be solved using an EIO-LCA model rather than a process-based LCA.

Although the EIO-LCA method is powerful, easy, and convenient to use, the model's system boundary and interrelationships among the sectors inside the economic system are not clearly identifiable. This would be effective if the user only wanted to know the final impact result from a single product or system, but if each sector or stage of the product or system needed to be well understood, using an EIO-LCA model could be challenging. Although the cutoff uncertainty is eliminated, the data collection of so many products to different sectors could not eliminate any remaining uncertainties. Also, because EIO-LCA uses broad, national economic data, this approach may make it difficult to determine details regarding a specific product or system process at a particular time or at particular locations [23]. For example, when the economic data is modified on a national scale, a researcher could obtain a similar impact result from mobile manufacturers in Iowa and Missouri by using an EIO-LCA, while results for these mobile manufactories in two different states may be significantly different. Timeliness of economic data is another issue in the EIO-LCA model. The latest version of the EIO-LCA online tool is updated to 2002; the previous version before that update represented technology and emission intensities of the U.S. economy from 1997 [24]. Keeping the EIO-LCA database updated is challenging, especially considering how sensitive the economy is to change. Using outdated data can have an uncertain effect on the outcome.

2.2.3 Hybrid LCA.

A hybrid LCA approach combines a process-based LCA and an EIO-LCA when analyzing a product or system process. In the hybrid LCA approach, the environmental impacts of flows, not usually included in a process-based LCA, are estimated using an environmentally extended EIO-LCA [25]. It has been reported that using a hybrid LCA enables better and faster modeling by incorporating the completeness of the EIO-LCA with the accuracy of the process-based LCA. In a water treatment chemical LCA, Gaitan, et al., [26] developed a hybrid LCA model demonstrating that the method not only expanded system boundaries in the modeling but also enabled use of detailed information at the process level. In general, the hybrid LCA combines the advantages of both the process-based LCA and the EIO-LCA to minimize drawbacks of both approaches.

2.3 PREVIOUS LCA STUDIES ON CONVENTIONAL SNOW REMOVAL.

Snow removal is required during winter road maintenance to make travel easier and safer. To evaluate the energy requirement and environmental impacts of winter road maintenance, LCA can be conducted by analyzing the whole process in a cradle-to-grave approach. The life cycle of snow-removal applications may include extraction of anti-icing material for winter road maintenance, anti-icing material gritting, snow clearance using different types of mechanical equipment, mowing and clearing of verges, and removal of snow posts [27]. Life-cycle inventory usually relies upon data collection from previous studies or databases of industries or businesses.

Salt and sand are frequently used as deicing/anti-icing materials for winter road maintenance. However, there are multiple types and combinations of sand and salt applications. The energy required for extraction of salt used for snow removal is associated with either coal or natural gas. Sand can be produced from extraction from aggregate or crushed materials. However, different material production industries use various manufacturing processes or techniques [28], which results in variations and uncertainties with respect to energy consumption and emissions from deicer/anti-icer extraction.

Material gritting is considered to be achieved by truck, and both the gritting process and the material transportation stage are considered in the LCA. However, a snow-removal truck operation strategy that determines emissions and energy consumption of the material gritting process could vary by location [28]. Considering the variations in local traffic conditions, regulations, or laws, it is challenging to construct a consolidated model applicable to every case.

A truck with an attached snow-clearance unit, such as a snowplow, is generally used for snow clearance, verge mowing, and snow post removal [29]. To evaluate the energy consumption and emissions from snow-clearance operations, a specific type of equipment is selected as an example; and assumptions, which are based on previous studies with respect to equipment behavior, are made for assessment [30]. However, assumptions and variations in truck engines and attached snow-clearance equipment could cause uncertainty in energy consumption and emission determination, which could result in misleading answers.

Although LCA modeling attempts to duplicate the actual production or system operation process, there is not a great deal of available data for all sectors. Using the snow-removal application LCA as an example, labor activity is hard to quantify and usually neglected in the operation life cycle, and equipment maintenance may also not be considered [31]. However, it is not known if these cutoff sectors may contribute significant impact to the system life cycle. In summary, while LCA is widely used to analyze different products or systems, it is still under development [16]; therefore, some errors are difficult to avoid.

3. METHODOLOGY.

This section addresses and discusses the methodology adapted in this study.

3.1 TYPES OF HPS.

This study focuses on three types of HPS: HHPS-NG, HHPS-G, and EHPS.

3.1.1 Type 1—HHPS-NG.

Hydronic heated pavement systems (HHPS) generally use fossil fuel heaters, such as natural gas water boilers/furnaces or electric water heaters, as energy sources for warming the PG (antifreeze) solution usually used as a heat-transfer medium and circulating it inside a cross-linked polyethylene (PEX) tube under the pavement [32].

Generally, a natural gas boiler has an efficiency of 60%, and an electric water heater has an efficiency of 90% [31]. However, systems that use natural gas combustion for heating (e.g. HHPS) could be more sustainable than systems using electricity (e.g. EHPS), because natural gas combustion has a much lower GHG emission factor than electricity generation. Natural gas furnaces are also considered to have higher efficiencies than traditional gas boilers [33]. From the aspect of sustainability, a natural gas furnace was evaluated as the heating source for HHPS-NG in this study.

3.1.2 Type 2—HHPS-G.

Geothermal power is a sustainable energy technology that is commonly used for electricity generation; it was also evaluated in a previous study as a heating source for HHPS for bridge snow-melting applications [34]. Unlike HHPS-NG, which works with natural gas, HHPS-G uses a ground-source heat pump (GSHP) instead of fossil fuels or electricity to extract geothermal energy to warm a hot solution and circulate it through embedded pipes in the pavement using a circulating pump to heat the pavement and melt the ice.

There are three types of HHPS-G: a direct-exchange geothermal system, a closed-loop geothermal system, and an open-loop geothermal system. 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 the high construction cost of both closed- and open-loop systems [35], this study focused on the use of direct-exchange-based HHPS-G. The direct-exchange HHPS-G uses a single loop to circulate fluid in contact with the ground to directly extract or dissipate heat.

3.1.3 Type 3—EHPS.

In contrast to HHPS-G and HHPS-NG, which use a heated solution as a heat-transfer media, an EHPS uses electric radiant heat from heated wires or panels to directly warm the concrete pavement surface [5]. Another difference of EHPS is that, rather than using buried PEX tubes in the pavement, conductive materials (e.g. polyacrylonitrile (PAN)-based carbon fiber) are added during the pavement material mixing process to transform the regular pavement into electrically conductive pavement [35 and 36]. Electrically conductive concrete (ECON) is one that conductive materials is added to Portland cement concrete (PCC) and ECON is one that conductive materials is added to hot mix asphalt (HMA). EHPS should be designed for increasing electrical conductivity of the slab to reduce energy consumption.

As a technique for assessing the environmental and potential impacts associated with a product, process, or system, an LCA can compile an inventory of input and output and evaluate their potential impact to help the designer or user make a more informed decision [13]. For this study, a hybrid LCA, including both a process-based LCA and an EIO-LCA, was used to analyze and compare four different snow-removal systems.

The primary goal of this study was to provide a more comprehensive understanding of snow-removal system operations from both an economic perspective and an environmental impact aspect, to help the airport operator make a more informed decision on snow-removal strategy. The secondary goal is to determine the inventories or steps that contribute the most economic and environmental burdens for each snow-removal system operation and to provide guidance in minimizing system energy usage and environmental impacts. Particularly, energy consumption and global-warming potential effects of four different kinds of snow-removal systems—HHPS-G, HHPS-NG, EHPS, and CSRS—were assessed. The methods were evaluated and compared to see which one would be best to achieve these goals.

As the first LCA study to compare HPSs to alternative apron snow-removal strategies, this study provides a general overview of the life-cycle phases for different airport apron snow-removal strategies. Since HPSs are relatively new technologies for airport snow-removal application, detailed information related to their construction and maintenance (i.e., frequency, energy consumption, etc.) required to conduct a full-fledged LCA study was not available [37]. Therefore, the scope of this study focuses only on the impact of the snow-removal operation phase and related life-cycle stages.

System boundaries of the four snow-removal systems included only sectors defined as processes of snow-removal operation. Snow-removal systems can be classified into four subsystem processes: power generation, material production, snow-removal application, and waste treatment. The operation system boundary in this study therefore included these four sectors. A well-to-wheel assessment for a power generation facility was performed to help understand the GHG emission from the power production phase. An EIO-LCA online model was applied to the material production stage, and its system boundary was defined in the 2002 U.S. benchmark version of the EIO LCA model [28].

Life-cycle inventories are significantly related to the system boundary [38]. Because this study evaluated the energy consumption and global-warming potential of different airport apron snow-removal system operations, inventories that contribute efforts (e.g., increasing thermal conductivity or preventing heat lost) to snow removal and their upstream stage life cycle (e.g., raw-material extraction) were assessed. Life-cycle inventories of snow-removal systems were collected through previous studies, government official documents, or company manual scripts and defined in the following sections [39].The four snow-removal systems analyzed in this study were designed for a short- to medium-range airport apron area of 19,000 ft^2.

The systems were analyzed at 20°F air temperature, 10-mile-per-hour (mph) wind speed, and under 0.5-, 0.75-, 1-, 1.5- and 2-inch-per-hour (in./h) snowfall rate conditions. Based on the lifetime of PCC pavement, HPSs are assumed to be designed for a 20-year life [40].

3.2 MODELING EQUATIONS.

The energy consumption rates for modeling different HPS types in this study were calculated by using a set of standard equations on pavement-idling energy consumption, snow-melting energy consumption, geothermal heat pump operating energy demand, hydronic system flow rate, and circulating pump operating energy demand. These equations were reviewed and discussed in the following sections. A sample calculation of the LCA for the operation phase of HHPS-G using these equations are provided in appendix A.

3.2.1 Pavement-Idling Energy Consumption.

In this study, a heated pavement surface must be heated to 32°F. The energy consumption (q_i) given by a pavement idling equation is given in equation 1[41]:

$$q_i = \frac{C \cdot \Delta T \cdot M}{t} \tag{1}$$

where:

q_i = heat required for concrete pavement idling (Btu/h)
C = specific heat of concrete pavement (Btu/lb·°F)
ΔT = temperature difference (°F)
M = mass of concrete pavement (lb)
t = snow period (h)

3.2.2 Snow-Melting Energy Consumption.

After the concrete slab surface is heated to 32°F, HPSs use heat to melt the snow. To understand the heat (q_o) required in melting snow using an HPS, equation 2 can be applied [41].

$$q_o = q_s + q_m + A_r(q_e + q_h) \tag{2}$$

where:

q_o = heat required in melting snow (Btu/h·ft^2)
q_s = sensible heat transferred to the snow (Btu/h·ft^2)
q_m = heat of fusion (Btu/h·ft^2)
A_r = ratio of snow-free area to total area
q_e = heat of evaporation (Btu/h·ft^2)
q_h = heat transfer by convection and (Btu/h·ft^2)

The sensible heat (q_s) to bring the snow to 32°F is [41]:

$$q_s = s \cdot D \cdot [c_{p,snow}(t_s - t_a)] + c_{p,water}(t_f - t_s)] / c_1 \tag{3}$$

where:

s = rate of snowfall (inches of water equivalent per hour)
D = density of water equivalent of snow (lb/ft^3)
$c_{p,snow}$ = specific heat of snow (Btu/lb/°F)
$c_{p,water}$ = specific heat of water (Btu/lb/°F)
t_s = melting temperature (°F)
t_f = liquid film temperature (°F)
t_a = ambient temperature (°F)
c_1 = conversion factor (in./ft)

The heat of fusion (q_m) to melt the snow is [41]:

$$q_m = s \cdot h_f \cdot D / c_1 \tag{4}$$

where:

h_f = heat of fusion for water (Btu/lb)

The heat of evaporation (q_e) is:

$$q_e = P_{dry\_air} \cdot h_m (W_f - W_a) h_{fg} \tag{5}$$

where:

P_{dry_air} = density of dry air (lb/ft^3)
h_m = mass transfer coefficient of concrete slab (ft/h)
W_f = humidity ratio of saturated air at film surface temperature (lb$_{vapor}$/lb$_{air}$)
W_a = humidity ratio of ambient air (lb$_{vapor}$/lb$_{air}$)
h_{fg} = heat of evaporation at the film temperature (Btu/lb)

The heat of fusion (q_m) to melt the snow is [41]:

$$q_h = h_c (t_f - t_a) + \delta \cdot \varepsilon_s (T^4{}_f - T^4_{MR}) \tag{6}$$

where:

h_c = convection heat transfer coefficient for turbulent flow (Btu/h·ft^2·tu)
δ = Stephan-Boltzmann constant (0.17×10^{-8} Btu/h·ft^2·tR)
ε_s = emittance of wet slab
T_f = liquid film temperature (°F)
T_{MR} = mean radiant temperature of surroundings (°F)

3.2.3 Geothermal Heat Pump Operating Energy Demand.

Energy consumption (E) in Megajoule per hour (MJ/h) of a geothermal heat pump was calculated by using equation 7 [42]:

$$E = \frac{Q_t}{COP} \tag{7}$$

where:

E = electric geothermal heat pump energy requirement (MJ/h)
Q_t = total heat required for pavement idling and snow melting (MJ/h)
COP = coefficient of performance

3.2.4 Hydronic System Flow Rate.

Flow rate calculation is based on the equation below equation 8 [43]:

$$Q = \frac{Q_0}{Cp \times \Delta T} \times (1 + M_f) \tag{8}$$

where:

Q = flow rate (gpm)
Q_o = heat required in melting snow (Btu/h)
Cp = heat capacity of water (Btu/gallon·°F)
ΔT = temperature difference (°F)
M_f = flow rate increase multiplier (%)

3.2.5 Circulating Pump Operating Energy Demand.

To calculate the energy demand for a circulating pump, the following equation for required water horsepower (WHP) in HP was applied [43].

$$WHP = \frac{Q \times H \times SG}{3960 \times n} \tag{9}$$

where:

