2015

Life cycle assessment of heated airfield pavement system for snow removal

Weibin Shen
Iowa State University

Recommended Citation

Shen, Weibin, "Life cycle assessment of heated airfield pavement system for snow removal" (2015). *Graduate Theses and Dissertations*. 14742.
https://lib.dr.iastate.edu/etd/14742

Life cycle assessment of heated airfield pavement system for snow removal

by

Weibin Shen

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Environmental Engineering)

Program of Study Committee:
Halil Ceylan, Co-Major Professor
Chris Robert Rehmann, Co-Major Professor
Kasthurirangan Gopalakrishnan, Co-Major Professor
Sunghwan Kim, Co-Major Professor
Peter C. Taylor, Co-Major Professor
Timothy Gage Ellis

Iowa State University

Ames, Iowa

2015

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Firstly I would like to acknowledge my major professor Dr. Halil Ceylan for his invaluable guidance and support throughout my graduate study. With Dr. Ceylan's support, I joined the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) and Program for Sustainable Pavement Engineering and Research (PROSPER) research team at Iowa State University (ISU) as a graduate research assistant to work with him. During these two years, he provided me with so many opportunities to work on a very interesting research topic and to present my research findings at a number of meetings. He has been very instrumental in motivating and supporting me in order to grow and succeed during my graduate school career.

I also would like to thank Drs. Sunghwan Kim and Kasthurirangan Gopalakrishnan for their constructive comments on my research. Without their guidance, I am not able to achieve such academic accomplishments in my life. Also, I appreciate the efforts and time that Drs. Peter C. Taylor, Chris Robert Rehmann, and Timothy Gage Ellis spent for my graduate study. In addition, I would like to thank Mr. Robert F. Steffes, PCC Lab Manager, for all of his assistance and support during the laboratory investigation portion of this research.

This research is supported by Federal Aviation Administration (FAA) Air Transportation Center of Excellence (COE) Cooperative Agreement 12-C-GA-ISU for PEGASAS and the support provided by FAA and ISU is greatly appreciated. I would like to thank the former project Technical Monitors Mr. Don Barbagallo and Dr. Charles A. Ishee and the PEGASAS Program Manager Mr. Peter L. Sparacino of FAA for their invaluable guidance on this ongoing study.

Last but definitely not the least, I thank my parents for all their support and providing me this wonderful opportunity to study at one of the great engineering schools in USA. They

encourage me to think critically and give me freedom to become who I am. Thank you, dad and mom!

ABSTRACT

Airport operations are heavily and repeatedly impacted by snow and ice during winter seasons. Considering the potential economic losses resulting from ice/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. Traditional snow removal systems that employ de-icers and anti-icers have the potential to generate Foreign Object Debris (FOD) and could cause damage to aircraft parts and the pavements. In addition, traditional snow plows and equipment have difficulty accessing critical airside operations areas such as the apron/gate areas. An emerging technology, referred to as the heated pavement systems (HPS) are promising alternatives to traditional snow removal systems. Although heated pavement systems have been used widely in European countries for airport snow removal, there are no practical applications in US, and their environmental impacts were unknown. The purpose of this research is to evaluate and quantify greenhouse gas (GHG) emissions and energy consumptions of heated pavement systems applied in airfield in order to give decision makers a more informed view in snow removal application selections. As the very first research on environmental impacts of heated pavement systems in removing snow, this research includes three individual studies. Each one builds on the understanding of previous one.

The first study uses life cycle assessment (LCA) to compare geothermal heated pavement system (GHPS) and traditional snow removal system applied in airport runway by evaluating their energy consumptions and GHG emissions. This study analyzes construction and operation phases of both snow removal systems. According to the limited data from previous studies, results show no significant differences between the construction phases of two snow removal systems. Also, airports show more interests in applying this new technology in airport apron area instead.

The second study is focused on energy consumption, GHG emission, and costs of operating geothermal heated pavement system, hydronic heated pavement system using electrical water heater, and hydronic heated pavement system using natural gas boiler, in removing snow from apron area. Different coefficients of performances of geothermal heated pavement system operations are analyzed in order to evaluate the behaviors of the systems. The results show geothermal heated pavement system has the least environmental impacts, and when efficiency of natural gas boiler energy extraction is improved, it can be a better alternative for place where there is not enough geothermal energy from the environmental and economic perspectives.

Based on the knowledge gained from previous two studies, the third study utilizes hybrid LCA to analyze energy consumptions and GHG emissions from apron snow removal operations. It evaluates the operations of four types of snow removal systems, 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), and traditional snow removal system (TSRS) applied in airport apron area. The life cycle analysis in this study is relatively more comprehensive than the previous two studies, it gives decision maker or airport manager a more informed view of operating heated pavement systems in removing snow from energy saving and global warming potential aspects.

This overall research shows heated pavement systems have potential to substitute for traditional snow removal system in decreasing energy demand and GHG emissions during apron snow removal operations. Because the theoretical models used to calculate energy consumption and GHG emissions from different types of snow removal systems are still under development, the results reported from this research should be taken into account from a qualitative view, and more comprehensive assessments which include broader system boundary are required for future study.

CHAPTER 1. GENERAL INTRODUCTION

Background and Motivation

The commercial airports in the U.S. play an important role in encouraging economic growth by providing a worldwide transportation network to enable efficient movement of people and goods (CDM Smith 2014). As stated in the report “The Economic Impact of Commercial Airports in 2013”, 485 commercial airports in the U.S. support 9.6 million jobs and produce an annual output of $1.1 trillion (CDM Smith 2014). Commercial airports also provide significant contributions to local economies. According to the Norfolk International Airport 2014 Economic Impact Study, airports produced an additional impact of $68 million and 2,134 jobs in addition to the airport service itself to the local wealth of Virginia (Norfolk Airport Authority 2007). It is therefore obviously important for commercial airports to maintain continuous operation, but this may become a challenge for airport operation during winter because presence of contaminants like snow, ice, or slush on airfield pavements (runways, taxiways, etc.), might lead to serious situations resulting in airline delay and other adverse incidents. Snow removal is therefore a top priority for airports (FAA 2012).

Snow removal systems

To maintain airport continuous operation during snowy days, airports generally use mechanical snow removal equipment (snow plows, snow blowers and chemical sprayers) to remove contaminants from transportation surfaces and also use chemical reagents such as potassium acetate, sodium acetate, and propylene glycol to prevent the reformation of snow, ice, or slush on airport surfaces (Amsler 2014). However, such snow removal equipment is usually designed for large areas like runways, sometimes making the equipment difficult to operate in a narrow space like an airport apron. Chemical de-icers are not only expensive but also might lead to potential environmental pollution problems. Many techniques such as heated pavement systems, super-hydrophobic coating, and phase change materials have been considered for application in removing snow from airport apron rather than using mechanic equipment or chemical reagents. Even though super-hydrophobic coating and phase change materials are still under development at a pilot scale, their longevities are not yet well understood. Because heated pavement systems, also known as snowmelt systems, are commonly used in areas like driveways, walkways, and parking areas (Subsequent Distribution Office 2001), this study focuses on heated pavement system operation.

Heated pavement systems fall into two broad types based on different heat sources: electric radiant heat or hydronic heat from a fossil-fuel boiler/heater combustion or geothermal source (Roth 2008). Because this is a relative new technology used in airport snow removal applications, even though there have been many studies focusing on the design and mechanical or thermal behavior of different types of heated pavement systems, very few have analyzed the environmental impact of such systems.

State-of-the-art practices in airport sustainability

Based on the environmental programs of the Federal Aviation Administration (FAA), examination of sustainability is a core rather than a secondary objective to be considered in an airport planning process (FAA 2015). One program called “Airport Sustainability Planning” has provided help and support to 44 airports and provided comprehensive sustainable initiation of reduction in environmental impact, assistance to airport companies in maintaining high and stable economic growth, and ensuring that local community needs and values can be achieved (FAA

2015). To be more specific, this program provides benefits to help airports reduce energy consumption, reduce noise impact, reduce hazardous and solid waste generation, reduce greenhouse gas emissions, improve water quality, and increase cost savings (FAA 2010).

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 to increase engagement in sustainable design during new project planning. An airport can be assisted in maintaining a proper focus on sustainability by following the program guidelines. Even though they might be unable to provide the most sustainable solution, sustainability plans will give airports a more informed view with respect to decision-making (FAA 2012). An airport's sustainability categories are limited not only to environmental impact issues, but may also include inventories like socioeconomics, airport facilities and procedures, land use, etc. (FAA 2010).

Research Objectives and Approach

Airports, as facilities that must increasingly pay attention to 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, called life cycle assessment (LCA), has been commonly used by industries or businesses to evaluate behavior or environmental impact of their own products or systems (Malmqvist et al., 2011). This study is intended to develop a sustainability assessment framework using life cycle assessment (LCA) and focused on operation of airfield heated pavements. LCA has been utilized to estimate the environmental impact of heated pavement systems compared to traditional snow-removal systems (TSRS) for removing snow from airport apron areas under different snow-rate conditions. This research focuses on different types of heated pavement systems.