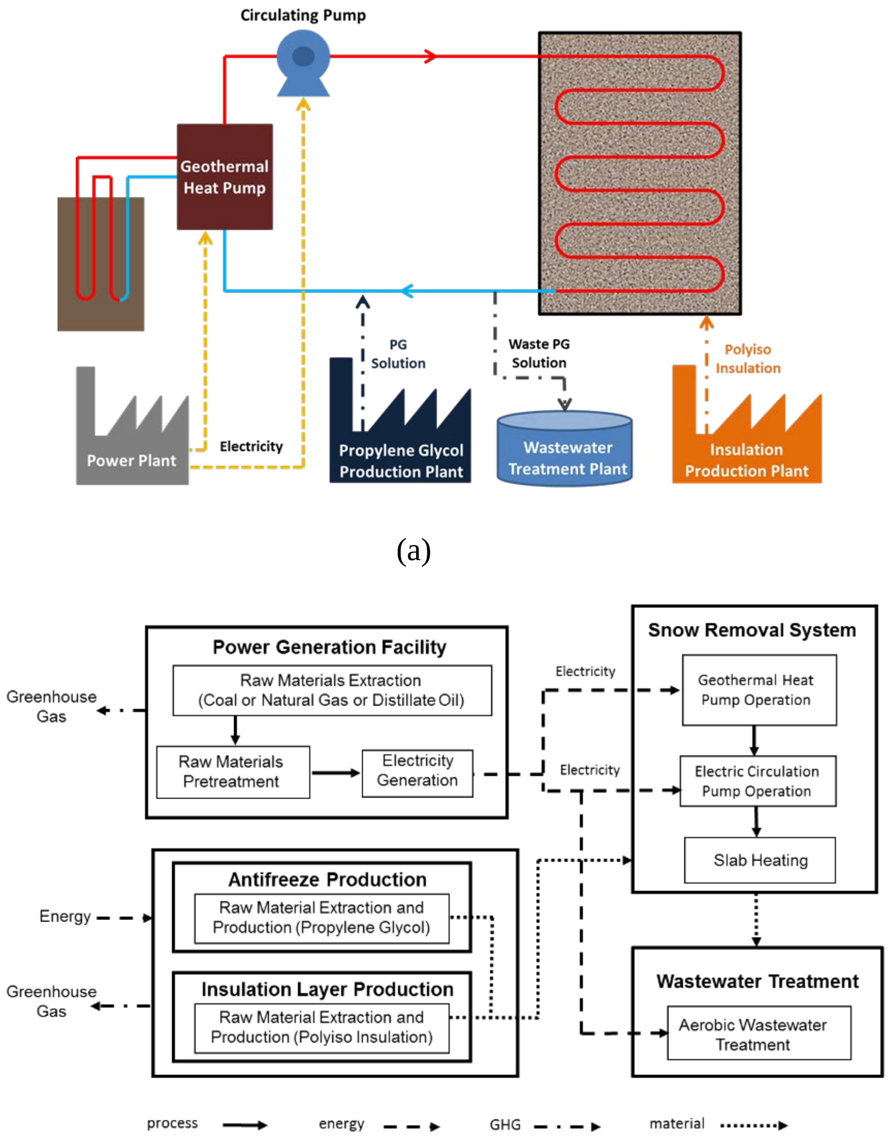
WHP = water horsepower (HP)
Q = flow rate (gpm)
H = total head (ft)
SG = specific gravity of heated solution
n = pump efficiency (%)

4. CASE 1: HHPS-G OPERATION.

Case 1 examined the operation system boundary, model, energy consumptions and GHG emission estimations on HHPS-G designed for a short- to medium-range airport apron area of 19,000 ft^2. The HHPS-G operation model was analyzed at 20°F air temperature, 10-mph wind speed, and under 0.5-, 0.75-, 1-, 1.5- and 2- in./h snowfall rate conditions.

4.1 SYSTEM BOUNDARY.

HHPS-G uses geothermal energy as a heating source to warm PG antifreeze solution circulating under the pavement to keep the concrete slab surface free of snow. Based on the methodology, the HHPS-G operation life cycle can be divided into four subset life cycles: a power generation life cycle, a snow-removal operation life cycle, a material production life cycle, and an antifreeze/wastewater treatment life cycle. The HHPS-G operation flow chart and the system boundary of the HHPS-G operation life cycle are shown in figure 2.



(a)

(b)

Figure 2. The HHPS-G Operation Flow Chart (a) and the System Boundary of HHPS-G Operation (b)

4.2 MODEL.

An HHPS-G uses a direct-exchange GSHP to extract geothermal energy from the ground to warm a heated solution that flows through embedded pipes in the pavement, which heats the pavement and melts the ice. The energy required to melt snow is calculated by applying the equations 1 through 6. Based on the geothermal heat pump's key product criteria, the coefficient of performance (COP) of a direct-ground exchange heat pump can be as high as 3.6 [44]. To understand the behavior of HHPS-G applied in different geothermal conditions, the COP of the geothermal heat pump is assumed to be 2, 2.5, 3, and 3.6 in this study. The heat pump's energy consumption for this study was calculated by applying equation 7.

HPS design is based on the energy requirement for snow melting [44]. The heaviest snow fall in this study was 2 in./h; therefore, HHPS-G at least needed to be feasibly operational under 2 in./h snow rate conditions. To support enough heating on a paved apron area of 19,000 ft^2, the designed HHPS-G required 28,500 ft of 3/4-in. PEX pipes (equivalent to 71 PEX tubing circuits).

HHPS-G circulates 40% by volume of PG solution in 3/4-in. PEX pipes. Based on the design for 2 in./h snow accumulation, the circulating solution flow rate was calculated using equation 8 to obtain a flow rate of 6.9 gallons per minute (gpm). Thus, the total flow rate is 493 gpm and the total pressure drop is about 125 ft of head. In consideration of applying 60% efficiency circulating pumps [45] in HHPS-G, the energy circulating pump demand was calculated as 26 hp using equation 9.

Since 40% by volume of propylene glycol solution has a very similar density to water, the unit volume of solution in 3/4-in. PEX pipe is about 0.018 gal/ft, and a total of 513 gallon of solution is required for HHPS-G operation. By using the GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) tool developed by Argonne National Laboratory [46], the energy to produce 1 kg of PG was estimated to require 27.57 kWh energy, which released 6.46 $kgCO_2eq$ in PG production.

The PG solution needs to be checked and replaced every year [47], and the waste solution can be discharged and treated in a municipal wastewater treatment plant. PG has a chemical oxygen demand (COD) content of about 1,680 g/kg [48] and produces 0.15 kgCOD/h of waste antifreeze solution for the 19,000 ft^2 apron area. In general, aerobic wastewater treatment energy requirement is 1 kWh/kgCOD [49]. Since such treatment requires electrical power, there is no direct GHG released from the wastewater plant itself, so the GHG emission is actually from the power generation phase. Calculations show that this is about 104 $kgCO_2eq/h$ for PG wastewater treatment.

A polyisocyanurate (polyiso) insulation layer is installed on the bottom and edge of the top 4 in. of the concrete slab to prevent heat loss. The heat loss of the HPS along the back and bottom edge of the concrete slab is assumed to be 0% [43]. A 1.5-in.-thick layer of polyiso insulation with a thermal resistance R_{IP} of 9.8 [50] was assumed to be used in the HHPS-G whose life time is about the same as that of PCC pavement. The life cycle of insulation layer manufacture has been studied, and its GHG emission factor is 0.39 $kgCO_2eq/ft^2$, with an energy consumption factor is of 8.66 MJ/ft^2 [50].

4.3 ENERGY CONSUMPTIONS.

To evaluate how much energy is needed to operate each HPS, the energy requirement for idling concrete pavement and melting snow should first be analyzed. Because of the insulation installed in the top 4 inches of the concrete slab under evaluation of each HPS, back and edge losses were assumed to be zero. PCC has a density of 150 lb/ft^3 [51] and a specific heat of 0.2 Btu/lb·°F [52]. HPS operation in this study maintained a pavement surface temperature as 32°F. Using equations 1 through 5, the energy requirements for melting snow for snow rate conditions, 0.5, 0.75, 1, 1.5, and 2 in./h, were calculated and determined to be 134, 153, 173, 211, and 251 $Btu/h{\cdot}ft^2$, respectively. Based on equation 1, to warm 19,000 ft^2 of concrete slab surface from

20°F to 32°F requires 2,405 MJ for a 1-hour snow period. The functional unit was time-based in this study, and allocating energy consumption of pavement idling depends on the corresponding snow periods, which were 1, 4, 8, and 12 hours, respectively. For each snow period evaluated, energy consumption for idling was determined to be 2405, 601, 301, and 200 MJ, respectively.

To operate a HHPS-G, the energy required includes the energy used for the geothermal heat pump and circulating pump operation, antifreeze solution production, insulation production, and solution waste treatment. The energy consumption of geothermal heat pumps with different COPs is calculated by applying equation 7 with the results based on different snow rates, as shown in table 1.

Table 1. Energy Consumptions of Geothermal Heat Pumps for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	Energy Consumptions of Geothermal Heat Pumps (MJ/h)			
		COP			
		2	2.5	3	3.6
1	0.5	3058	2657	2387	2165
	0.75	3219	2786	2497	2256
	1.0	3444	2965	2647	2382
	1.5	3797	3247	2883	2578
	2.0	4221	3587	3165	2813
4	0.5	2269	1868	1598	1376
	0.75	2430	1997	1708	1467
	1.0	2655	2176	1858	1593
	1.5	3008	2458	2094	1789
	2.0	3432	2798	2376	2024
8	0.5	2138	1737	1467	1245
	0.75	2299	1866	1577	1336
	1.0	2524	2045	1727	1462
	1.5	2877	2327	1963	1658
	2.0	3301	2667	2245	1893
12	0.5	2131	1730	1460	1238
	0.75	2292	1859	1570	1329
	1.0	2517	2038	1720	1455
	1.5	2870	2320	1956	1651
	2.0	3294	2660	2238	1886

Note: Equations 1 through 6 were used to calculate the energy consumption of geothermal heat pumps.

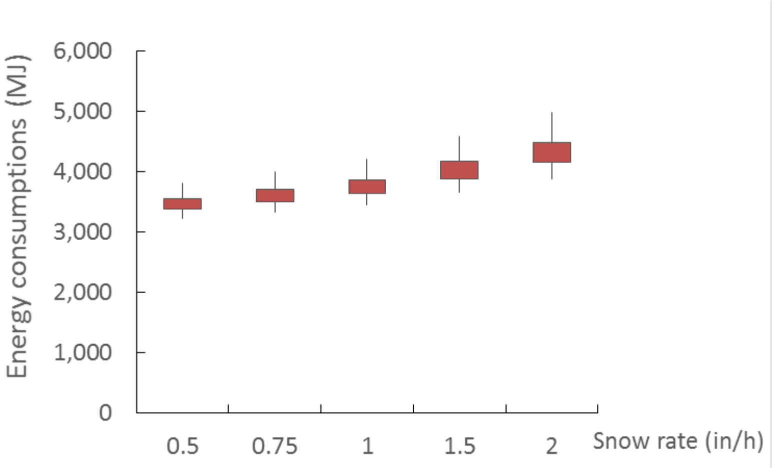
As table 1 shows, more energy is required for geothermal heat pump operation under a high snow rate or a low COP condition. Geothermal heat pump COP is highly related to soil conditions and the heat pump appliance; therefore, ground-heating conditions should be evaluated before applying HHPS-G. Because some areas do not have sufficient geothermal energy, HHPS-G requires relatively high energy consumption to support heating, or the system may not function. Table 1 also shows that when the snow period is longer, energy consumption of the HPS operations is less.

Using equation 8, the total flow rate of an HHPS-G for this study was calculated as 490 gpm, and a pressure drop of 125 ft was determined, based on a Viega manual script [43]. A circulating pump with 60% efficient horsepower was selected; using equation 9, the energy circulating pump demand was calculated as 26 hp.

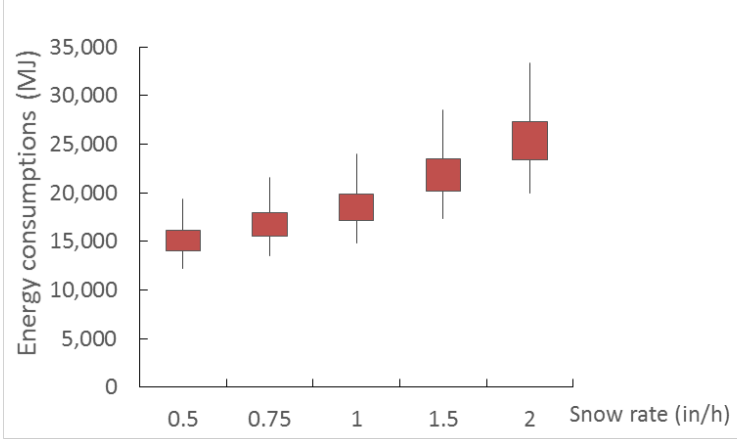
The apron area under review was 19,000 ft^2; 146 ft in length and 130 ft in width. The back and the top 10-in. edge of the apron were covered by a polyiso insulation layer to prevent heat loss and save energy, so the total required insulation layer area was about 19,184 ft^2. For the HHPS-G operation model described in section 4.2, the insulation layer production required 8.66 mJ/ft^2 of energy, so a total of 46,148 kW was consumed to produce 19,184 ft^2 insulation layers. Because the lifetime of the insulation layer is assumed the same as the pavement design lifetime, i.e., 20 years, energy consumption per hour of insulation layer production allocated was about 0.94 MJ/h.

For the HHPS-G operation model described in section 4.2, 808 kg of antifreeze (PG) was used for 1 year. Since the functional unit in this study was per hour, inventories were converted into hour-based values, and the PG demand was 90 g/h. LCA was conducted in analyzing antifreeze production stage using the GREET tool developed by Argonne National Laboratory [46], and the energy required for producing 90g/h of propylene glycol was 9 MJ/h.

PG has a COD content of roughly 1.68 kg/m^3. After the antifreeze is replaced, waste antifreeze solution with 0.15 kgCOD/h is discharged and treated in a municipal wastewater treatment plant. In general, aerobic wastewater treatment energy requirement is 1 kWh/kg COD [49], so the energy consumption of antifreeze waste treatment is 0.54 MJ/h. Figure 3 shows the total energy consumption of HHPS-G operation under different snow rates and an average snow period of 12 hours, and the total energy consumption of HHPS-G operation for different snow periods at average snow rates.



(a)



(b)

Figure 3. Energy Consumptions of HHPS-G Operation Life Cycle Against Snow Rates With (a) 1-h and (b) 12-h Snow Periods

As figure 3(a) demonstrates, the COP determines the energy demand of the heat pump operation, and the geothermal heat pump operation contributes most of the energy consumption in a HHPS-G operation life cycle. When the ambient temperature and the wind speed do not change, energy demand increases with an increasing snow rate. Figure 3(b) shows the influence of the COP geothermal heat pump. An LCA calculation example is provided in appendix A, which details the steps involved in the calculation of COP.

4.4 THE GHG EMISSIONS.

4.4.1 The GHG Emission Factors of Electricity, Natural Gas, and Distillate Oil.

Three types of fossil fuel power plants were considered in this case: coal, natural gas, and distillate (or diesel) oil. The phases of a coal-fired power plant life cycle include coal mining, coal preparation/cleaning, all necessary transportation of coal to the power plant, and grid electricity production. The GHG emissions of the different life phases of a coal-fired power plant are shown in table 2.

Table 2. The GHG Emissions From Coal-Fired Power Plant

Life Cycles of Coal Power Plant	GHG Emission Factor ($kgCO_2eq/kWh$)	Percentage (%)
Surface mining[1]	0.013	1.32
Coal washing[2]	1.1×10^{-4}	0.01
Coal transportation[3]	0.01	1.04
Grid electricity production[4]	0.94	97.9
Whole life cycle	0.96	100

[1] Illinois No. 6 coal as an example; electricity demand: 0.0143 kWh/kg of coal; distillate oil demand: 269 m^3/MMT of coal [53]; transportation of distillate oil GHG emission: 2.7 $kgCO_2eq/L$ [54]; 0.54 kg coal/kWh electricity produced [55].
[2] Jig washing is the technique used in this LCA [53].
[3] Distance from mining to power plant: 48 km; GHG emission: 0.01 $kgCO_2eq/t{\cdot}km$ [56].
[4] Data from U.S. Energy Information Administration (EIA)-1605 is used [57].

A natural gas-fired power plant life cycle includes natural gas extraction, natural gas pretreatment and transportation, and grid electricity production [58]. GHG emissions for different life-cycle phases of a natural gas-fired power plant are shown in table 3.

Table 3. The GHG Emissions From Natural Gas-Fired Power Plant

Life Cycles of Coal Power Plant	GHG Emission Factor ($kgCO_2eq/kWh$)	Percentage (%)
Natural gas extraction[1]	4.3×10^{-3}	0.97
Natural gas pretreatment and transportation[2]	9.9×10^{-5}	0.03
Grid electricity production[3]	4.2×10^{-1}	99.0
Whole life cycle	4.2×10^{-1}	100

[1] Natural gas density: 0.042 lb/ft^3; two-phase 95%-efficiency compressor is applied; power demand: 187 HP per 1,000,000 cubic feet of natural gas [58].
[2] Distance from mining to power plant: 48 km; GHG emission: 0.01 $kgCO_2eq/t{\cdot}km$ [57].
[3] Specific volume of natural gas: 23.8 ft^3/lb; auxiliary boiler natural gas consumption: 0.16 kg/MWh [58].

Because distillate oil-fired power plant GHG emissions factor is highly site-specific, a reasonable value based on a previous study of 0.78 $kgCO_2eq/kWh$ was assumed [59]. To confirm the applicability and use of this factor, it was compared with the U.S. Energy Information Administration (EIA) database [60].

The GHG emission factors of different fossil fuel applications are shown in table 4. A coal (bituminous)-fired power plant has a GHG emission factor of 0.96 $kgCO_2eq/kWh$ (see table 2), a natural gas-fired power plant has a GHG emission factor of 0.42 $kgCO_2eq/kWh$ (see table 3), and a distillate oil-fired power plant has a GHG emission factor of 0.78 $kgCO_2eq/kWh$. Based on the information provided by U.S. EIA [61], among these three types of power plants, 58% use coal as an energy source, 40% use natural gas, and only 2% use distillate oil to generate electricity. The estimated whole life-cycle natural gas (production and combustion) GHG emission factor is 0.185 kg CO_2 eq/kWh, whereas the estimated whole life-cycle electricity (production and combustion) GHG emissions factor is 0.42 kgCO_2eq/kWh [62].

Table 4. The GHG Emission Factors of Electricity, Natural Gas, and Distillate Oil

Fossil Fuel Application Emission Factors		Value (kgCO_2eq/kWh)
Electricity	Coal-fired power plant	0.96
	Natural gas-fired power plant	0.42
	Distillate oil-fired power plant	0.78
Natural gas [1]		0.18
Distillate oil [2]		0.46

[1] Natural gas upstream and combustion stages are included.
[2] Distillate oil upstream and combustion stages are included.

4.4.2 The GHG Emission Analysis.

A HHPS-G uses electricity to operate a geothermal heat pump and a circulating pump for extracting geothermal energy and circulating heated PG antifreeze solution, and their energy requirements are shown in table 1. Thus, there is no direct GHG released from either pumping operation; the GHG emissions actually occur during the energy production stage. GHG emissions from the electrical power production used for the operations of the geothermal heat pump and the circulating pump are shown in table 5.

Table 5. The GHG Emissions From Power Generation (Geothermal Heat Pump and Circulating Pump) for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	GHG Emissions (kgCO$_2$eq/h)			
		COP[1] = 2.0	COP = 2.5	COP = 3.0	COP = 3.6
1	2.0	884	753	667	594
	1.5	797	683	608	545
	1.0	724	625	560	504
	0.75	677	588	529	478
	0.5	644	561	506	460
4	2.0	722	591	505	432
	1.5	635	521	446	383
	1.0	562	463	398	342
	0.75	515	426	367	316
	0.5	482	399	344	298
8	2.0	695	564	478	405
	1.5	608	494	419	356
	1.0	535	436	371	315
	0.75	488	399	340	289
	0.5	455	372	317	271
12	2.0	686	555	469	396
	1.5	599	485	410	347
	1.0	526	427	362	306
	0.75	479	390	331	280
	0.5	446	363	308	262

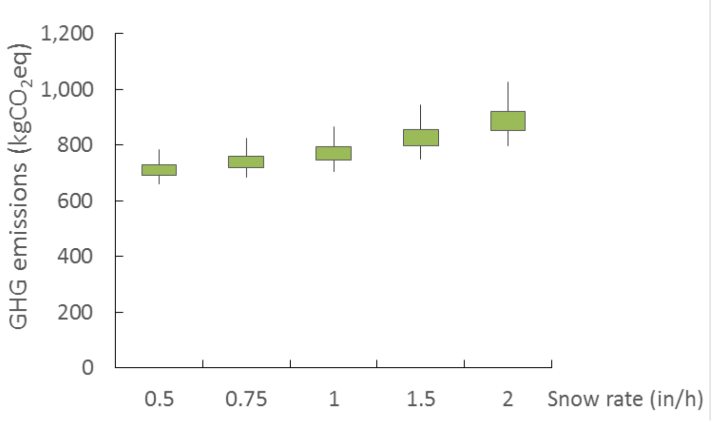
The GHG emission factor of 1.5-in.-thick insulation layer is approximately 0.39 kgCO$_2$eq/ft^2 [50]. A total of 19,184 ft^2 insulation layers is required for a 19,000 ft^2 concrete surfaced pavement, and the total GHG released from insulation layer production is about 7,482 kgCO$_2$eq. Because the insulation lifetime is assumed to be 20 years, the GHG emission result is converted into an hour-based value of 0.043 kgCO$_2$eq/h.

A 40%-by-volume solution of PG antifreeze is used in HHPS-G, and the GHG emission factor of antifreeze production is 6.46 kgCO$_2$eq/kg chemicals based on the GREET tool [46]. Converting the usage of PG antifreeze to an hourly basis resulted in an hourly requirement of 0.09 kg antifreeze per hour. Therefore, the total GHG emissions from PG antifreeze production were allocated as 0.6 kgCO$_2$eq/h.

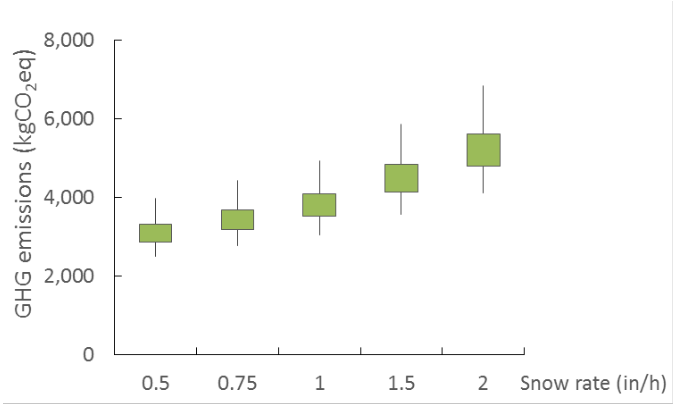
Waste PG antifreeze is treated in a municipal wastewater treatment plant. Aerobic treatment is the fundamental process that consumes electricity; an air bubble diffuser is used to aerate wastewater. The GHG emissions associated with the energy consumption of wastewater treatment are produced during the power generation stage. By applying the GHG emission factors from different types of power plants and percentages of each power application in the

U.S., GHG emissions from the electrical power production used for wastewater treatment were found to be 0.1 $kgCO_2eq/h$.

GHG emissions from HHPS-G operation depend on snow rate conditions and the COP of the geothermal heat pump, which was based on the model and assumptions made in this study. For example, figure 4 shows the total GHG emissions from HHPS-G operation for a 12-h snow period.



(a)



(b)

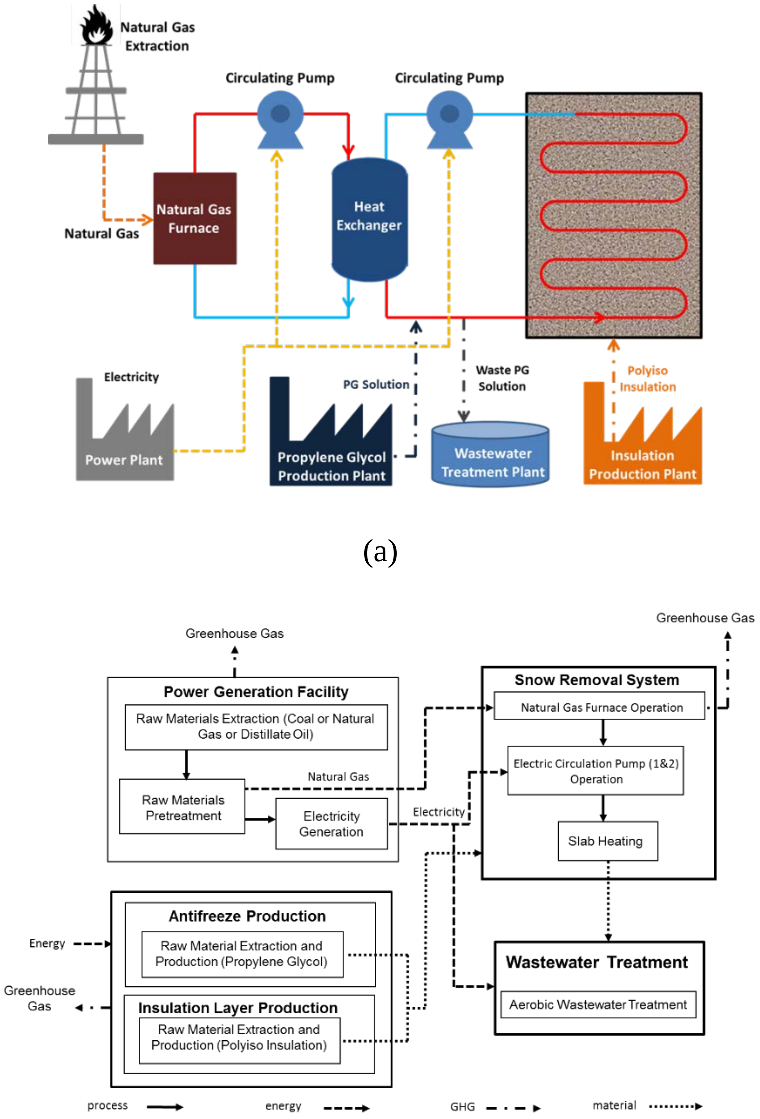
Figure 4. The GHG Emissions From HHPS-G Operation Life Cycle Against Different Snow Rates With (a) 1-h and (b) 12-h Snow Periods

5. CASE 2: HHPS-NG OPERATION.

Case 2 examines the operation system boundary, model, energy consumptions, and GHG emission estimations on HHPS-NG designed for a short- to medium-range airport apron area of 19,000 ft^2. The HHPS-NG operation model was analyzed at 20°F air temperature, 10-mph wind speed, and under 0.5-, 0.75-, 1-, 1.5- and 2-in./h snowfall rate conditions.

5.1 SYSTEM BOUNDARY.

Similar to the HHPS-G operation LCA, the HHPS-NG operation LCA includes both product and process LCAs. Based on the modeling and assumptions, the HHPS-NG operation life cycle can be divided into four subset life cycles: power generation, snow-removal operation, material production (e.g., antifreeze and insulation layer production), and antifreeze wastewater treatment. The only difference assumed between the HHPS and the HHPS-G is that the HHPS uses a fossil fuel heater as a heating source to heat the antifreeze solution. The HHPS-NG system boundary is similar to the boundary of the HHPS-G shown in figure 2, and the HHPS-NG operation flow chart and system boundary are shown in figure 5.



(a)

(b)

Figure 5. The HHPS-NG Operation Flow Chart (a) and the System Boundary of HHPS-NG Operation (b)

5.2 MODEL.

An HHPS-NG with a 60% efficient natural gas boiler has the potential to achieve fewer GHG emissions when the efficiency of the heating technique is improved. Thus, a natural gas furnace with 90% efficiency, which is considered to have a higher efficiency than a traditional gas boiler, was used in this assessment. A heat exchanger is required in the HHPS-NG because PG is used as antifreeze to prevent the heat transfer medium from freezing and cannot be heated directly by the furnace. Therefore, the HHPS-NG can be divided into two subsystems: a water-heating and pavement-heating. The water-heating system uses a natural gas furnace to heat water and then circulates the heated water through a 70% efficiency heat exchanger using a circulating pump. A 40%-by-volume of PG solution extracts heat from the water-heating system through the heat exchanger and circulates it under the concrete slab surface by the circulating pump to heat the pavement surface. As shown in figure 5, the HHPS-NG differs from the HHPS-G because the HHPS-NG requires two circulating pumps and a heat exchanger, and there are direct GHG emissions at the snow-removal system stage. However, the system design of HHPS-NG is generally similar to HHPS-G [43]. Because the only difference of the HHPS-NG from the HHPS-G is its heating source, the piping design, circulating pump selection, insulation layer design, PG solution usage, and solution waste treatment were the same as for the HHPS-G.

5.3 ENERGY CONSUMPTIONS.

Similar to the HHPS-G operation, warming the 19,000 ft^2 slab surface from 20°F to 32°F requires a 2,405 MJ snow period for HHPS-NG operation. For the 1-, 4-, 8-, and 12-hour snow periods evaluated in this study, energy consumption for idling were determined to be 2,405, 601, 301, and 200 MJ, respectively. Because of insulation installation in the HHPS-NG, zero back and edge losses were assumed to apply in the snow-melting heat calculation. Snow rate conditions for 0.5, 0.75, 1, 1.5, and 2 in./h were calculated by using equations 1 through 6, and energy requirements for snow melting under different snow rates were 134, 153, 173, 211, and 251 Btu/h·ft^2, respectively.

Equation 8 was used to calculate the total flow rate of the HHPS-NG as 490 gpm; and a 125-ft pressure drop was determined based on the Viega manual script [43]. A 60% efficient hp circulating pump was selected. Therefore, the energy demand of 1 circulating pump is calculated as 26 hp using equation 9. Considering circulating pumps are required for both the water and pavement heating systems, the total energy consumption for both circulating pumps was 52 hp.