- Hydronic heated pavement system using geothermal heat pump or called geothermal heated pavement system (HHPS-G or GHPS)
- Hydronic heated pavement system using natural gas boiler or furnace (HHPS-NG), or hydronic heated pavement system using electric water heater (HHPS-E)
- Electrically heated pavement system (EHPS)

The research considers the currently hot topics of energy crisis, global warming, and climate change, and evaluates energy consumption and greenhouse gas (GHG) emissions produced by snow removal systems as significant indicators of sustainability. The study is intended to provide airport decision makers or heated pavement system operators with a better understanding of the global-warming potential of different heated pavement systems to help them choose more sustainable snow removal strategies.

Thesis Organization

This thesis is divided into six chapters. Chapter 1 provides an introduction and background information to this thesis and Chapter 2 provides overall review of life cycle assessment (LCA) focusing on snow and ice removal practices on transportation infrastructure system. The main findings and results are presented in Chapters 3, 4 and 5. Each chapter comprises a paper that has been either published or ready for submission to peer reviewed journals and conference proceedings. The papers are ordered in the thesis as follows:

- Chapter 3: Weibin Shen, Kasthurirangan Gopalakrishnan, Sunghwan Kim, and Halil Ceylan. *Assessment of Greenhouse Gas Emissions from Geothermal Heated Airport Pavement System*. Accepted for publication in International Journal of Pavement Research and Technology (IJPRT). Chapter 3 presents environmental impacts from the construction phrase and operation phrase of geothermal heated pavement system and traditional snow removal system applied in airport runway.
- Chapter 4: Weibin Shen, Kasthurirangan Gopalakrishnan, Sunghwan Kim, and Halil Ceylan. *Airport Apron Heated Pavement System Operation Analysis: Energy Requirement, Greenhouse Gas Emissions, and Operating Cost Analysis.* A paper to be submitted for presentation and publication in ASCE Conference of Geo-Chicago 2016: Sustainability, Energy, and Environmental impacts. Chapter 4 demonstrates and compares operations of three different kinds of hydronic heated pavement systems used in an airport apron for different snow rate conditions. Energy consumptions, GHG emissions, and operation costs are the life cycle inventories analyzed in this study.
- Chapter 5: Weibin Shen, Halil Ceylan, Kasthurirangan Gopalakrishnan, Sunghwan Kim, Peter C. Taylor, and Chris Robert Rehmann. *Life Cycle Assessment of Heated Apron Pavement System Operation.* A paper to be submitted for presentation on 2016 Transportation Research Board (TRB) 95th Annual Meeting and publication in Transportation Research Record: Journal of the TRB. Chapter 5 developed more comprehensive life cycle models for heated apron pavement operation analysis. Energy consumptions and GHG emissions of HHPS-G, HHPS-NG, EHPS, and TSRS operations are assessed against various snow periods and snow rates.

Finally, Chapter 6 presents the major findings and conclusions of the study and the recommendations for future research. Appendix presents one example of detailed LCA calculation procedures among many cases conducted in this study to help reader better understand how the analyses are done. Figure 1 is a flow chart representing the thesis structure.

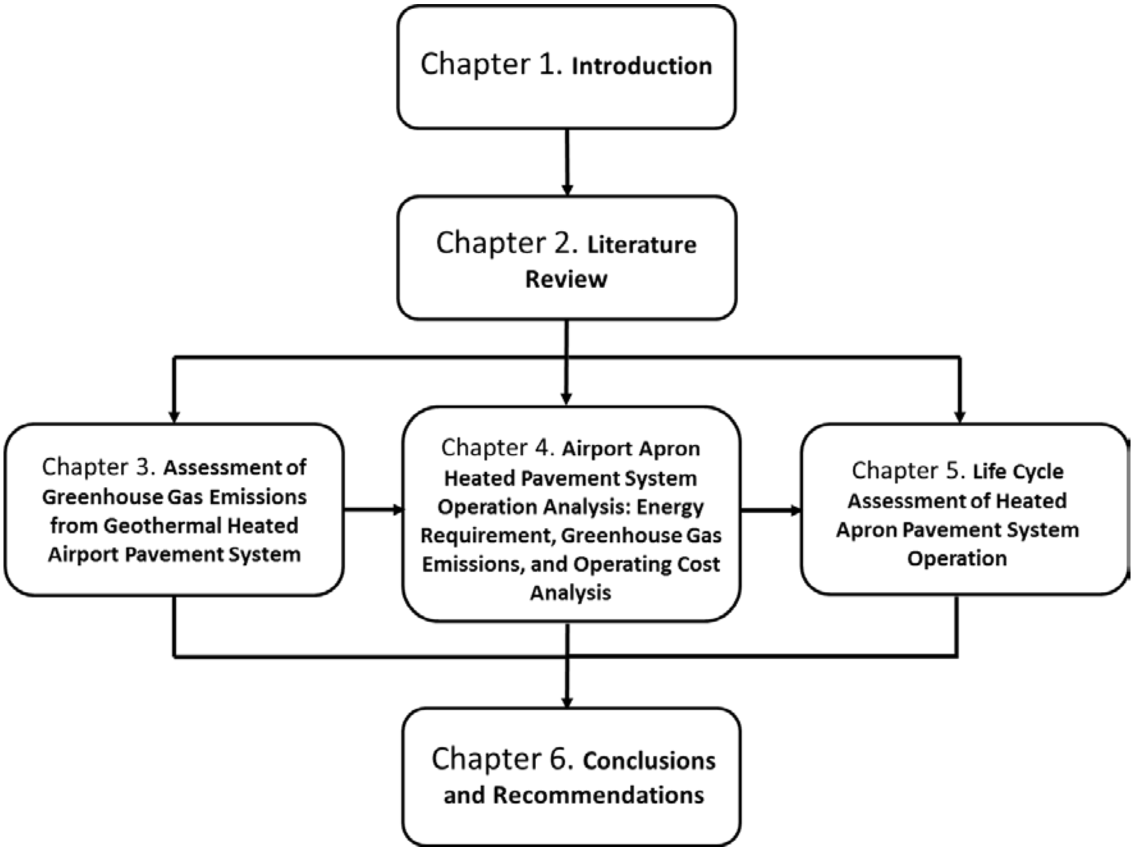


Figure 1. Thesis Organization Flow Chart

References

CDM Smith. (2014). The Economic Impact of Commercial Airports in 2013. CDM Smith. Governor’s Hill Drive, Cincinnati, Ohio. [cited by 2015 Mar 4th]. Retrieved from http://airportsforthefuture.org/did-you know/files/2014/09/Economic-Impact-of-Commercial-Aviation-2013.pdf/

Norfolk Airport Authority. (2007). Economic Impact Study 2004 Norfolk International Airport. *Norfolk Airport Authority*, Norfolk, Virginia. [cited by 2015 Mar 27th]. Retrieved from http://www.norfolkairport.com/sites/default/files/pdfs/ORF_Econ_Impact_Study_2004.pdf

FAA. (2012). Airport Winter Safety and Operations. *Washington, DC: Federal Aviation Administration*. U.S. Department of Transportation. Publication FAA 150/5200-30C

Amsler, D. E. (2014). Snow and Ice Control 2014. *Publication CLRP No. 13-04*. Cornell Local Roads Program, New York LTAP Center, NY, 2014. [cited by 2015 Feb 14th]. Retrieved from http://www.clrp.cornell.edu/workshops/manuals/snow_and_ice_control.pdf

Subsequent Distribution Office. (2001). Airside Use of Heated Pavement Systems. *Publication FAA 150/5370-xx*. U.S. Department of Transportation, Washington, DC: Federal Aviation Administration

Roth. (2008). Snowmelt Systems Installers Handbook. Watertown, NY. [cited by 2015 Feb 17th]. Retrieved from http://www.roth-usa.com/PDF_Download_Files/snowmelt_install.pdf

FAA. (2015). Airport Sustainability. *U.S. Department of Transportation*, Washington, DC: Federal Aviation Administration. [cited by 2015 Mar 5th]. Retrieved from http://www.faa.gov/airports/environmental/sustainability/\

FAA. (2010). Memorandum. U.S. Department of Transportation, Washington, DC: Federal Aviation Administration. [cited by 2015 Mar 21st]. Retrieved from http://www.faa.gov/airports/environmental/sustainability/media/interim_guidance_sustainable_master_plan_pilot.pdf

FAA. (2012). Airport Winter Safety and Operations. Washington, DC: Federal Aviation Administration. U.S. Department of Transportation. Publication FAA 150/5200-30C

FAA. (2012). Report on the Sustainable Master Plan Pilot Program and Lessons Learned. Washington, DC: Federal Aviation Administration. U.S. Department of Transportation. [cited by 2015 Mar 5th]. Retrieved from http://www.faa.gov/airports/environmental/sustainability/

Malmqvist, T., Glaumanna, M., Scarpellinib, S., Zabalzab, I., Arandab, A., Llerab, E., and Díaz, S. (2010). Life Cycle Assessment in Buildings: The ENSLIC Simplified Method and Guidelines. *Energy* 36 (4): 1900–1907.