Because of the system boundary and model similarities between the HHPS-G and the HHPS-NG, energy consumption of insulation production, antifreeze production, and antifreeze wastewater treatment was assumed to be the same. The total energy consumption for HHPS-NG operation is shown in table 6. Because the system energy requirement is determined by snow rate, the energy consumption of HHPS-NG operation increases as snowfall increases.

Table 6. Energy Consumptions of HHPS-NG Operation Life Cycle for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	Energy Consumption (MJ/h)	Total Energy Consumption (MJ)
1	2.0	10,542	10,542
	1.5	9,274	9,274
	1.0	8,055	8,055
	0.75	7,421	7,421
	0.5	6,812	6,812
4	2.0	8,738	34,953
	1.5	7,470	29,880
	1.0	6,251	25,006
	0.75	5,617	22,469
	0.5	5,008	20,032
8	2.0	8,438	67,501
	1.5	7,169	57,355
	1.0	5,951	47,606
	0.75	5,317	42,533
	0.5	4,707	37,659
12	2.0	8,337	100,049
	1.5	7,069	84,830
	1.0	5,851	70,206
	0.75	5,216	62,597
	0.5	4,607	55,285

Note: Equations 1 through 6, 8, and 9 were used to calculate energy consumption.

5.4 THE GHG EMISSIONS.

The GHG emission factors are shown in table 4. HHPS-NG uses a natural gas furnace to heat water; then, an electric circulating pump circulates the heated water and PG antifreeze solution in two subsystems. Because natural gas is combusted as a heating source, there is direct GHG released from the natural gas furnace. Similar to the HHPS-G, GHG emissions from the electric circulating pump are produced during the energy production stage. The total GHG emissions from natural gas combustion and electrical power production used for the circulating pump operation are shown in table 7.

Table 7. Total GHG Emissions From Natural Gas Furnace Operation and Power Generation (Circulating Pump)

Snow Period (h)	Electricity Power Source	Snow Rate (in./h)	GHG Emissions ($kgCO_2eq/h$)
1	Coal	2.0	482
	Natural gas	2.0	442
	Distillate oil	2.0	469

Similar to the HHPS-G operation, GHG emissions for the HHPS-NG are highly related to energy sources that have different emission factors. As table 7 shows, total GHG emissions from natural gas combustion and electrical power production used for the circulating pump operations varied only slightly when circulating pumps used electrical power generated from different fossil fuels.

The GHG emissions from the insulation layer production, the PG antifreeze production, and the antifreeze wastewater treatment for the HHPS-NG was the same as for the HHPS-G. The total GHG emissions from HHPS-NG operation is shown in table 8. Because GHG emissions are significantly related to energy consumption, HHPS-NG operation GHG emissions are dependent on snow rate conditions and snow periods as well.

Table 8. The GHG Emissions From HHPS-NG Operation Life Cycle for Different Snow Periods and Snow Rates

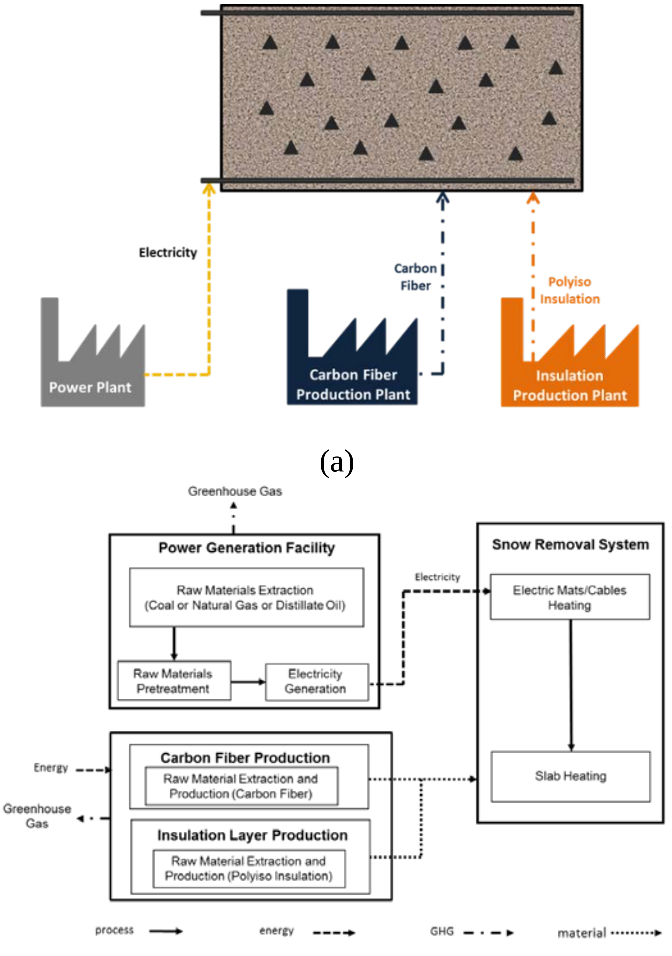
Snow Period (h)	Snow Rate (in./h)	GHG Emissions ($kgCO_2eq/h$)	Total GHG Emissions ($kgCO_2eq$)
1	2.0	931	931
	1.5	866	866
	1.0	804	804
	0.75	772	772
	0.5	741	741
4	2.0	560	2240
	1.5	495	1980
	1.0	433	1732
	0.75	401	1604
	0.5	370	1480
8	2.0	498	3984
	1.5	434	3472
	1.0	372	2976
	0.75	339	2712
	0.5	308	2464
12	2.0	478	5736
	1.5	413	4956
	1.0	351	4212
	0.75	319	3828
	0.5	288	3456

6. CASE 3: EHPS OPERATION.

Case 3 examines the operation system boundary, model, energy consumptions and GHG emission estimations on EHPS designed for a short- to medium-range airport apron area of 19,000 ft^2. The EHPS operation model was analyzed at 20°F air temperature, 10-mph wind speed, and under 0.5-, 0.75-, 1-, 1.5- and 2-in./h snowfall rate conditions.

6.1 SYSTEM BOUNDARY.

An EHPS uses electric mats or cables to transform electricity into radiant heat for pavement heating. EHPS operation life cycle can be divided into three subset life cycles: a power generation life cycle, a snow-removal operation life cycle, and a material production life cycle (e.g., carbon fiber and insulation layer production life cycles). The EHPS operation system boundary is similar to the other HPS boundaries, except that it does not include the wastewater treatment stage. An EHPS operation flow chart and system boundary are shown in figure 6.



(a)

(b)

Figure 6. The EHPS Operation Flow Chart (a) and the System Boundary of EHPS Operation (b)

6.2 MODEL.

For this case, a 4-ft-long, 3-ft-wide, and 4-in.-thick electronically heated pavement slab was assessed to evaluate how long it takes to heat the surface temperature from 20°F to 32°F. The electrical input was 950W, and edge and bottom insulation layers were installed to prevent heat loss through those surfaces. The 0.8% carbon fiber was mixed into the concrete mix to increase its conductivity [63]. Under these conditions, it required 20 minutes to heat the 12 ft^2 slab from 20°F to 32°F, and the energy consumption for conductive concrete pavement idling was 0.07 MJ/ft^2.

Instead of using a heated PG antifreeze solution, as with HHPS-G and HHPS-NG systems, an EHPS uses electrically heated cable as a heating source to warm concrete pavement directly. It has been determined that when the concrete conductivity increases, the EHPS efficiency also increases. One approach to do this is to mix conductive material, such as carbon fiber, into the concrete pavement mix. For this case, 0.8% by volume of PAN carbon fiber was mixed into the top 4 inches of concrete to increase the heat transfer rate [63]. Because the apron area analyzed in this study was 146 ft long and 130 ft wide, the total volume of active carbon for EHPS was 62.5 ft^3. Carbon fiber has a density of 1.55 g/cm^3 [64], and the total mass of carbon fiber required for a 19,000 ft^2 apron is about 2,736 kg. Concrete lifetime is about 20 years, and the carbon fiber lifetime was also assumed to be 20 years. Allocating carbon fiber usage on an hourly basis, 16 g/h of carbon is required. Based on a previous study [65], a carbon fiber production life cycle has an energy consumption factor of 704 MJ/kg and a GHG emission factor of 31 $kgCO_2eq/kg$.

Because EHPS uses electricity as the only energy input for heating, and there is an insulation layer installed in the system to prevent heat loss, all electrical power is assumed to transform into radiant heat for snow melting.

6.3 ENERGY CONSUMPTIONS.

Similar to other HPSs, the energy required for EHPS to melt snow is calculated by equations 1 through 5 and adding an 1803 MJ/snow period to determine the power input for system operation. Considering that electricity only is used for heating in EHPS operation, the energy consumption of the electrical heating under different snow rate conditions is shown in table 9. Similar to HHPS-G and HHPS-NG, EHPS energy consumption is significantly impacted by snow rate conditions. A higher snow rate requires more energy consumption for snow melting.

Table 9. Electrical Heating Energy Consumptions for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	Energy Requirement of Electrical Heating (MJ/h)
1	2.0	6833
	1.5	6034
	1.0	5266
	0.75	4866
	0.5	4482
4	2.0	5481
	1.5	4682
	1.0	3914
	0.75	3515
	0.5	3131
8	2.0	5255
	1.5	4456
	1.0	3688
	0.75	3288
	0.5	2905
12	2.0	5180
	1.5	4381
	1.0	3614
	0.75	3214
	0.5	2830

Note: Equations 1 through 6 were used to calculate the energy consumption of electric heating.

The total EHPS operation energy consumptions for different snow rates are shown in table 10. The insulation layer design for EHPS was the same as for HHPS-G and HHPS-NG, so the energy demand was also the same.

Table 10. Energy Consumptions of EHPS Operation Life Cycle for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	Energy Requirement of Electrical Heating (MJ/h)	Total Energy Requirement of Electrical Heating (MJ)
1	2.0	6,847	6,847
	1.5	6,048	6,048
	1.0	5,280	5,280
	0.75	4,880	4,880
	0.5	4,496	4,496
4	2.0	5,493	21,972
	1.5	4,694	18,776
	1.0	3,926	15,704
	0.75	3,527	14,108
	0.5	3,143	12,572
8	2.0	5,267	42,136
	1.5	4,468	35,744
	1.0	3,700	29,600
	0.75	3,301	26,408
	0.5	2,917	23,336
12	2.0	5,192	62,304
	1.5	4,393	52,716
	1.0	3,625	43,500
	0.75	3,226	38,712
	0.5	2,842	34,104

Note: Equations 1 through 6 were used to calculate energy consumption.

6.4 THE GHG EMISSIONS.

For EHPS, GHG is released during the power generation stage. GHG emissions from electrical power production used for electrical heating have been determined and are shown in table 11.

Table 11. The GHG Emissions From Power Generation (Electrical Heating) for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	GHG Emissions ($kgCO_2eq/h$)
1	2.0	1409
	1.5	1244
	1.0	1086
	0.75	1004
	0.5	924
4	2.0	1131
	1.5	966
	1.0	808
	0.75	725
	0.5	646
8	2.0	1084
	1.5	920
	1.0	761
	0.75	679
	0.5	600
12	2.0	1069
	1.5	904
	1.0	746
	0.75	663
	0.5	584

For EHPS operation, a 16-g/h carbon fiber usage was calculated, and a 31 $kgCO_2eq/kg$ GHG emission factor was used. The GHG emissions from the insulation layer production was the same that used for HHPS-G and HHPS-NG assessments, which were 0.48-$kgCO_2eq/h$ for carbon fiber production and 0.043 $kgCO_2eq$ for the insulation layer production. Total GHG emissions from EHPS operation is shown in table 12.

Table 12. The GHG Emissions From EHPS Operation Life Cycle for Different Snow Periods and Snow Rates

Snow Period (h)	Snow Rate (in./h)	GHG Emissions (kgCO_2eq/h)	Total GHG Emissions (kgCO_2eq)
1	2.0	1410	1,410
	1.5	1245	1,245
	1.0	1087	1,087
	0.75	1005	1,005
	0.5	925	925
4	2.0	1132	4,528
	1.5	967	3,868
	1.0	809	3,236
	0.75	726	2,904
	0.5	647	2,588
8	2.0	1085	8,680
	1.5	921	7,368
	1.0	762	6,096
	0.75	680	5,440
	0.5	601	4,808
12	2.0	1070	12,840
	1.5	905	10,860
	1.0	747	8,964
	0.75	664	7,968
	0.5	585	7,020

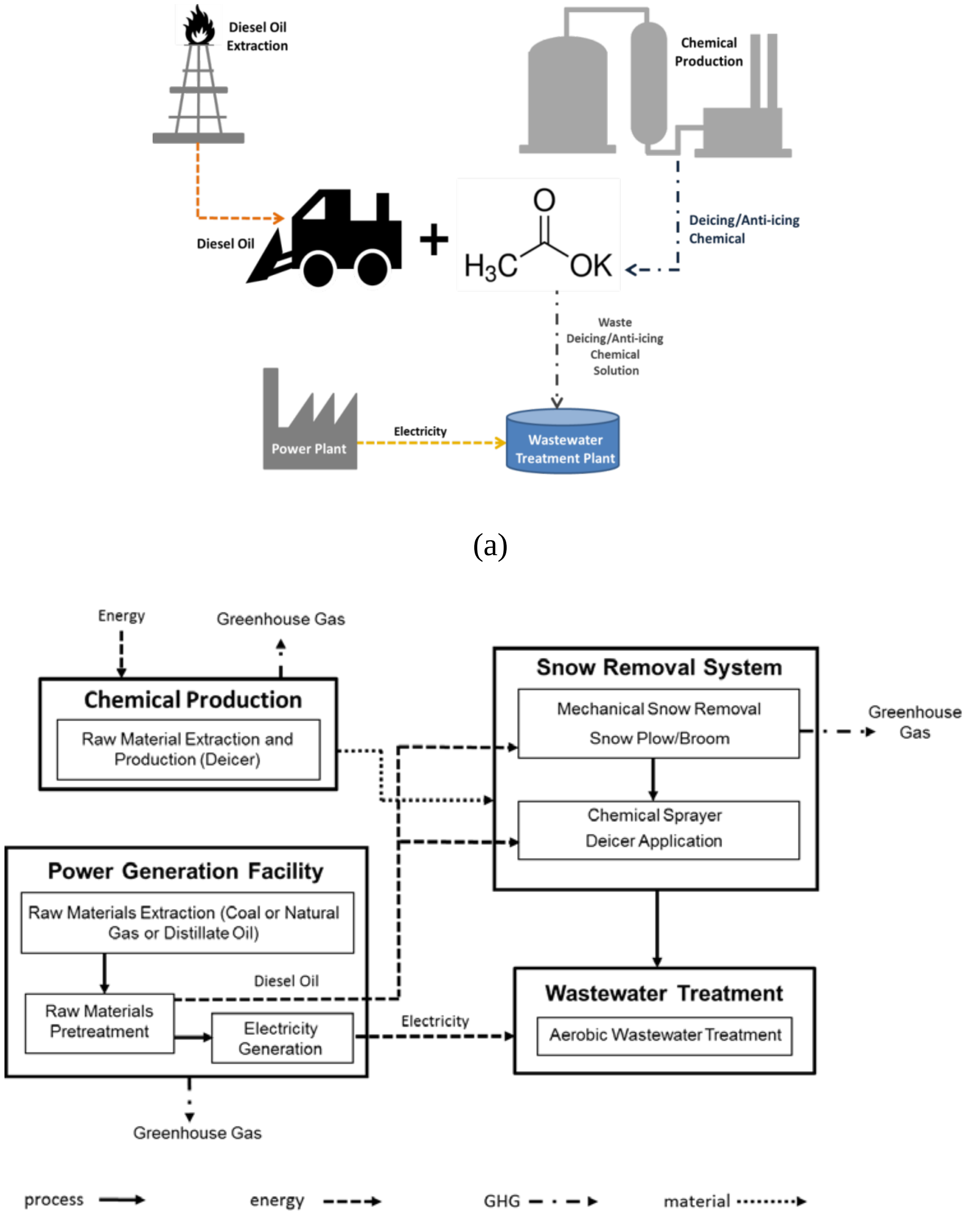
Considering the results from tables 11 and 12, it is clear that most GHG emissions were related to the heating stage from the EHPS operation life cycle.