CHAPTER 2-LITERATURE REVIEW

We rely on fossil fuel, coal, oil, and natural gas for more than 80% of our current energy requirements, and this situation is likely to exist without change for a long time. High energy demand is expected to increase during the next two decades, and global energy supplies are largely controlled by a small group of countries considered to be political unstable, making the availability of a long-term energy supply somewhat questionable (Global Economic Symposium 2014). Currently, technology efficiency and energy consumption no longer represent just economic problems, but are being studied from a sustainability perspective.

The continuous increase in global temperature, commonly referred to as global warming, is becoming a serious environmental threat that may cause environmental problems like sea level rise, extreme weather, ocean acidification, and species extinctions (Lu 2007) (BASC 2011). Based on its fifth assessment in 2014, the Intergovernmental Panel on Climate Change (IPCC) reported that most global warming is caused by an increasing concentration of greenhouse gases (GHG), and increasing anthropogenic and industrial activities such as power-plant coal combustion are often cited as a principal cause of such emissions leading. Among the different types of GHG, the greatest contribution to the greenhouse effect has been recognized as coming from CO_2, CH_4, and N_2O (Zona, et al. 2013), so these gases have been considered as the most significant global warming indicators in LCA.

LCA Overview

LCA provides a macroscopic view for studying the environmental impacts of products, techniques, processes, and systems. Because 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 capabilities to (United Nations Environment Programme 2015):

- 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.

Because of these capabilities, LCA has been applied to analyze energy consumption GHG emissions associated with various industries or businesses (Malmqvist et al., 2011). The best understanding of LCA regards it as a “cradle-to-grave” approach for assessment of production processes or industrial systems. The term “cradle-to-grave” implies system analysis beginning with raw material extraction all the way through use of a product or operation of a system, including the end-of-life stage (ISO 14040 1997). In another words, LCA enables estimation of cumulative impacts from all stages of a product or system life cycle, and “life cycle” refers to the activities in a product’s or system’s life span that can range 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 definition and scoping, inventory analysis, impact assessment, and interpretation, as illustrated in Figure 2 (United Nations Environment Programme 2015).

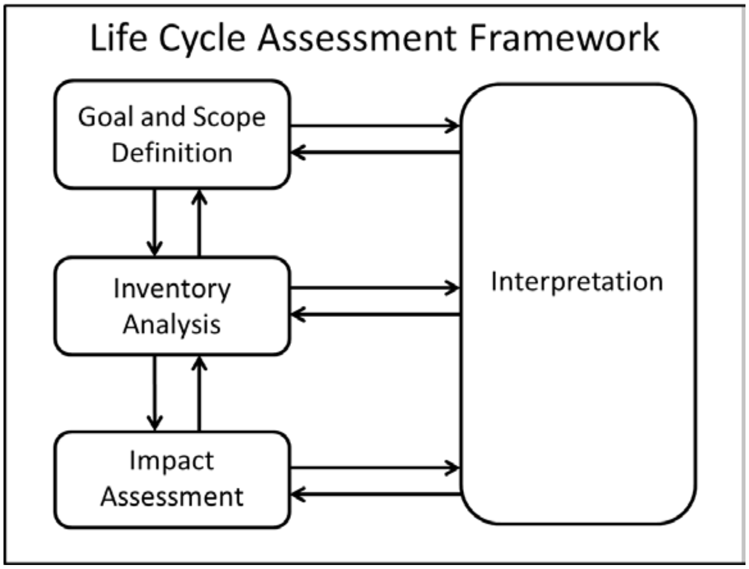


Figure 2. Phase of an LCA

- Goal definition and scoping: 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, wastewater discharge)
- Interpretation: evaluate the consequences of each defined inventories and analyze the total impacts in order to select the preferred product, process or system.

In accordance with the "Life Cycle Assessment: Principles and Practice" written by Scientific Applications International Corporation (SAIC), the process of defining the goal and scope of a LCA is critical because it determines the system boundary and time frame of the study and identifies meaningful inventories (SAIC 2006). The purpose of conducting a LCA can be to deliver a broad environmental assessment since the LCA not only studies the product or system itself but also analyzes environmental burdens resulting from associated processes (SAIC 2006). The goal of a LCA can also be to choose the best product, process, and system with the least undesirable environmental impact and human-health effect, and/or to help develop and enhance the technology, process, and system to a new level that requires less energy and reduces emissions (ISO 14040 1997). Because a LCA provides detailed information about each step in the whole system life cycle, the step representing the greatest environmental emissions and energy/material input will be identified during inventory collection (SAIC 2006). LCA is thus able to provide direction to a decision maker seeking to discover the step contributing the greatest pollution prevention, resource conservation, and emission minimization during a system or product life cycle.

During the life-cycle inventory phase, all relevant data is collected and calculated to evaluate potential environmental impact. Based on EPA's 1993 document, "Life-Cycle Assessment: Inventory Guidelines and Principles" (EPA 1993) and the 1995 document, "Guidelines for Assessment the Quality of Life Cycle Inventory Analysis" (EPA 1995), the first step is the development of a flow diagram and a data collection plan for the processes being evaluated. The inventory data collection and evaluation follows. The final step is reporting of results.

Variants of Life Cycle Assessment

LCA can be used to analyze a wide variety of production processes or systems under different system boundaries or time frames, so this analysis may sometimes be relatively simple and sometimes much more complex. There are multiple approaches to performing a LCA to achieve the defined objectives. The three most commonly-used methods are a process-based LCA, an economic input-output LCA, and a hybrid LCA (Finnveden et al 2009).

As a traditional LCA approach, the process-based LCA has been used somewhat earlier than the other two approaches for analyzing existing material-processing models and energy flows

(Carnegie Mellon University 2015). The process-based LCA was summarized in the ISO 14040 standard. 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 cradle-to-gate (i.e., life cycle from raw material extraction to factory gate) analysis usually performed at the system boundary determination (ISO 14040 1997). 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 speaking, processed-based life cycle assessment utilizes 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 thus effectively illustrate the complexity and variety of a production or system process.

Although a process-based LCA can easily be done when each of the process inventories of a production or a system can be assessed, collecting all the inventory data for a comprehensively process-based LCA is a challenge, and a process-based LCA is usually limited by sufficiency of data resources. Taking a product-manufacture life cycle as an example, it is not easy to collect process-specific data in the LCA because there can be an essentially infinite possibility of supply chain paths, making it difficult to analyze all inventories from all production supply-chain paths (Lenzen 2002).

There are two ways to solve this problem. The first is to make assumptions regarding the missing inventories and instead perform a partial process-based LCA neglecting some parts of the system. However, assumptions regarding cutoff system boundary selection are usually subjective and might 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 (Dale et al. 2013). 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 cutoff has about a 20% impact for many impact categories (Suh et al. 2004) but may have a considerably larger impact at the raw-material extraction stage in some product processing life cycles (Ferrao and Nhambiu 2009). Taking biofuel production life cycle as an example, 23% of total CO2eq was attributed to biofuel upstream emissions that were normally excluded from the process-based life cycle (Acquaye et al. 2011).

In contrast to a process-based LCA, an economic input-output LCA (EIO-LCA) does not require an investigator to analyze 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 (Hendrickson 2005). It is therefore able to identify direct and indirect economic, energy, or environmental outputs resulting from economic inputs of purchases. Carnegie Mellon University has developed an on-line software EIO-LCA model theorized by economist Wassily Leontief in the 1970s (Carnegie Mellon University 2015). This model applies the EIO-LCA method and its construction contains the whole national economy including imports. The EIO-LCA on-line tool reports relative impacts of different material production processes, services, or system processes with respect to resource use and emissions throughout the supply chain. A previous study (Gaitan 2013) showed that it was essential to analyze at least 20 different supply-chain paths usually neglected by a process-based LCA in order to cover at least 87% of GHG emissions in a chemical industry sector. Because the EIO-LCA model utilizes 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.

Even though the EIO-LCA method is powerful, easy, and convenient to use, the model is like a “black box” whose system boundary and interrelationships among the sectors inside the economic system are not clearly identified. This would be fine if the user only wanted to know the final impact result from a product or system, but if each sector or stage of the product or system needs to be well understood, using an EIO-LCA model might be challenging. Uncertainty might be increased through aggregation of several products to sectors, although the cutoff uncertainty is eliminated. Also, when using an EIO-LCA it might be not easy to determine details regarding a specific product or system process at a particular time or at particular locations because this model utilizes economic data from national accounts (Weibin et al. 2010). For example, in a case where the economic data is modified in a national scale, a researcher might obtain a similar impact result from mobile manufacturers in Iowa and Missouri by using an EIO-LCA. Of course, results for these mobile manufactories in two different states in reality might be significantly different. Timeliness of economic data can be another problem in the EIO-LCA model. According to the description of this EIO-LCA on-line model, the latest version of data is updated to 2002, and the prior version represented 1997 technology and emission intensities of the U.S. economy (Hendrickson, et al. 2006). The EIO-LCA is monetary-dependent and the economy is highly sensitive to timeliness; therefore, uncertainty can occur when using outdated data.

The Hybrid LCA is an approach combining a process-based LCA and an EIO-LCA in analyzing a product or system process. In the hybrid LCA, the environmental impacts of flows not usually included in a process-based LCA are estimated using an environmentally-extended EIO-LCA (Suh and Huppes 2005). 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. (2013) 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.

Previous Life Cycle Assessment Studies for 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, life-cycle assessment can be conducted in analyzing the whole process from "cradle to grave". The life cycle of snow removal application might 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 (Sripple 2001). Life cycle inventory data collection from previous study or databases of industries or businesses is usually relied on.

For winter road maintenance, salt and sand are used as deicing/anti-icing materials. However, there can be multiple types and combinations of sand and salt applications. Energy for extraction of salt used for snow removal can be classified as 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 (Massachusetts Department of Transportation Standard Operating Procedures 2014). Such factors result in varieties and uncertainties with respect to energy consumption and emissions from de-icer/anti-icer extraction. Under these uncertainties and varieties, energy consumption and emissions from salt and sand production are based either on EIO-LCA modelling or rough estimation.

Deicing material spraying is considered to be achieved by truck, and both the spraying process and the material transportation stage is considered in the life-cycle analysis. However, a snow-removal truck operation strategy that determines emissions and energy consumption of the material greeting process could vary by location (Massachusetts Department of Transportation Standard Operating Procedures 2014). Considering variation in local traffic conditions or regulation/law, it is challenging to construct a consolidated model applicable to every different case.

Snow clearance, mowing of verges, and removal of snow posts most commonly use a truck with an attached snow-clearance unit such as a snowplow (Bosely 2008). To evaluate the energy consumption and emissions from the snow-clearance operation, a specific type of equipment is selected as an example and assumptions based on previous studies with respect to equipment behavior are made for assessment (Kecojevic et al. 2011). However, assumptions and variation in truck engines and attached snow-clearance equipment might cause uncertainty in energy consumption and emission determination, possibly resulting 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. Taking 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 (MassDOT SOP 2014). However, it is not well known that these cut-off sectors may contribute significant impact to the system life cycle.

In summary, while LCA is widely-used in analyzing different products or systems, LCA is still under development (Finnveden et al. 2009) and there are some errors that are hard to avoid. By relying on the goal and scope of the analysis, only the related life cycle inventories and stages can be considered and system boundary definition can be subjective. Unknown inventories or stages might be overlooked or cut off because of lack of data or complexity of the product/system life cycle. The LCA is thus challenging to use in fully evaluating the complex life cycle of a product or system. However, LCA can be a useful approach for comparing different products or systems from a more comprehensive angle.

References

Global Economic Symposium. (2014). Proposal-The Energy Crisis and Climate Change. Kiel, Germany. [cited by 2015 Mar 27th]. Retrieved from http://www.global-economic-symposium.org/contact

Board on Atmospheric Sciences and Climate (BASC). (2011). Division on Earth and Life Studies (DELS) and National Research Council. *America's Climate Choices*. Washington, DC: The National Academies Press.

Lu, J., Vecchi, G.A., and Reichler, T. (2007). Expansion of the Hadley Cell under Global Warming. *Geophysical Research Letters* 34 (6): 1-5. [cited by 2015 Mar 22nd]. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/2006GL028443/pdf

Zona, D., Janssens, I.A., Aubinet, M., Gioli, B., Vicca, S., Fichot, R., and Ceulemans, R. (2013). Fluxes of the Greenhouse Gases (CO2, CH4 and N2O) above a Short-Rotation Poplar Plantation after Conversion from Agricultural Land. *Agricultural and Forest Meteorology* 169, 15: p. 100-110.

United Nations Environment Programme. (2015). Life Cycle Assessment. Nairobi, Kenya. [cited by 2015 Mar 30th]. Retrieved from http://www.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx

ISO 14040. (1997). Environmental Management-Life Cycle Assessment-Principles and Framework. [cited by 2015 Mar 27th]. Retrieved from http://web.stanford.edu/class/cee214/Readings/ISOLCA.pdf

Scientific Applications International Corporation (SAIC). (2006). Life Cycle Assessment: Principles and Practice. U.S. Environmental Protection Agency. Contract No. 68-C02-067. Cincinnati, OH, USA. [cited by 2015 Mar 28th]. Retrieved from http://www.epa.gov/nrmrl/std/lca/pdfs/chapter1_frontmatter_lca101.pdf

Suh, S., Lenzen, M., Treloar, GJ., Hondo, H., Horvath, A., Huppes, G., and Jolliet, O. (2004). System Boundary Selection in Life Cycle Inventories Using Hybrid Approaches. *Environ. Sci. Technol* 38: 657-664.

EPA. (1993). Life-Cycle Assessment: Inventory Guidelines and Principles. *Washington, DC: United States Environmental Protection Agency*. EPA/600/SR-92/245. Washington, DC, USA. [cited by 2015 May 3th]. Retrieved from http://goo.gl/gHQeTH

EPA. (1995). Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis. *Washington, DC: United States Environmental Protection Agency*. EPA-R-95-010. Washington, DC, USA. [cited by 2015 May 3th]. Retrieved from http://goo.gl/O9ZPbD

Finnvedena, G., Hauschildb, M.Z., Ekvallc, T., Guinéed, J., Heijungsd, R., Hellwege, S., . . . Suh, S. (2009). Recent Development in Life Cycle Assessment. *Journal of Environmental Management* 91: 1-21. [cited by 2015 Feb 25th]. Retrieved from http://www.sciencedirect.com/science/article/pii/S0301479709002345#

Carnegie Mellon University. (2015). Approaches to Life Cycle Assessment. Pittsburgh, PA, USA. [cited by 2015 Mar 2nd]. Retrieved from http://www.eiolca.net/Method/LCAapproaches.html

Lenzen, M. (2002). Differential Convergence of Life-Cycle Inventories toward Upstream Production Layers. *J. Ind. Eco* 6 (3-4): 137-160.

Dale, A.T., Khanna, V., Vidiv, R.D., and Bilec, M.M. (2013). Process Based Life-Cycle Assessment of Natural Gas from the Marcellus Shale. *Environ. Sci. Technol* 47: 5459-5466.

Ferrao, P., and Nhambiu, J. A. (2009). Comparison between Conventional LCA and Hybrid EIO-LCA: Analyzing Crystal Giftware Contribution to Global Warming Potential. *In Handbook of Input-Output Economics in Industrial Ecology*. Springer: New York.

Acquaye, A.A., Wiedmann, T., Feng, K., Crawford, R.H., Barrett, J., Kuylenstierna, J., . . . McQueen-Mason, S. (2011). Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environ. Sci. Techno.* 45: 2471-2478.

Hendrickson, C. T., Lave, L.B., and Matthews, H.S. (2005). *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach, Resources for the Future Press*. ISBN 978-1-933115-24-5

Suh, S., and Huppes, G. (2005). Methods for Life Cycle Inventory of A Product. *J. Cleaner Prod.* 13: 687-697.

Alvarez-Gaitan, J.P., Peters, G.M., Rowley, H.V., Moore, S., and Short, M.D. (2013). A Hybrid Life Cycle Assessment of Water Treatment Chemicals: An Australian Experience. *Int J Life Cycle Assessment* 18: 1291-1301.

Sripple, H. (2001). Life Cycle Assessment of Road a Pilot Study for Inventory Analysis. *IVL Swedish Environmental Research Institute Report*. Gothenburg, Sweden. [cited by 2015 Mar 20th]. Retrieved from http://www.academia.edu/6634759/Life_Cycle_Assessment_of_Road_A_Pilot_Study_for_Inventory_Analysis_Second_Revised_Edition

Massachusetts Department of Transportation Standard Operating Procedures. (2014). Reduced Salt Policy. *S.O.P. NO. HMD-01-01-1-000*. Massachusetts, US. [cited by 2015 Mar 29th]. Retrieved from http://www.massdot.state.ma.us/Portals/8/docs/SnowAndIce/saltpolicy/salt_policy.pdf

Bosely S.E. (2008). Update of The AASHTO Guide for Snow and Ice Control. *American Association of State Highway and Transportation Officials*. Olympia, WA, USA. [cited by 2015 Mar 2nd]. Retrieved from http://maintenance.transportation.org/Documents/Final%20Report%2020-07%20Task%20250.pdf

Kecojevic, V., and Komljenovic, D. (2011). Impact of Bulldozer's Engine Load Factor on Fuel Consumption, CO_2 Emission and Cost. *American Journal of Environmental Sciences* 7(2): 125-131.