7. CASE 4: CSRS OPERATION.

Case 3 examines the operation system boundary, model, energy consumptions and GHG emission estimations on CSRS designed for a short- to medium-range airport apron area of 19,000 ft^2. The CSRS operation model was analyzed at 20°F air temperature, 10-mph wind speed, and under 0.5-, 0.75-, 1-, 1.5-, and 2-in./h snowfall rate conditions.

7.1 SYSTEM BOUNDARY.

CSRSs use mechanical equipment, such as snowplows or snow blowers, to first remove snow and then apply deicing chemicals on the pavement to prevent snow reformation. The chemically polluted water from snow melting is subsequently treated in a municipal wastewater treatment plant. Therefore, life cycles in the assessment should include deicing chemical production, power generation, snow-removal operations and wastewater treatment. Figure 7 shows the CSRS flow chart and system boundary, which differs from the HPSs under assessment.



(a)

(b)

Figure 7. The CSRS Operation Flow Chart (a) and the System Boundary of CSRS Operation (b)

7.2 MODEL.

Potassium acetate, sodium acetate, and PG are the chemicals commonly used in airport pavement deicing [66]. A 50% by weight potassium acetate solution, a 60% by weight PG solution, and a sodium acetate solid deicer are assessed in this study, applied at levels of 75 g/m^2 [67], 65 g/m^2 [68], and 50 g/m^2 [69], respectively. Because the amount of chemicals for a deicing application is based on air temperature, and the air temperature is constant under different snow rate conditions, deicer usage is the same for all snow rates. Among these three chemicals, 67% of airports in U.S. use potassium acetate, 11% use PG, and 22% use sodium acetate. Deicing chemicals are sprayed on the pavement once per hour.

The Perkins® 1104D-E44TA Industrial Diesel Engine is a multifunctional vehicle that requires 97 kW and a transmission power demand of 68 kW [70]. This vehicle was used to spray the deicing chemical on the 19,000 ft^2 apron pavement to prevent ice adhesion. One hour after the application of the chemical, the vehicle was converted into a snowplow to remove snow from the apron area. Considering the size of the apron area is relatively small, the total operating time of the vehicle, including chemical spraying and snowplowing, was assumed to be 10 minutes.

Because a deicing chemical is used in the CSRS operation, a wastewater treatment process is required. In general, most airport pavement runoff is treated in municipal wastewater treatment plant using an aerobic treatment.

7.3 ENERGY CONSUMPTIONS.

The strategy for CSRS is to spray deicing chemicals every hour to prevent ice or snow adhering to pavement and then to use a snowplow to move snow away from apron area. The power demand for the mechanical equipment assessed is 165 kW. By multiplying the operation time of 10 minutes with equipment engine power, total combined energy consumption of distillate oil raw-material production and distillate oil combustion for the snow-removal operation is 99 MJ/h.

Three kinds of deicing chemicals, potassium acetate, PG, and sodium acetate, were analyzed. LCA tools, such as Argonne GREET and the Carnegie Mellon EIO-LCA model, were used to calculate the energy consumption of deicer production. The results show that to produce 1 kg of potassium acetate requires 18 kWh of energy; 28 kWh is required to manufacture 1 kg of PG; and 1 kg of sodium acetate requires 12 kWh. The chemical usage values for the 19,000 ft^2 apron area are 139 kg/h for potassium acetate, 193 kg/h for PG, and 88 kg/h for sodium acetate. Therefore, to produce certain amounts of chemicals, the energy consumptions are 8374 MJ/h, 7258 MJ/h, and 5584 MJ/h, respectively. According to a U.S. EPA report [66], 67% of airports in the U.S. use potassium acetate, 11% use PG, and 22% use sodium acetate.

Based on a previous study [71], the COD of the different chemicals are 1050 g/kg for potassium acetate, 1680 g/kg for PG, and 1010 g/kg for sodium acetate. Thus, the total COD of deicing wastewater is 139 kg for potassium acetate, 193 kg for PG, and 89 kg for sodium acetate. Usually, apron wastewater is discharged to a municipal wastewater treatment plant that generally applies aerobic biological treatment, and 1 kWh of electricity demand per kg COD is assumed for such aerobic treatment [49]. The energy required for a wastewater plant to treat different kinds of deicing wastewater would thus be 500, 695, and 320 MJ/h, for potassium acetate, PG, and sodium acetate, respectively.

Because the operational strategy of CSRS is to use mechanical equipment to clear accumulated snow before applying chemical deicer, operational time of mechanical equipment and deicer usage for 19,000 ft^2 apron area were not affected by snow rate. Energy consumption of CSRS operation therefore does not change with increasing snow rate. By applying the percentage of deicer usage in the energy calculation, the total energy consumption of CSRS operation for a

19,000 ft^2 apron was found to be 8,359 MJ/h, and the results for different snow periods are shown in table 13.

Table 13. Energy Consumptions of CSRS Operation Life Cycle for Different Snow Periods

Snow Period (h)	Total Energy Consumptions (MJ)
1	8,361
4	33,443
8	66,886
12	100,329

7.4 THE GHG EMISSIONS.

Chemicals and mechanical force are two CSRS approaches for removing snow. GHG emissions from CSRS operation include GHG from electricity and distillate oil generation, combustion of vehicle oil, and deicing chemical production. The multifunctional vehicle that uses distillate oil for the deicing operation has a GHG emission of 13 $kgCO_2eq/h$.

GREET and EIO-LCA tools were used for the LCA of the deicing chemical production. The GHG emission factor was 3.82 $kgCO_2eq/kg$ for potassium acetate, 6.46 $kgCO_2eq/kg$ for PG, and 2.73 $kgCO_2eq/kg$ for sodium acetate. Calculating the chemical production for a 19,000 ft^2 apron, the GHG released from potassium was 506 $kgCO_2eq/h$ from acetate, 742 $kgCO_2eq/h$ from PG, and 241 $kgCO_2eq/h$ from sodium acetate.

The wastewater treatment stage in CSRS was the same as for HHPS-G and HHPS-NG. Wastewater treatment requires electrical power, but there is no direct GHG released from the wastewater plant itself; so any GHG emission actually comes from the power generation phase. Calculations show that treating a given amount of wastewater releases 129 $kgCO_2eq/h$ for potassium acetate, 104 $kgCO_2eq/h$ for PG, and 56 $kgCO_2eq/h$ sodium for acetate.

Multiplying the percentages of different chemical usages, the average GHG emission from CSRS airport apron snow removal under different snow rate conditions was found to be 585 $kgCO_2eq/h$. GHG emissions for different snow periods are shown in table 14.

Table 14. The GHG Emissions From CSRS Operation Life Cycle for Different Snow Periods

Snow Period (h)	Total GHG Emissions ($kgCO_2eq$)
1	585
4	2341
8	4682
12	7023

8. COMPARISONS OF CASES.

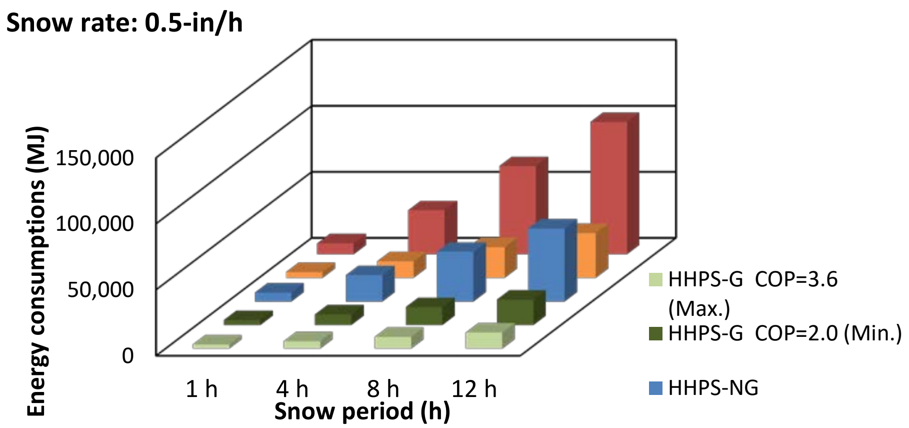
Four case studies of operations of conventional snow-removal systems and three alternative HPSs were analyzed to evaluate the sustainability of such systems. As the analyses for different snow-removal system operations demonstrated, energy consumption conditions and environmental impact were influenced by several factors such as snow rates, snow periods, and system efficiencies. These factors varied among the four system operations. Energy consumption and GHG emissions were also compared to estimate which snow-removal system was most sustainable.

8.1 ENERGY CONSUMPTIONS COMPARISON.

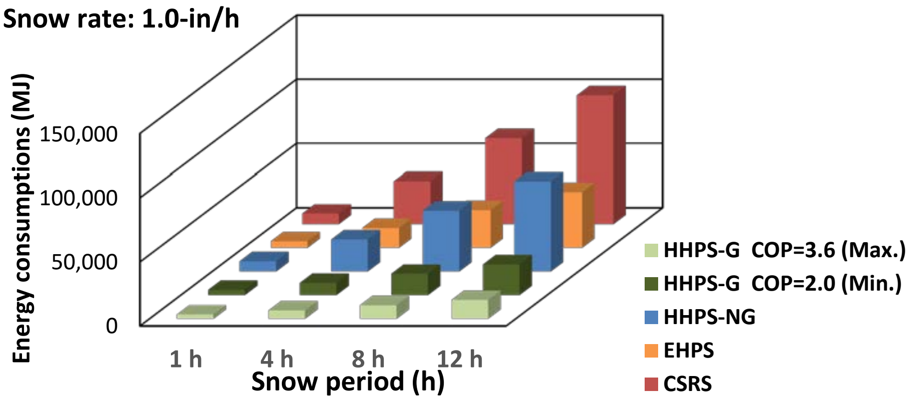
The equations and system operation models assessed in this study showed that snow rate and snow period had significant effects on energy consumption. To compare four different system operations, energy consumptions for 1-, 4-, 8-, and 12–h snow periods, and 0.5-, 1-, and 2-in./h snow rate conditions are summarized in figure 8.

As figure 8 shows, CSRS requires more energy for snow-removal operation than HPS operations under the various snow rate and snow period conditions, because the energy consumption of HPS operations are significantly related to snow rate. Given that energy consumption of HPS operations increases when snowfall rate increases, when the snow rate exceeds 2 in./h, energy consumption of an HHPS-NG operation could be more than for CSRS, as shown in figure 8(c).

Although it is expected that HPSs require energy to heat the pavement surface to remove snow, it was unexpected to find that more energy is consumed in CSRS operation life cycle, as figures 8(a) and (b) demonstrate. Also, among the three HPS operations under assessment, the HHPS-NG operation had higher energy consumption than the HHPS-G and EHPS operations. The energy consumption contributions of the different inventories of each system were analyzed and are summarized in table 15.



(a)



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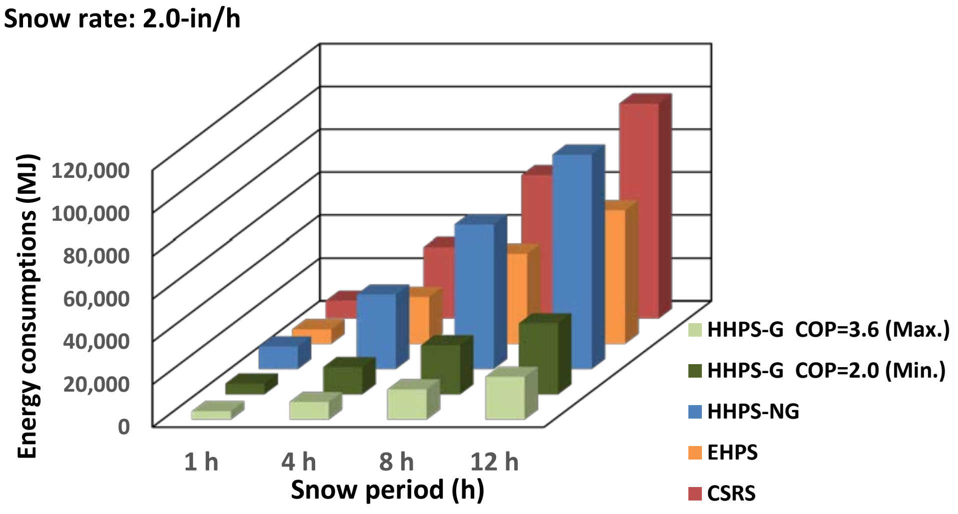


(c)

Figure 8. Energy Consumptions of Snow-Removal System Operations Against Different Snow Periods Under (a) 0.5-in./h, (b) 1-in./h, and (c) 2-in./h Snow Rate Conditions

Table 15. Operation Energy Contributions of Different Inventories in Different Snow-Removal Systems

Energy Consumption (%)	HHPS-G (COP max)[1]	HHPS-G (COP min)[2]	HHPS-NG[3]	EHPS[4]	CSRS[5]
Geothermal heat pump + circulating pump	99.04	99.45	-	-	-
Natural gas furnace + circulating pump	-	-	99.82	-	-
Electrically heating	-	-	-	99.68	-
Deicer production + wastewater treatment	-	-	-	-	98.80
Other	0.96	0.55	0.18	0.32	1.20

[1-3] Other includes insulation layer production, antifreeze production, and antifreeze waste treatment stages.
[4] Other includes insulation layer production and carbon fiber production stages.
[5] Other includes distillate oil for mechanical equipment operation.