Finnvedena, G., Hauschildb, M.Z., Ekvallc, T., Guinéed, J., Heijungsd, R., Hellwege, S., ... Suh, S. (2009). Recent Development in Life Cycle Assessment. *Journal of Environmental Management* 91: 1-21. [cited by 2015 Feb 25th]. Retrieved from http://www.sciencedirect.com/science/article/pii/S0301479709002345#

CHAPTER 3- ASSESSMENT OF GREENHOUSE GAS EMISSIONS FROM GEOTHERMAL HEATED AIRPORT PAVEMENT SYSTEM

A paper accepted for publication in the International Journal of Pavement Research and Technology (IJPRT)

Weibin Shen[1*], Kasthurirangan Gopalakrishnan[*], Sunghwan Kim[*], and Halil Ceylan[*]

Abstract

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

---

[1] Primary researcher and author

[*] Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA, 50010

Introduction

Snow, ice, or slush on airfield surfaces can result in aircraft-related accidents, so snow removal is a top priority for airports (FAA 2012). De-icing and anti-icing are two major techniques for removal of snow, frost, or ice from transportation surfaces to increase traffic safety. Airports typically use mechanical snow-removal equipment such as snow plows and snow blowers to move snow from traffic areas to other locations and use chemical reagents for deicing/anti-icing for removal or preventing formation of ice on airport runways, taxi-ways, and other surface areas accessible by snow-removal equipment (Amsler 2014).

Heated pavement systems are being explored as efficient alternatives to mechanical and chemical de-icing techniques. Heated pavement systems refer to the idea of heating a pavement surface using either electrical means or through hydronic heating, i.e., running heated fluid through embedded pipes (Subsequent Distribution Office 2001). A geothermally-heated pavement system (GHPS) uses a ground-source heat pump (GSHP) to extract geothermal energy for warming up and circulating a hot water/glycol mixture through pipes embedded within the pavement to heat up the pavement and thereby melt the ice. A GSHP can also provide space heating by capturing heat present in the soil or groundwater using a heat exchanger (Kreith and Goswami 2008). Geothermal heat-exchanger systems fall into one of three types: direct-exchange, closed-loop, and open-loop. Open-loop systems are highly dependent on groundwater extraction and have relatively low efficiency; closed-loop systems require longer and larger pipes and consequently result in increased construction costs. Because of these disadvantages, this study focused on only direct-exchange-based GHPS.

A direct-exchange system uses a single loop to circulate fluid in contact with the ground to directly extract or dissipate heat. There are two kinds of piping systems, viz., horizontal systems and vertical systems. The depths of horizontal heat exchangers range from three to eight feet, while vertical heat exchangers may require depths ranging from 30 to 152 m (Rafferty 1997). It has been claimed that a vertical-loop system is relatively more efficient than a horizontal one because the ground temperature remains relatively constant at depths greater than 61 m (ICAX^{TM} 2007), so only vertical direct-exchange geothermal systems will be considered in this study. Geothermal heating has been used in numerous residential and industrial applications.

Although previous studies on heated pavement systems have analyzed their snow-removal efficiency and cost–effectiveness, few if any studies have attempted to investigate in a systematic manner their environmental efficiency based on greenhouse gas (GHG) emissions of CO_2, CH_4, and N_2O. An analysis of GHG emissions from newly-developed man-made processes/techniques is essential because there is “a more than 90 percent probability” that anthropogenic GHG emissions have contributed to many of the current global-warming trends, as described in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). Well-publicized global-warming effects can cause serious environmental problems such as sea-level rise, subtropical desert expansion, and even extinction of species (BASC 2011) (IPCC 2007) (Lu et al 2007).

To help understand GHG emissions of airport snow-removal systems, a life-cycle assessment (LCA) technique for conducting carbon footprint analysis (CFA) can be used. CFA analyzes the total amount of CO_2 and other GHG emissions released over the life cycle of a product or system expressed in metric tons of CO_2 equivalents or tCO_2eq. The use of a LCA and a CFA to assess the GHG emissions of both traditional and alternative airport snow-removal systems will enable airport owners or operators to consider various what-if scenarios and identify airport pavement locations where such a system is most likely to have the highest/least environmental impact.

Scope and Objectives

The overall goal of this study is to compare the energy use and carbon footprint of a GHPS with that of a traditional airport runway snow-removal system. LCA methodology will be used to estimate GHG emissions from both the snow-removal systems by defining and establishing the boundaries for the system analysis, by developing a full understanding of the amount of energy used and GHG emissions from the systems, by assessing potential environmental effects through an inventory analysis, and by evaluating the consequences of the inventory analysis and impact assessment to provide actionable insights for system operators (SAIC 2006).

There are three broad approaches to conducting a LCA: process life-cycle assessment, economic input-out life-cycle assessment, and hybrid life-cycle assessment. Although the LCA process has disadvantages, such as subjective boundary selection, lack of comprehensive data in many cases, and some uncertainty, it does provide detailed information with respect to the assessment of specific processes and is generally considered to be an effective methodology for product comparisons (Melissa 2007). The LCA process considers material and energy input and GHG output within the pre-defined system boundary at every stage in the life cycle. Since the objective of this study is to do a comparative CFA and environmental impact assessment of traditional snow-removal and heated pavement systems rather than a detailed cradle-to-grave LCA of airport snow-removal systems, a partial LCA methodology has been adopted, one that excludes those phases of the life cycle that are exactly the same for both systems with respect to energy consumption and GHG emissions.

The GHGs considered in this study include CO_2, CH_4 and N_2O emissions resulting from construction and operation phases of both snow-removal systems. The concept of global-warming potential (GWP) is typically used to express the capability of a certain GHG to trap heat in the atmosphere relative to CO_2 over a specified time horizon. Based on the Fifth Assessment Report of the IPCC (IPCC 2007), CO_2 has a global-warming potential (GWP) of 1 over 100 years; CH_4 has a GWP of 25 (i.e., Methane is capable of trapping 25 times more heat than CO_2 per unit weight over a 100-year time period) and N_2O has a GWP of 298.

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

Carbon Footprint Analysis Methodology

Overview of snow-removal system life-cycle phases

The life cycle of a snow-removal system includes several different stages in its production, implementation, and operation, beginning with the extraction of its raw materials. As the first LCA study on GHPS at airports, this study considered only life-cycle phases making significant contributions towards overall GHG emissions from both GHPS and traditional snow-removal systems. GHPS also is a relatively new technology applied to airport snow removal, and therefore detailed information needed to conduct a full-fledged LCA study related to its maintenance (frequency, energy consumption, etc.) is lacking in the literature. Thus, for the sake of simplicity, this study focused more on GHG emissions from the construction and operational phases of the traditional snow-removal system and the GHPS. The time horizon for analysis was assumed to be 20 years, ranging from construction through operation. The GHGs from wastewater treatment and incineration plants have previously been reported as being significant, so waste treatment was included separately as a life-cycle phase. Assuming that the waste released consists mostly of chemical pavement deicer (mixed with melted ice/snow slush) from the operational phase of the traditional runway snow-removal system, the wastewater treatment phase is included in the LCA of the traditional snow-removal system. However, based on reported literature, viz., Life Cycle Assessment: Principle and Practice (SAIC 2006), landfills have not been considered as a life-cycle phase in this study.

To compare the GHG emissions of both snow-removal systems under identically conditions, both are assumed to be used to remove 2.5 cm (1 in.) of snow at an ambient temperature of -21°C (-6°F, a freezing rainy day) on identical airport runways. The runway area for analysis is assumed to be 1.67×10^5 m^2 (1,190 m. × 14 m.) and the runway section is assumed to consist of 30 cm thick Portland cement concrete (PCC) pavement.

Geothermally-heated pavement system model and life cycle

For the vertical direct-exchange geothermal system considered in this study it is assumed that one unit of hydronic piping (see Figure 3 (a)) can heat an area of 0.85 m^2. A three-quarter-inch polyethylene (PE) pipe is assumed in this study to circulate a propylene glycol solution (FAA 2011); the maximum pipe length is about 91 m for a single circuit. Since one unit of hydronic piping requires 5.2 m of pipe length, there can be 18 units per circuit (see Figure 3 (b)). In this study, 40 circuits were calculated to have been placed into one well to minimize the number of heat wells (see Figure 3 (c)); one 152-m heat well can thus warm up to about 613 m^2 of slab area.

Assuming a 3.8 liter per minute water-flow rate per circuit, the total flow rate is 2.5×10^{-3} m^3/s per heat well.

The GHPS life cycle phases include a construction materials production phase, a system construction phase, an energy production phase, and a system operation phase. There is no waste treatment phase since there is no use of deicer with heated pavements. The energy production phase also accounts for GHG emissions from cradle to grid. In this study, the critical factors in the GHPS construction phase are the drilling of the heat well and the PCC pavement production. The only energy demand to run the system is assumed to be that for the pumping operation. An electric pump is selected as an example of a power-supply device for circulating the heated fluid. System boundary of the GHPS life cycle considered in this study is shown in Figure 4.

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

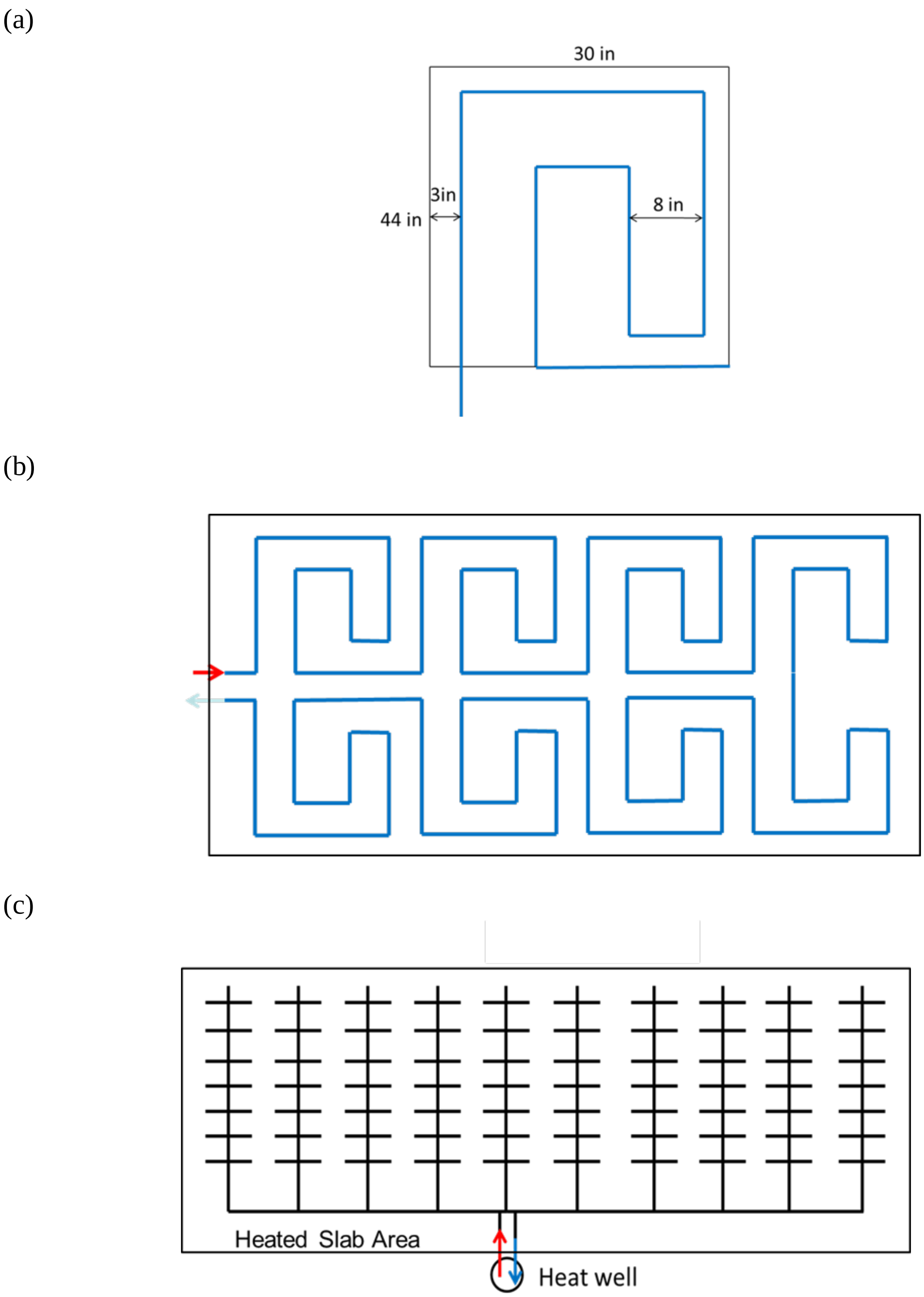


Figure 3. Plan view of hydronic piping model: (a) one unit of hydronic piping, (b) one circuit of hydronic piping, and (c) hydronic piping model per heat well

The GHPS life cycle phases include a construction materials production phase, a system construction phase, an energy production phase, and a system operation phase. There is no waste treatment phase since there is no use of deicer with heated pavements. The energy production phase also accounts for GHG emissions from cradle to grid. In this study, the critical factors in the GHPS construction phase are the drilling of the heat well and the PCC pavement production. The only energy demand to run the system is assumed to be that for the pumping operation. An electric pump is selected as an example of a power-supply device for circulating the heated fluid. System boundary of the GHPS life cycle considered in this study is shown in Figure 4.

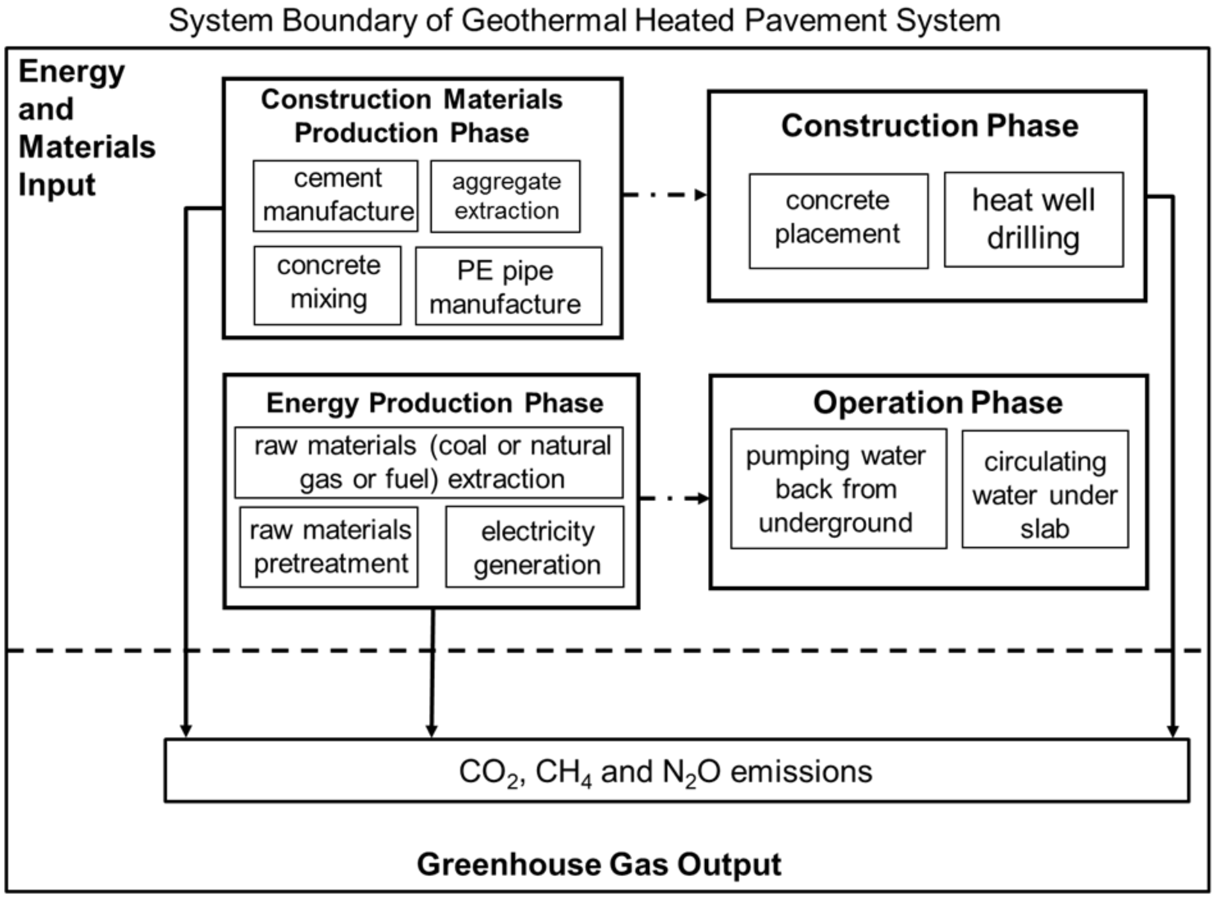


Figure 4. System boundary of geothermal heated pavement system

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

Construction material production phase and construction phase

The airport runway PCC, with a 20-year design life, has an assumed composition of 12% cement, 82% aggregates, and 6% water by total volume. Using system boundaries, technical applications, fuel sources, and raw material sources described in previous studies, the GHG emission factors from concrete manufacturing, assumed to be the same as reported in those (Hanson et al 2012) (Loijos 2014) (Marceau et al 2006) (Zapata and Gambatese 2005) (Mukherjee and Cass 2011) vary from 0.10 to 0.13 tCO_2eq/t of concrete. A GHG emission factor of 0.13 tCO_2eq/t of concrete is assumed as a conservative estimate for the pavement-construction materials production phase in this study. The total mass of concrete required for building a runway area of 1.67×10^5 m^2 with 30 cm thickness is estimated to be 1.35×10^5 t (density of concrete is assumed to be 2.68 t/m^3). Consequently, the GHG emissions from pavement-construction materials manufacturing is about 1.7×10^4 tCO_2eq. Based on a previous study (Carolin et al 2011), a GHG emission factor of 0.004 tCO2eq per 30.5 m pipe is assumed for PE pipe manufacturing. Based on the geothermal-heated pavement model, about one million meters of PE pipe are needed to heat the 1.67×10^5 m^2 runway area, so the total GHG emissions from PE pipe manufacturing are estimated to be 43 tCO^2eq.