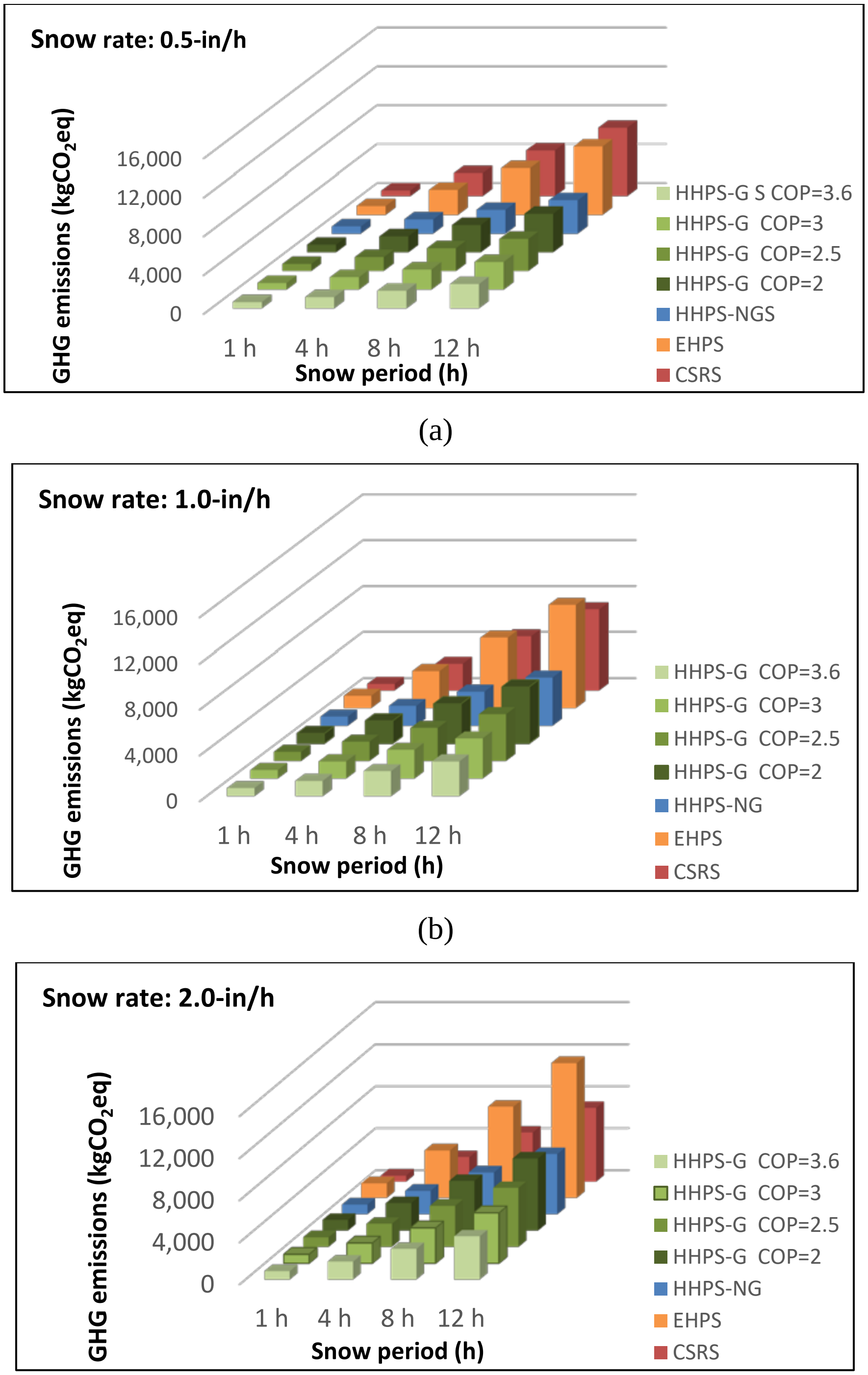
Most of the energy used in a CSRS operation is related to deicing chemical production. Significant amount of deicing chemicals are required for a 19,000 ft^2 apron area, and the energy demand for deicer manufacture is relatively high. This results in a higher energy consumption rate for the CSRS operation life cycle than for the HPSs, which do not require deicing materials. Therefore, if an airport company's goal is to reduce energy consumption during snow removal, using less deicer is an effective way to reduce much of the energy demand.

More than 99% of the total energy consumed in HPS operation is used for heating, as shown in table 15. Due to differences in system models and equipment used for HPSs, energy consumption may vary. Using HHPS-NG as an example, the system utilizes a 90% efficient natural gas furnace, a 60% efficient circulating pump, and a 70% efficient heat exchanger. Compared to the other two system models, the HHPS-NG exhibits more heat loss during the heating process, so the HHPS-NG operation requires the most energy consumption among the three HPSs under assessment.

HHPS-G efficiency is highly dependent on the COP related to the geothermal condition of the area. Since analysis for HHPS-G operation assumes geothermal energy is sufficient for heating support, HHPS-G with a low COP still has the least energy demand among the three HPSs.

8.2 COMPARISON OF GHG EMISSIONS.

Based on the system boundaries, models, and assumptions made in this study, GHG emissions are determined by the energy consumption of snow-removal system operations. For example, HHPS-G (COP max) requires the least amount of energy, therefore it has lower GHG emissions than the other snow-removal system operations, as figures 8(a) and 9(a) show.



(a)

(b)

(c)

Figure 9. The GHG Emissions From Snow-Removal System Operations Against Different Snow Periods Under (a) 0.5 in./h, (b) 1 in./h, and (c) 2 in./h Snow Rate Conditions

GHG emissions are determined by energy consumption; consequently, GHG emissions from CSRS operation are not affected by an increase in snow rate. However, HPS operations produce more GHG emissions when snow rate increases since operating HPS types at a higher snow rate requires more energy, which affects the amount of GHG emissions. Conversely, when the snow period is greater than 9 hours, the three types of HPS operations produce less GHG emissions than CSRS applied in an apron snow removal under 0.5 in./h snow rate conditions.

However, GHG emissions also depend on the type of energy source, because different energy sources have different emission factors, and a system operation that consumes more energy does not necessarily release more GHG than others. For example, an HHPS-NG requires about 1.6 times more energy for snow-removal operation than an EHPS; however, an HHPS-NG releases only half the GHG than an EHPS. Also, although an HHPS-G requires much less energy than the other snow-removal systems under assessment, an HHPS-G with a COP of 2 may be able to release more GHG than the amount of GHG released from the HHPS-NG. This is because natural gas combustion has a much lower GHG emission factor than electrical power generation, as table 4 shows. Although the system efficiency does not increase, switching the energy source to natural gas could dramatically reduce GHG emissions.

GHG emission contributions from different life-cycle inventories of snow-removal systems were analyzed to identify the inventory that released the most GHG in each system operation. The results are summarized in table 16.

Table 16. Operation GHG Emissions From Different Inventories in Different Snow-Removal Systems

GHG Emission (%)	HHPS-G (COP max)[1]	HHPS-G (COP min)[2]	HHPS-NG[3]	EHPS[4]	CSRS[5]
Geothermal heat pump + circulating pump	99.67	99.81	-	-	-
Natural gas furnace + circulating pump	-	-	99.77	-	-
Electrically heating	-	-	-	99.93	-
Deicer production + wastewater treatment	-	-	-	-	97.78
Other	0.33	0.19	0.23	0.07	2.22

[1-3] Other includes insulation layer production, antifreeze production, and antifreeze waste treatment stages.
[4] Other includes insulation layer production and carbon fiber production stages.
[5] Other includes distillate oil for mechanical equipment operation.

Table 16 shows that most GHG emissions result from heating energy production in HPS and deicer production in CSRS. Since GHG emissions are significantly positively correlated to energy consumption, the more energy used, the more GHG will be released, as shown in tables 15 and 16. For a similar strategy to reduce energy consumption of snow-removal operation, using less deicer can be a significant way to reduce GHG emissions in CSRS; and using a HPS instead of deicing chemical application has an additional potential for reducing GHG emissions. Also, for longer snow periods, less GHG per hour are released from HPS operations, as shown in figure 9(a).

In conclusion, analysis of energy consumption and GHG emissions from different snow-removal system operations show that, under a 5-in./h snow rate and more than 6 hours of snowfall conditions, HPS operations produce less energy consumption and GHG emissions than CSRS operations.

9. POTENTIAL HHPS BENEFITS.

HPSs offer a number of potential benefits over CSRS. The various categories of potential benefits that can be attributed to HPS are summarized in sections 9.1 through 9.5.

9.1 OVERALL BENEFITS.

Potential overall benefits of HPS include:

- Facilitates expedited and efficient snow- and ice-removal operations that can reduce traffic delays, especially at large airports.
- Eliminates the risk of airplanes skidding off runways, high-speed taxiways, etc., thus possibly reducing accidents, injuries, and fatalities.
- Reduces the downtime required to clear ice and snow.
- Improves safety for ground crews servicing the aircraft at the gate areas.
- Improves safety of passengers embarking/disembarking the aircraft.
- Improves air travel capacity during winter operations. Utilization of an HPS assists airports to remain open and accessible during winter operations, enabling safe travels for the passengers.
- Reduces the time required to clear snow and/or ice in priority areas.
- Provides a platform for the development of innovative anti-icing systems, such as nanostructured superhydrophobic coatings and systems, conductive paving materials, etc.
- Provides an efficient operation time window, i.e., the HPS deicing operation can be automated to start and end exactly for the duration of ice and snow formation. (The heating process can be initiated ahead of an ice/snow storm and can be automated by using sensor systems.)
- Reduces the amount of labor and equipment costs associated with using and applying deicing methods.
- Provides a viable option from an energy or financial perspective for achieving pavement surfaces free of ice/snow without using mechanical or chemical snow and ice removal methods.

9.2 ENVIRONMENTAL AND SUSTAINABILITY BENEFITS.

Potential environmental and sustainability benefits of HPS are listed below.

- Eliminates environmental concerns, such as the contamination of nearby bodies of water and foreign object debris/damage to aircraft engines. Both these concerns can be the result of using deicing and anti-icing chemicals.

- Saves airports significant money by eliminating the need to treat and clean the contaminated snow and storm water associated with the use of deicing chemical agents on airfield pavements.

- Curbs and prevents the corrosion and deterioration of airfield lighting fixtures by eliminating (or reducing) the use of deicing chemicals. This may provide significant cost savings, especially considering that some airports have between 20,000 and 50,000 airfield lighting fixtures installed in airfield pavements.

- Mitigates pavement durability failures that potentially result from using deicing chemicals. Also, extends the life of airfield pavement systems, thus leading to significant savings in maintenance and repair costs.

- Improves efficiency and sustainability of surface drainage systems.

- Facilitates of the application of clean energies, e.g., use of geothermal energy.

- Reduces GHG emissions and overall energy consumption compared to conventional snow- and ice-removal systems.

9.3 SAFETY BENEFITS.

Potential safety benefits of HPS include:

- Improved safety for ground crews servicing the aircraft at the gate areas by providing ice and snow free airfield pavements.

- Improved safety of passengers embarking/disembarking the aircraft.

- Decreased risk of collision between aircraft and SRE.

- Zero-to-minimal noise pollution compared to that resulting from the use of SRE.

10. CONCLUSIONS.

Ineffective snow and ice removal activities can result in airline delays, employee injuries, and potential environmental risks from the overuse of deicers or anti-icers. As an industry with facilities that must pay attention to environmental impact and sustainability of its products or systems under conditions of increased environmental awareness, airports seek more sustainable systems with the capability to effectively replace conventional snow-removal systems (CSRS). This study was carried out with the specific goal of applying a hybrid life cycle assessment (LCA) approach for evaluating energy consumption and greenhouse gas (GHG) emissions from the operations of heated pavement systems (HPS), including hydronic heated pavement systems using geothermal energy (HHPS-G), hydronic heated pavement systems using a natural gas furnace (HHPS-NG), and electrically heated pavement systems (EHPS). The findings and future recommendations of the study are summarized in the following sections.

10.1 FINDINGS.

The key findings of all case studies in this study are summarized below.

- HPS applications in apron paved surfaces are a viable option from an energy or environmental perspective for achieving ice- and snow-free pavement surfaces.

- The production of deicing chemicals, considered in the operation phase of the CSRS life cycle, requires relatively high energy (which is typically drawn from nonrenewable energy sources) and releases associated GHG emissions. The use of HPSs as an alternative to chemical deicers enables effective snow removal with reduced energy consumption and GHG emissions.

- The energy demand and the GHG emissions from the operation of HPSs are significantly impacted by snowfall rate.

- Compared to CSRS, HPS operations have a greater advantage during a snow event with a relatively smaller snow rate and longer snow period.

- Energy production (i.e., electrical power generation) and energy consumption (i.e., natural gas combustion) phases for heating require the most energy and contribute the most GHG emissions during the operation phase of the HPS life cycle.

- HHPS-G using geothermal heat pumps with a COP higher than 2.5 resulted in less energy consumption and less GHG emissions than the other types of snow-removal systems under assessment under the same snow rate conditions. From an environmental impact perspective, natural gas, which has a relatively low emission factor, has the potential to replace electricity or distillate (or diesel) oil as a more environmentally friendly energy source.

Although this study only focused on the operation phase of both HPSs and CSRSs, it provides airport planners and management a more informed view of operating an HPS for snow removal in terms of energy saving and potential global-warming aspects. However, it should be stressed that the theoretical models in this study used to calculate energy consumption and GHG emissions from different types of apron snow-removal systems are still under development. Consequently, the study’s results should be regarded as a qualitative view, and more comprehensive assessments that include broader system boundaries are required for future study.

10.2 RECOMMENDATIONS.

The recommendations from this study are summarized below.

- Airport authorities could conduct a comprehensive LCA of various airport snow-removal strategies to determine the sustainability and environmental impacts of their snow-removal systems. However, the success of any assessment largely depends on the availability of data, which is currently limited for airport HPS applications. With the availability of more data and studies, the LCA models used in this study could be more fully developed and calibrated to reflect realistic airport scenarios; this would assist airport authorities engaged in airport sustainability planning to choose the most sustainable snow-removal strategy under various what-if scenarios.

- Based on more comprehensive studies, guidance and feedback could be provided to HPS designers to optimize those processes and subsystems that were identified as having caused, or having been involved in causing, high environmental impacts.

- Based on the assumptions for system boundaries defined in this study, most of the energy consumed is used for heating, which causes high GHG emissions during the HPS operations phase. Thus, heating source efficiency and coefficient of performance are critical aspects in HPS operations.

- A study on the full life cycle of snow-removal systems may reveal an increase in the energy spent during the pavement maintenance phase. This needs further investigation.