The construction phase of the GHPS includes PCC placement and heat-well drilling. Based on a previous study (Loijos 2014), the GHG emission factor for PCC placement taken to be 2.5×10^{-3} tCO_2eq/t concrete which is much less than 23.3×10^{-1}, the emission factor for construction-materials manufacturing. The GHG emission from PCC placement is thus 338 tCO_2eq. Heat-well drilling utilizes a driller to dig deep holes, and a driller equipped with a 1,500 kW engine and exhibiting a 39.6 m/min drilling speed is assumed in this study. Based on the geothermally-heated system model considered in this study, 263 wells are required, so the total drilling time works out to be 34 hours. To accurately determine the amount of GHG released from heat-well drilling, an estimation of diesel oil consumption must be included; the fuel consumption estimated as in (Kecojevic and Komljenovic 2001) is:

$$FC = RP \times 0.3 \times LF \qquad (1)$$

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

The diesel fuel CO_2 conversion factor (99% of total GHG) emission can be calculated as (Kecojevic and Komljenovic 2001):

$$GHG\,emission = FC \times 0.00268 \qquad (2)$$

where the conversion factor for diesel fuel is taken to be 0.00268 t (EPA 2005). GHG emissions from heat well drilling are estimated to be 42 tCO_2eq.

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

Energy production phase and operation phase

The energy production phase GHG emissions analysis is based on previous studies (EIA 2014) (NETL 2000) of life-cycle assessment of electrical power production. Three different power-plant energy sources are considered in this study: coal, natural gas and distillate oil. Because coal-fired power plant GHG emissions can vary by location, a power plant located in Iowa has been assumed in this analysis. The phases of coal-fired power-plant life cycle include coal mining, coal preparation/cleaning, all necessary transportation of coal to power plant, and electrical grid power production. GHG emissions of different life phases of the assumed coal power plant are shown in Table 1.

Table 1. GHG emissions from coal-fired power plant

Life Cycles of Coal Power Plant		GHG Emission Factor (tCO_2eq/MWh)	Percentage (%)
Surface mining[1]		7.0×10^{-3}	0.70
Coal washing[2]		1.0×10^{-4}	0.01
Coal transportation	Shipping[3]	1.0×10^{-1}	10.1
	Railway[4]	2.6×10^{-4}	0.03
Grid electricity production[5]		8.8×10^{-1}	89.2
Whole life cycle		9.9×10^{-1}	100

[1] Illinois No. 6 coal as an example; electricity demand: 0.0143 MWh/t of coal; diesel oil demand: 269 m^3/MMT of coal; transportation of diesel oil GHG emission: 2.7 $kgCO_2eq/L$; 0.54 kg coal/kWh electricity produced (Spath et al 1999) (CDM-Executive Board 2001) (EIA 2014).

[2] Jig washing is the technique used in this LCA (Spath et al 1999).

[3] Distance from mining to power plant: 434 km; GHG emission: 0.43 $kgCO_2eq/t{\cdot}km$ (Chen et al 2013).

[4] Distance from mining to power plant: 48 km; GHG emission: 0.01 $kgCO_2eq/t{\cdot}km$ (Chen et al 2013).

[5] Data from US Energy Information Administration EIA-1605 is used (EIA 2007)

A natural gas-fired power plant life cycle includes natural gas extraction, natural gas pretreatment, natural gas pipeline transportation, and electrical grid power production (NETL

2000). GHG emissions from different life cycle phases of a natural gas-fired power plant are shown in Table 2.

Table 2. GHG emissions from natural gas-fired power plant

Life Cycles of Coal Power Plant	GHG Emission Factor (tCO_2eq/MWh)	Percentage (%)
Natural gas extraction[1]	4.3×10^{-3}	1.01
Natural gas pretreatment and transportation[2, 3]	9.9×10^{-5}	0.03
Grid electricity production[4]	4.2×10^{-1}	99.0
Whole life cycle	4.2×10^{-1}	100

[1] Natural gas density: 0.7 kg/m^3; 2-phases 95%-efficiency compressor is applied, power demand: 4.9×10^{-3} kw/m^3 of natural gas (NETL 2000).
[2] Total distance: 482 km by pipeline transportation (Chen et al 2013).
[3] Specific volume of natural gas: 1.49 m^3/kg; auxiliary boiler natural gas consumption: 0.16 kg/MWh (NETL 2000).

Because the distillate oil-fired power plant GHG emissions factor is highly site-specific, a reasonable value of 0.778 tCO_2eq/MWh based on a previous study (Gagnon et al 2002) was assumed. To confirm the applicability and use of this factor, it was compared with the US Energy Information Administration (EIA) database (EIA 2014).

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

To determine the amount of energy required to melt a 2.5 cm thick snow cover, the following equation for calculating the required pavement heat output (qo) in $Btu/h\cdot ft^2$ was applied (Chapman 1952):

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

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

The energy demand (qo) was estimated to be 205 Btu/h·ft^2 (2.5×10^5 J/h·m^2) for snow removal. Approximately 20% back and edge losses (American Society of Heating 2003) were assumed in the heat output calculations. Because the total area for one runway is 1.67×10^5 m^2, the total energy demand to melt 2.5 cm snow is estimated to be 452 million kJ. Using the geothermally-heated pavement model discussed above, there is a demand of 263 heat wells and each heat well is 152 m deep. The energy supplied by the geothermal vertical loop can be calculated using the following equation (Ozyurt and Ekinci 2011):

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

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

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

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

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

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

Traditional snow-removal system model and life cycle

Based on the FAA snow-removal standard (FAA 2012), snow-clearing time for each runway at a commercial service airport whose annual airplane operations exceed 40,000 in number should be limited to 0.5 hours. Snow plows, snow brooms, snow blowers and chemical deicer trucks are the assumed snow removal equipment units to be used in removing 2.5 cm of snow from a runway in this study. Snow-removal equipment is assumed to operate at a speed of 32 km/h, and the traditional snow-removal strategy assumed in this study is as follows: a snow-plow is run to move the snow to the side (it is assumed that 6 snow plows and 6 snow brooms with a 8,600 kW total engine power will be employed), followed by two snow blowers with a total engine power of 1,640 kW and two chemical sprayers with a total engine power of 1,200 kW to spray deicer on the runway to prevent snow formation.

One of the major differences in life cycle phases between the GHPS and a traditional snow-removal system is the waste-treatment phase required during the traditional snow-removal system life-cycle phase. Because chemical deicer is used in snow equipment application, the resulting polluted water must be treated in a wastewater treatment plant, contributing considerable GHG emissions to the system life cycle. It is assumed that the traditional snow-removal system is operated over a conventional PCC pavement, and that diesel oil is used for snow-removal equipment operation. The system boundary for the traditional snow-removal system operation life cycle considered in this study is shown in Figure 5.