11. REFERENCES.

1. CDM Smith, for the Airports Council International—North America, “The Economic Impact of Commercial Airports in 2013,” September 2014, available at http://airportsforthefuture.org/did-you know/files/2014/09/Economic-Impact-of-Commercial-Aviation-2013.pdf/ (date last visited 03/21/17).

2. Jacobs Consultancy for the Norfolk Airport Authority, “Economic Impact Study—2004 Norfolk International Airport,” Norfolk Airport Authority, October 2007, available at http://www.norfolkairport.com/sites/default/files/pdfs/ORF_Econ_Impact_Study_2004.pdf (date last visited 03/21/17).

3. Federal Aviation Administration (FAA), “Airport Winter Safety and Operations,” Advisory Circular (AC) 150/5200-30C, December 9, 2008 (cancelled July 29, 2016).

4. Amsler, D.E., “Snow and Ice Control 2014,” Publication CLRP No. 13-04, Cornell Local Roads Program, New York Local Technical Assistance Program Center, New York, 2014.

5. FAA, “Airside Use of Heated Pavement Systems,” AC 150/5370-17, March 29, 2011.

6. Roth Industries, Inc., "Snowmelt Systems Installers Handbook," Watertown, New York, April 2008. http://www.roth-usa.com/PDF_Download_Files/snowmelt_install.pdf (date last visited 03/21/17).

7. FAA, "Airport Sustainability," available at http://www.faa.gov/airports/environmental/sustainability (date last visited 03/21/17).

8. FAA, "Airport Sustainable Master Plan Pilot Program," Memorandum, May 27, 2010, available at http://www.faa.gov/airports/environmental/sustainability/media/interim_guidance_sustainable_master_plan_pilot.pdf (date last visited 03/21/17).

9. FAA, "Report on the Sustainable Master Plan Pilot Program and Lessons Learned," available at http://www.faa.gov/airports/environmental/sustainability/ (date last visited 03/22/17).

10. Malmqvista, T., Glaumanna, M., Scarpellinib, S., Zabalzab, I., Arandab, A., Llerab, E., and Díaz, S., "Life Cycle Assessment in Buildings: The ENSLIC Simplified Method and Guidelines," *Energy*, Vol. 36, No. 4, April 2011, pp. 1900–1907.

11. United Nations Environment Programme, "Life Cycle Assessment," available at http://staging.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx (date last visited 03/22/17).

12. International Organization for Standardization (ISO), "Environmental Management-Life Cycle Assessment-Principles and Framework," ISO 14040:1997, Geneva, Switzerland, June 15, 1997, available at https://www.iso.org/standard/37456.html.

13. Scientific Applications International Corporation (SAIC), "Life Cycle Assessment: Principles and Practice." U.S. Environmental Protection Agency (EPA). Contract No. 68-C02-067. Cincinnati, Ohio, 2006.

14. United States (U.S.) EPA, "Life-Cycle Assessment: Inventory Guidelines and Principles," EPA/600/SR-92/245, February 1993, available at http://goo.gl/gHQeTH (date last visited 03/22/17).

15. U.S. EPA, "Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis," EPA-R-95-010, April 1995, available at .http://goo.gl/O9ZPbD (date last visited 03/22/17).

16. Finnveden, G., Hauschildb, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., and Suh, S., "Recent Development in Life Cycle Assessment," *Journal of Environmental Management*, Vol. 91, No. 1, October 2009, pp. 1-21, available at http://www.sciencedirect.com/science/article/pii/S0301479709002345# (date last visited 03/22/17).

17. Green Design Institute – Carnegie Mellon University (GDI-CMU), "Approaches to Life Cycle Assessment," 2008, available at http://www.eiolca.net/Method/LCAapproaches.html (date last visited 03/22/17).

18. Lenzen, M., and Treloar, G., "Differential Convergence of Life-Cycle Inventories Toward Upstream Production Layers," *Journal of Industrial Ecology*, Vol. 6, No. 3-4, pp. 137-160, July 2002.

19. Dale, A.T., Khanna, V., Vidiv, R.D., and Bilec, M.M., "Process Based Life-Cycle Assessment of Natural Gas from the Marcellus Shale," *Environmental Science & Technology*, Vol. 47, No. 10, April 2013, pp. 5459-5466.

20. Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O. et al., "System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches," *Environmental Science & Technology,* Vol. 38, No. 3, December 18, 2003, pp. 657-664.

21. Ferrao, P. and Nhambiu, J.A., "Comparison Between Conventional LCA and Hybrid EIO-LCA: Analyzing Crystal Giftware Contribution to Global Warming Potential," *Handbook of Input-Output Economics in Industrial Ecology*, Vol. 23, 2009, pp.219-230.

22. Acquaye, A.A., Wiedmann, T., Feng, K., Crawford, R.H., Barrett, J., Kuylenstierna, J., McQueen-Mason, S. et al., "Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis," *Environmental Science & Technology*, Vol. 45, No. 6, February 2011, pp. 2471-2478.

23. Alvarez-Gaitan, J.P., Peters, G.M., Rowley, H.V., Moore, S., and Short, M.D., "A Hybrid Life Cycle Assessment of Water Treatment Chemicals: An Australian Experience," *International Journal of Life Cycle Assessment*, Vol. 18, April 11, 2013, pp. 1291-1301.

24. Hendrickson, C.T., Lave, L.B., and Matthews, H.S. et al., "Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach," Resources for the Future Press, Washington, DC, April 19, 2006.

25. Weber, C., Matthews, D., Venkatesh, A., Costello, C., and Matthews, H.S., "The 2002 US Benchmark Version of the Economic Input-Output Life Cycle Assessment (EIO-LCA) Model," Green Design Institute, Carnegie Mellon Technical Report January 2009, available at: http://www.eiolca.net/docs/full-document-2002-042310.pdf (date last visited 03/22/17).

26. Suh, S. and Huppes, G., "Methods for Life Cycle Inventory of a Product," *Journal of Cleaner Production*, Vol. 13, No. 7, June 2005, pp. 687-697.

27. Stripple, H., "Life Cycle Assessment of Road a Pilot Study for Inventory Analysis," Swedish Environmental Research Institute IVL Report Issue No. 1210, Gothenburg, Sweden, 2001.

28. Massachusetts Department of Transportation, "Standard Operating Procedures (S.O.P.), Reduced Salt Policy," S.O.P. NO. HMD-01-01-1-000, April 1, 2014, available at http://www.massdot.state.ma.us/Portals/8/docs/SnowAndIce/saltpolicy/salt_policy.pdf (date last visited 03/22/17).

29. Boselly, S.E., "Update of the AASHTO Guide for Snow and Ice Control," requested by American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highways, December 2008, available at http://maintenance.transportation.org/Documents/Final%20Report%2020-07%20Task%20250.pdf (date last visited 03/22/17).

30. Kecojevic, V. and Komljenovic, D., "Impact of Bulldozer's Engine Load Factor on Fuel Consumption, CO_2 Emission and Cost," *American Journal of Environmental Sciences*, Vol. 7, No. 2, February 2011, pp. 125-131.

31. American Council for an Energy-Efficient Economy, "Water Heating," available at http://www.aceee.org/consumer/water-heating (date last visited 03/22/17).

32. U.S. Department of Energy, "Furnaces and Boilers," available at http://energy.gov/energysaver/articles/furnaces-and-boilers (date last visited 03/23/17).

33. Xie, F. and Whiteley. J.R., "Model Predictive Control of A Geothermally Heated Bridge Deck," *2007 American Control Conference*, New York City, New York, July 9-13, 2007.

34. Minnesota Geothermal Heat Pump Association, "Geothermal Loop Options," available at http://minnesotageothermalheatpumpassociation.com/geothermal/earth-loop-options/ (date last visited 03/23/17).

35. Gopalakrishnan, K., Ceylan, H., Kim, S., Yang, S., and Abdullah, H., "Electrically Conductive Mortar Characterization for Self-Heating Airfield Concrete Pavement Mix Design," *International Journal of Pavement Research and Technology*, Vol. 8, No. 5, September 2015, pp. 315–324.

36. Ceylan, H., "FAA PEGASAS COE Project 1: Heated Airport Pavements," FAA PEGASAS COE 2015 Annual Meeting, Purdue University, West Lafayette, Indiana, May 27-28, 2015.

37. Melissa, M.M., "A Hybrid Life Cycle Assessment Model for Construction Processes," Doctoral Dissertation, University of Pittsburgh, 2007, available at http://d-scholarship.pitt.edu/8065/1/bilec_July_11_2007_7.pdf (date last visited 03/23/17).

38. Shen, W., Gopalakrishnan, K., Kim, S., and Ceylan, H., "Assessment of the Greenhouse Gas Emissions From Geothermal Heated Airport Pavement System," *International Journal of Pavement Research and Technology*, Vol. 8, No. 4, July 2015, pp. 233–242.

39. Airliners.net, “Aircraft Technical Data & Specifications,” available at http://www.airliners.net/aircraft-data (date last visited 03/23/17).

40. CTC & Associates LLC, Wisconsin Department of Transportation Research, Development and Test Program, “Pavement Service Life-rev.2,” *Transportation Synthesis Report*, September 8, 2004, available at http://research.transportation.org/Documents/tsrpavementservicelife2withattachments.pdf (date last visited 03/23/17).

41. *American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook*, “HVAC Applications: Snow Melting and Freeze Protection,” Chapter 50, Atlanta, Georgia, July 2007, pp. 50.1–50.20.

42. Mix, J., “HVAC Efficiency Definitions,” *Carrier Corporation*, May 2006, available at http://www.usair-eng.com/pdfs/efficiency-definitions.pdf (date last visited 03/23/17).

43. Viega LLC, “S-no-Ice® Snow Melting System Installation Manual,” IM-SNO-01/05, available at http://www.viega.us/xbcr/en-us/Viega_S-no-ice_Snow_Melting_System.pdf (date last visited 03/23/17).

44. U.S. EPA Energy Star, “Geothermal Heat Pumps Key Product Criteria,” available at https://www.energystar.gov/index.cfm?c=geo_heat.pr_crit_geo_heat_pumps (date last visited 03/23/17).

45. Wilo SE, “Catalogue Heating, Air-Conditioning, Cooling Circulating Pumps,” Catalogue A1-50Hz-2009, available at http://www.majo.rs/page_files/page_97/A1-Glandless%20Pumps%20-%202009.pdf (date last visited 03/23/17).

46. Argonne National Laboratory, U.S. Department of Energy, “Input Fuel Specifications,” Regulated Emissions, and Energy Use in Transportation (GREET®) Model, version 1, Argonne, Illinois, 2003.

47. Raypak, Inc., “Anti-Freeze in Hydronic Systems,” available at http://www.raypak.com/support/tech_corner/anti_freeze (date last visited 03/23/17).

48. University of South Carolina (USC). “Formulations for Aircraft and Airfield Deicing and Anti-icing: Aquatic Toxicity and Biochemical Oxygen Demand,” Airport Cooperation Research Program (ACRP) Web-Only, Transportation Research Board, Document 3, 2008, available at http://onlinepubs.trb.org/onlinepubs/acrp/acrp_webdoc_003.pdf (date last visited 03/13/2015).

49. Geest, V.J., and Kiechle, C., “Anaerobic Wastewater Treatment,” *Brewing and Beverage Industry International*. No. 1, Verlag W. Sachon GmbH+Co.KG, Germany, 2010.

50. Polyisocyanurate Insulation Manufacturers Association (PIMA), “Polyiso Wall Insulation Boards,” NSF International Certified Product Declaration, Date of Issue January 1, 2015, available at http://c.ymcdn.com/sites/www.polyiso.org/resource/resmgr/Health_&_Environment/PIMA_EPD_Wall_Final_Publicat.pdf (date last visited 03/23/17).

51. Washington State Department of Transportation, “The Metrics International System of Units,” available at http://www.wsdot.wa.gov/reference/metrics/factors.htm (date last visited 03/23/17).

52. Lamond, J.F. and Pielert, J.H., “Significance of Tests and Properties of Concrete and Concrete-Making Materials,” ASTM International Standards and Publications STP169D, West Conshohocken, Pennsylvania, 2006.

53. Spath, P.L., Mann, M.K., and Kerr, D.R., “Life Cycle Assessment of Coal-Fired Power Production,” National Renewable Energy Laboratory NREL/TP-570-25119, available at http://www.nrel.gov/docs/fy99osti/25119.pdf (date last visited 03/23/17).

54. Clean Development Mechanism (CDM) Executive Board, Clean Development Mechanism Project Design Document Form, CDM-SSC-PDD Version 03, December 22, 2006, available at http://www.energy.gov.za/files/esources/kyoto/2012/Greenfield_PDD_310112.pdf (date last visited 03/23/17).

55. U.S. Department of Energy, Energy Information Administration (EIA),”How Much Coal, Natural Gas, or Petroleum is Used to Generate a Kilowatthour of Electricity?”, available at *EIA Frequently Asked Questions*, http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=8 (date last visited 03/23/17).

56. Chen, G., Chen, B., Zhou, H., and Dai, P., “Life Cycle Carbon Emission Flow Analysis for Electricity Supply System: A Case Study of China,” *Energy Policy*, Vol. 61, October 2013, pp. 1276-1284.

57. U.S. Department of Energy, EIA, “Voluntary Reporting of Greenhouse Gases,” Form EIA-1605 OMB No. 1905-0194, October 15, 2007.

58. National Energy Technology Laboratory, “Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant,” DOE/NETL-403/110509, September 30, 2010.

59. Gagnon, L., Belanger, C., and Uchiyama, Y., “Life Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001,” *Energy Policy*, Vol. 30, No. 14, February 2002, pp. 1267-1278.

60. U.S. Department of Energy, EIA, “How Much Carbon Dioxide is Produced per Kilowatthour When Generating Electricity With Fossil Fuels?” *EIA Frequently Asked Questions*, available at http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11 (date last visited 03/23/17).

61. U.S. Department of Energy, EIA, "What is U.S. Electricity Generation by Energy Source?" *EIA Frequently Asked Questions*, available at http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3 (date last visited 03/23/17).

62. Shen, W., Ceylan, H., Gopalakrishnan, K., Kim, S., Taylor, P.C., and Rehmann, C., "Life Cycle Assessment of Heated Apron Pavement System Operations," *Transportation Research Part D: Transport and Environment*, Vol. 48, October 2016, pp. 316-331.

63. Gopalakrishnan, K., Ceylan, H., Kim, S., Yang, S., and Abdualla, H., "Self-Heating Electrically Conductive Concrete for Pavement Deicing: A Revisit," *Transportation Research Board Conference*, TRB Paper 15-4764, Washington, DC, 2015.

64. Clearwater Composites, LLC, "Properties of Carbon Fiber," available at http://www.clearwatercomposites.com/resources/Properties-of-carbon-fiber (date last visited 03/23/17).

65. Das, S., "Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites," *The International Journal Life Cycle Assessment*, Vol. 16, No. 3, March 2011, pp. 268-282.

66. U.S. EPA, "Technical Development Document for the Final Effluent Limitations Guidelines and New Source Performance Standards for the Airport," EPA report EPA-821-R-12-005, April 2012, available at https://www.epa.gov/sites/production/files/2015-06/documents/airport-deicing-tdd-final-2012.pdf (date last visited 03/23/17).

67. Chemical Solutions, Inc., MeltSnow.com, "Acetates," available at http://meltsnow.com/products/acetates/ (date last visited 03/23/17).

68. FAA, "Airport Snow and Ice Control Equipment," AC 150/5220-20A, September 24, 2014, available at http://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5220-20A.pdf (date last visited 03/23/17).

69. Cryotech NAAC®, "Solid Commercial Deicer," available at http://www.cryotech.com/websites/cryotech/images/docs/products/commercial/MKT900__NAAC_Commercial_Fact_Sheet.pdf (date last visited 03/23/17).

70. RPM Tech. (2015). The Cameleon®, "A Multifunctional Vehicle With Dual Traction Modes," available at http://grouperpmtech.com/en/municipal-vehicle.aspx (date last visited 03/23 17).

71. Ferguson, L., Corsi, S.R, Geis, S.W., Anderson, G. et al., "Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand," Airport Cooperation Research Program, Transportation Research Board, available at http://onlinepubs.trb.org/onlinepubs/acrp/acrp_webdoc_003.pdf (date last visited 03/23/17).

APPENDIX A—LIFE-CYCLE ASSESSMENT CALCULATION EXAMPLE

This appendix shows a sample calculation of the life-cycle assessment (LCA) for the operation phase of a hydronic heated pavement system using geothermal heat pump (HHPS-G) with a coefficient of performance (COP) of 3 for a 1-in./h snow rate and a 4-h snow period condition.

Table A-1. Assumptions to Calculate the LCA for the HHPS-G

Category	Value
Airport area	19,000 ft^2
Air temperature	20°F
Wind speed	10 mph
Snow rate	1.0 in./h
Density of dry air	14.696 lb/ft^3
Mass transfer coefficient, concrete slab	1.7 ft/h
Melting temperature	32°F
Liquid film temperature	33°F
Emittance of wet slab	0.9
Life time of insulation layer, carbon fiber	20 years
Concrete slab density	150 lb/ft^3
Concrete specific heat	0.2 Btu/lb·°F
Thickness of concrete slab insulation covered	4 in.
Geothermal heat pump COP	3
Operation time (snow period)	4 h
Concentration of antifreeze	40%
Temperature drop	30°F
Ground-source heat pump and piping style	Parallel
Pressure drop	Only consider pressure drop in pipe
Efficiency of circulating pump	60%
Antifreeze lifetime	One year

A.1 GREENHOUSE GAS (GHG) EMISSION FACTORS.

- 0.96 kgCO_2eq/kWh for coal (bituminous)-fired power plant
- 0.42 kgCO_2eq/kWh for natural gas-fired power plant
- 0.778 kgCO_2eq/kWh for distillate oil power plant
- Electricity can be produced
  - 58% from coal-fired power plant
  - 40% from natural gas-fired power plant
  - 2% from distillate oil power plant
- 0.0019 kgCO_2eq/kWh for natural gas production
- 0.181 kgCO_2eq/kWh for natural gas combustion
- 0.27 kgCO_2eq/kWh for distillate (diesel) oil combustion
- 0.19 kgCO_2eq/kWh for distillate (diesel) oil production

A.2 ENERGY DEMAND FOR IDLING AND SNOW MELTING DESCRIPTIONS.

A.2.1 Energy Consumption of Pavement Idling (20°F to 32°F).

$$q_i = \frac{C \cdot \Delta \mathrm{T} \cdot \mathrm{M}}{t} \times 0.00105\ MJ/Btu = 601\ MJ/h$$

where:

C = specific heat of concrete pavement (0.2 Btu/lb·°F)
ΔT = temperature difference (32°F - 20°F)
M = mass of concrete pavement ((150 lb/ft^3 × 19,000 ft^2 × 4 in × 0.083 ft/in.) lb)
t = snow period (4h)

A.2.2 Heat Required for Melting Snow.

$$q_o = q_s + q_m + A_r\,(q_e + q_h) = 173\ Btu/h/ft^2$$

where:

q_o = heat required in melting snow
q_s = sensible heat transferred to the snow (Btu/h·ft^2)
q_m = heat of fusion (Btu/h·ft^2)
A_r = ratio of snow-free area to total area
q_e = heat of evaporation (Btu/h·ft^2)
q_h = heat transfer by convection and (Btu/h·ft^2)

A.2.3 The Sensible Heat (qs) to Bring Snow to 32°F.

$$q_s = s\,D\,[c_{p,ice}\,(t_s - t_a)]+c_{p,water}\,(t_f - ts)]/\,c_1 = 3.64\ Btu/h/ft^2$$

where:

s = 0.1 = rate of snowfall (inches of water equivalent per hour)
$cp,snow$ = specific heat of snow (0.5 Btu/lb/°F)
$cp,water$ = specific heat of water(1 Btu/lb/°F)
D = density of water equivalent of snow (62.4 lb/ft^3)
tf = liquid film temperature, usually accepted as 33°F
ts = melting temperature (32°F)
ta = air temperature (20°F)
c_1 = conversion factor (12 in./ft)

A.2.4 The Heat of Fusion (q_m) to Melt Snow.

$$q_m = s\,h_f\,D\,/\,c_1 = 74.52\ Btu/h/ft^2$$

where:

h_f = 143.5 = heat of fusion for water (143.3 Btu/lb)

A.2.5 The Heat of Evaporation (*qe*).

$$q_e = P_{dry\ air}\, h_m(W_f - W_a)h_{fg} = 48.16\ Btu/h/ft^2$$

where:

$P_{dry\ air}$ = 14.696 = density of dry air (lb/ft^3)

h_m = 1.7 = mass transfer coefficient, concrete slab (ft/h)

W_f = 0.003947 = humidity ratio of saturated air at film surface temperature at 33°F (lb_{vapor}/lb_{air})

W_a = 0.00215 = humidity ratio of ambient air at 20°F (lb_{vapor}/lb_{air})

h_{fg} = 1074.64 = heat of evaporation at the film temperature at 33°F (Btu/lb)

A.2.6 The Heat of Fusion (q_m) to Melt Snow.

$$q_h = h_c\ (t_f - t_a) + \sigma\varepsilon_s(T^4{}_f - T^4{}_{MR}) = 46.54\ Btu/h/ft^2$$

where:

h_c = convection heat transfer coefficient for turbulent flow ($2.85\ Btu/h{\cdot}ft^2{\cdot}°F^4$)
$\sigma = 0.1712\times10^{-8}$ = Stephan-Boltzmann constant ($Btu/h{\cdot}ft^2{\cdot}°F^4$)
ε_s = 0.9 = emittance of wet slab
T_f = 462.67 = liquid film temperature (°F)
T_{MR} = 479.67 = mean radiant temperature of surroundings (°F)

A.2.7 Total Energy for Melting 1 in. of 19,000 ft^2 Snow.

$$Q_t = q_i + q_o = 601\ MJ/h + 3467\ MJ/h = 4068\ MJ/h\ (4\text{-}h\ operation\ time)$$

A.2.8 Total Energy Demand for Operating Geothermal Heat Pump.

$$E = \frac{Qt}{\mathrm{COP}} = 1356\ MJ/h$$

where:

Q_t = total heat required for pavement idling and snow melting (4068 MJ/h)
COP = coefficient of performance (3).

A.2.9 The GHG Emissions From Power Plant Generating Electricity for Geothermal Heat Pump Operation.

$$(1356 \times 0.96 \times 58\% + 1356 \times 0.42 \times 40\% + 1356 \times 0.778 \times 2\%) \times 2.778\ kWh/MJ = 279\ kgCO_2/h$$

A.3 PIPING DESIGN AND CIRCULATING PUMP DESCRIPTIONS.

(Viega Snow Melting System Installation Manual [A-1])

- 3/4-inch, cross-linked polyethylene (PEX) pipe
- Maximum circuit length: 400 ft
- Parallel tubing spacing in concrete: 9 in.
- Tubing length multiplier: 1.5
- Total tubing length: 19,000 $\text{ft}^2 \times 1.5\ \text{ft/ft}^2 = 28{,}500$ ft
- Number of circuit: 71
- Flow rate % increase multiplier: 1.085
- Pressure drop % increase multiplier: 1.25
- Temperature drop: 30°F
- Water heat capacity: 1 Btu/lb °F
- Flow rate per circuit: $\frac{4{,}769{,}225\ Btu/h}{500 \times 30°F} \times 1.085 = 6.9$ gpm
- Total flow rate: 71 × 6.9 gpm = 490 gpm

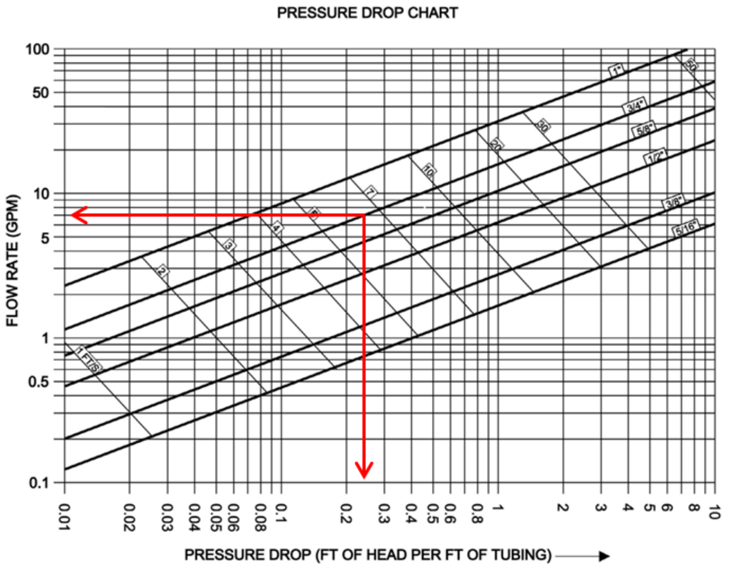


Figure A-1. Diagram of Piping Design (Pressure Drop of 3/4-in. Pipe) [A-1]

- Pressure drop: 0.25 ft of head per ft of tubing
- Total pressure drop: 0.25 ft × 400 ft = 125 ft

A.3.1 Total Energy for Circulating Pump Operation.

$$WHP = \frac{Q \times H \times SG}{3960 \times n} = 26\ HP$$

where:

WHP = Water horsepower (HP)

Q = flow rate (490 gpm),

H = total head (125 ft),

SG = specific gravity of heated solution (1 of water and 1.034 of 40% propylene glycol (PG)),

n = pump efficiency (60%).

A.3.2 Total GHG Emissions From Power Plant Generating Electricity for Circulating Pump Operation.

$$(26 \times 0.96 \times 58\% + 26 \times 0.42 \times 40\% + 26 \times 0.778 \times 2\%) \times 0.75\ kW/HP = 19\ kgCO_2/h$$

A.4 ANTIFREEZE USAGE DESCRIPTIONS.

(Viega Snow Melting System Installation Manual [A-1])

- Antifreeze solution life time is assumed to be: 1 year
- Antifreeze: PG
- 40% by volume of solution content in ¾ inch pipe: 0.018 gal/ft
- Total volume of solution: 28,500 ft × 0.018 Gal/ft= 513 gal
- Volume of PG: 513 Gal × 40% = 205 gal
- Density of PG solution: 1.04 g/ml
- Solution mass: $\frac{205 \text{ Gal} \times 0.0038 \text{ m}^3/\text{Gal} \times 1.04 \text{ g/ml}}{1000} = 808 \text{ kg}$
- Energy consumption factor: 27.57 kWh/kgPG
- GHG emission factor: 6.46 $kgCO_2/kgPG$

A.4.1 Total Energy for PG Production.

$$\frac{27.57\times808}{365\times24}\times 3.6\ MJ/kWh = 9MJ/h$$

A.4.2 Total GHG Emissions From PG Production.

$$\frac{6.46\times808}{365\times24} = 0.6\ kgCO_2/h$$

A.5 WASTEWATER TREATMENT DESCRIPTIONS [A-2].

- Deicing and antifreeze solution treatment: Municipal wastewater treatment plant
- Energy supply source of wastewater treatment: Electricity
- Energy requirement for aerobic system: 1 kWh/kg COD
- Antifreeze COD: 1.68 kgCOD/kgPG

A.5.1 Total Energy for Antifreeze Solution Wastewater Treatment.

$$\frac{808\times1}{24\times365}\times 3.6\ MJ/kWh = 0.54\ MJ/h$$

A.5.2 Total GHG Emissions From Power Plant Generating Electricity for Antifreeze Solution Wastewater Treatment.

$$(0.54\times 0.96\times 58\%+0.54\times 0.42\times 40\%+0.54\times 0.778\times 2\%)\times 0.2778\ kWh/MJ = 0.1\ kgCO_2/h$$

A.6 INSULATION LAYER DESCRIPTIONS.

(PIMA—Polyisocyanurate Insulation Manufacturers Association Wall Insulation Boards [A-3])

- Insulation layer life time is assumed to be: 20 years
- Length, width and thickness of top layer: 146 ft, 130 ft and 4 in.
- Insulation area: 19,000 ft^2+2×(146 ft +130 ft)×4 in.× 0.083 ft/in. = 19,184 ft^2
- Energy consumption factor: 8.66 MJ/ft^2
- GHG emission factor: 0.39 $kgCO_2eq/ft^2$

A.6.1 Total Energy for Insulation Layer Production.

$$\frac{19184\times 8.66}{20\times 365/24} = 1\ MJ/h$$

A.6.2 Total GHG Emissions From Insulation Layer Production.

$$\frac{19184\times 0.39}{20\times 365\times 24} = 0.043\ kgCO_2eq/h$$

A.7 REFERENCES.

A-1. Viega LLC, “S-no-Ice® Snow Melting System Installation Manual,” IM-SNO-01/05, available at http://www.viega.us/xbcr/en-us/Viega_S-no-ice_Snow_Melting_System.pdf (date last visited 03/23/17).

A-2. Geest, V.J., and Kiechle, C., “Anaerobic Wastewater Treatment,” *Brewing and Beverage Industry International*. No. 1, Verlag W. Sachon GmbH+Co.KG, Germany, 2010.

A-3. Polyisocyanurate Insulation Manufacturers Association (PIMA), “Polyiso Wall Insulation Boards,” NSF International Certified Product Declaration, Date of Issue January 1, 2015, available at http://c.ymcdn.com/sites/www.polyiso.org/resource/resmgr/Health_&_Environment/PIMA_EPD_Wall_Final_Publicat.pdf (date last visited 03/23/17).