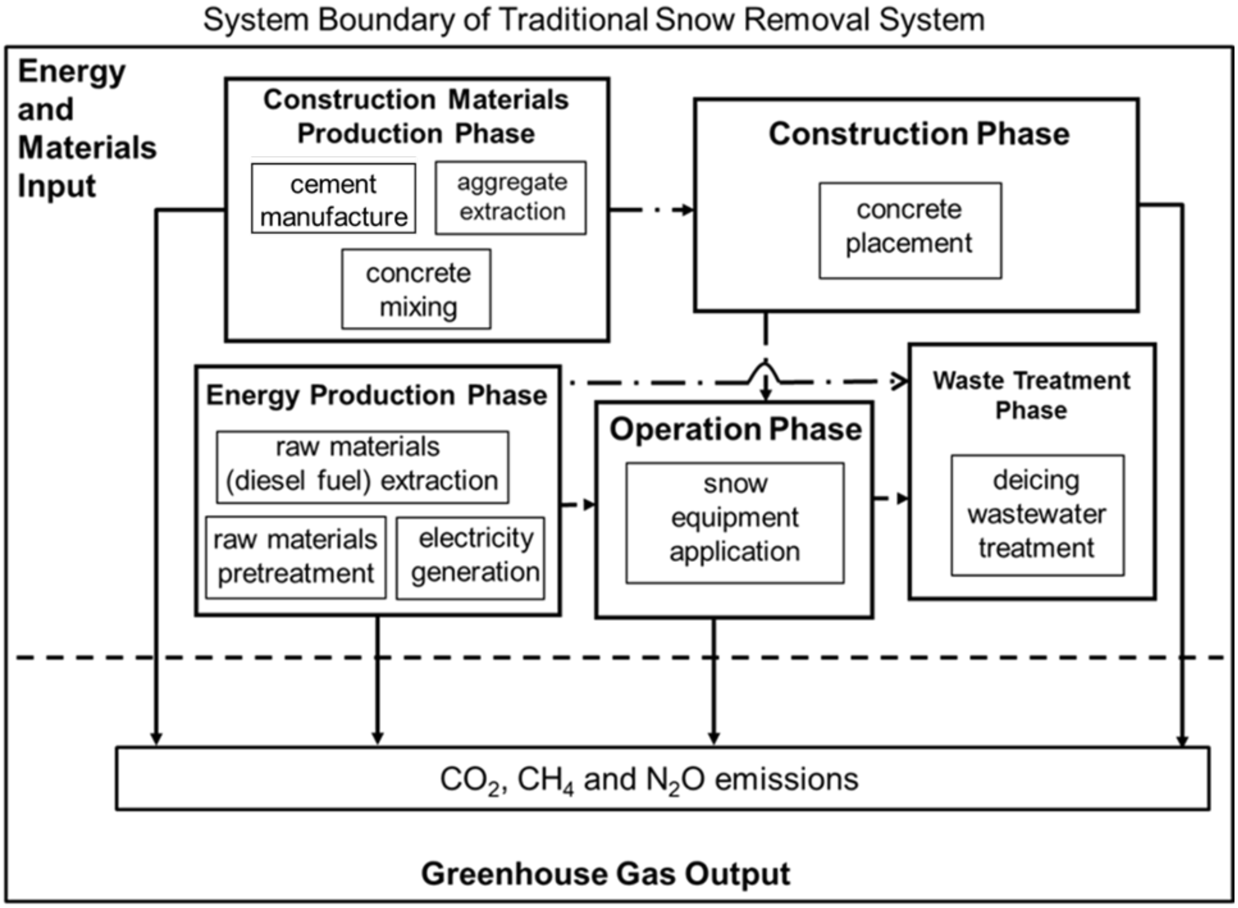


Figure 5. System boundary of traditional snow removal system

Construction materials production phase and construction phase

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

Energy production phase and operational phase

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

Waste-treatment phase

At an ambient temperature of -21°C on a freezing rainy day, the potassium acetate de-icer demand is approximately 11 liters per 93 m^2 runway for melting 2.5 cm of snow (CRYOTECH 2014). The total potassium acetate demand is about 20,000 liters, and 90% of the de-icing wastewater is assumed captured (EPA 2014). The concentration of the 50% potassium acetate component is 7.8×10^{-4} t/L (CRYOTECH 2014), so the Chemical Oxygen Demand (COD) content of potassium acetate de-icer can be calculated as:

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

where the ThOD of potassium acetate is 0.92 mole/g, the Potassium acetate molecular weight is 0.01 mole/g, and the O_2 molecular weight is 32 g/mole (National Center for Biotechnology Information 2014).

The total wastewater COD is 4.2 t. The airport runway wastewater is assumed to be treated by the nearest city wastewater treatment plant that uses an aerobic biological treatment, and a value of 1×10^{-3} kWh electricity demand per t COD is assumed for such treatment (Geest and Kiechle 2010). Therefore, the total electricity demand for deicer wastewater treatment will be about 4,202 kWh. With respect to the GHG emission factors of the power plant, the GHG emissions of wastewater treatment are estimated to be 5.83 tCO_2eq from coal-fired plants, 2.85 from natural gas-fired plants, and 4.74 from distillate-oil-fired power plants.

Comparison of Results and Discussions

The GHG emissions from both snow-removal systems to remove 2.5 cm of snow on a freezing rainy day are summarized in Table 3 and Table 4, respectively. Energy production and construction materials production are two phases that release more GHG emissions than other life-cycle phases in both snow-removal systems. The GHG emissions from the operational phase are not included in Table 3 since they are already accounted for in the energy production phase (electrical power is consumed during the operation of the GHPS). Similarly, GHG emissions from the waste-treatment phase are not included in Table 4 since they are already accounted for in the energy production phase (electricity is consumed during deicer wastewater treatment). However, operational-phase GHG emissions are separately presented in Table 4 since diesel fuel is consumed during the operation of snow-removal equipment and this has not been accounted for in other life cycle phases of the traditional snow-removal system.

Table 3. GHG emissions from geothermal heated pavement system

Life Cycle Phases		GHG emissions (tCO_2eq/day)
Construction materials production	Pavement construction materials manufacturing	23.3×10^{-1}
	PE pipe manufacturing	5.9×10^{-3}
Construction	Concrete placement	4.6×10^{-2}
	Heat well drilling	5.8×10^{-3}
Energy production	Coal power plant	54.6×10^{-1}
	Natural gas power plant	23.2×10^{-1}
	Distillate oil power plant	43.0×10^{-1}
Total	Case 1: Energy generated by coal power plant	78.5×10^{-1}
	Case 2: Energy generated by natural gas power plant	47.1×10^{-1}
	Case 3: Energy generated by distillate oil power plant	66.9×10^{-1}

Table 4. GHG emissions from traditional snow removal system

Life Cycle Phases (20 year time frame)			GHG emissions (tCO_2eq/day)
Construction materials production	Pavement construction materials manufacturing		23.3×10^{-1}
Construction	Concrete placement		4.6×10^{-2}
Energy Production	Diesel fuel manufacture		1.7×10^{-2}
	Electricity for wastewater treatment	Coal power plant	58.3×10^{-1}
		Natural gas power plant	28.5×10^{-1}
		Distillate oil power plant	47.4×10^{-1}
Operation	Snow equipment application		6.2×10^{-2}
Total	Case 1: Energy generated by coal power plant		82.1×10^{-1}
	Case 2: Energy generated by natural gas power plant		52.3×10^{-1}
	Case 3: Energy generated by distillate oil power plant		71.2×10^{-1}

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

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

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

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

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

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

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

Table 5. GHG emissions from geothermal heated pavement system applied in gate area

Life Cycle Phases (20 year time frame)		GHG emissions (tCO_2eq/day)
Construction materials production	Pavement construction materials manufacturing	2.5×10^{-2}
	PE pipe manufacturing	6.2×10^{-2}
Construction	Concrete placement	4.9×10^{-4}
	Heat well drilling	6.1×10^{-5}
Energy production	Coal power plant	5.7×10^{-2}
	Natural gas power plant	2.4×10^{-2}
	Distillate oil power plant	4.5×10^{-2}
Total	Case 1: Energy generated by coal power plant	8.3×10^{-2}
	Case 2: Energy generated by natural gas power plant	5.0×10^{-2}
	Case 3: Energy generated by distillate oil power plant	7.1×10^{-2}

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

Conclusions and Recommendations

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

Findings

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

- The independent LCA carried out for the airport gate area shows that the GHG emission from GHPS is about 100 times less than the emission from a similar system used on a runway, so the use of a geothermally-heated pavement system in an airport gate area not only has less environmental impact, but also overcomes a number of problems associated with removing snow from gate areas using mechanical equipment, environmental pollution caused by use of chemicals, and safety issues involving snow-clearing ground crews on cold winter days.
- The deicer wastewater treatment phase accounts for the majority of GHG emissions when using a traditional snow-removal system.

Recommendations

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

References

American Society of Heating. (2003). Refrigerating and Air-Conditioning Research, 2003 ASHRAE Handbook: HVAC Applications IP Edition, Atlanta: ASHRAE Engineers, Inc. Atlanta, GA, USA.

Amsler, D.E. (2014). Snow and Ice Control 2014 [Internet]. Cornell Local Roads Program, Publication CLRP No. 13-04, New York: LTAP Center, New York, USA. [cited 2014 July 29]. Available from: http://www.clrp.cornell.edu/workshops/manuals/snow_and_ice_control.pdf.

Board on Atmospheric Sciences and Climate (BASC). (2011). Division on Earth and Life Studies (DELS) and National Research Council, America's Climate Choices, Washington, DC: The National Academies Press. Washington, D.C., USA.

Carolin, S., Vanderreydt, I., Vercalsteren, A., and Boonen, K. (2011). Life Cycle Assessment of a PE Pipe System for Water Distribution (according to EN 12201) [Internet], Brussels Belgium: European Plastic Pipes and Fittings Association-TEPPFA, Brussels, Belgium. [cited 2014 July 29]. Available from: http://www.bureauleiding.nl/kennisdossier/Milieu%20Product%20Verklaringen/EPD/PE-Thirdpartyreport-June2011.pdf.

CDM-Executive Board. (2014). Clean Development Mechanism Project Design Document Form [Internet], Bonn, Germany: CDM-SSC-PDD Version 03, Bonn, Germany. [cited 2014 July 29]. Available from: http://www.dnv.com/focus/climate_change/Upload/DNV_Vers%C3%A3o%20Ingl%C3%AAs_PDD%2001_Ecobio_20mar.pdf.

Chapman, W.P. Design of snow melting systems. (1952). Heating and Ventilating, (April): 95 and (November):88.

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

CRYOTECH. (2014). Potassium acetate-liquid runway deicer [Internet], CRYOTECH ISO 9001:2000 Certified Company, Fort Madison, IA, USA [cited 2014 February 6]. Available from: http://meltsnow.com/pdf/potassium-acetate.pdf.

Energy Information Administration. (2007). Electricity Emission Factors, Washington, DC: Publication EIA-1605, OMB No. 1905-0194. Washington, D.C., USA.

Energy Information Administration. (2014). How Much Carbon Dioxide Is Produced Per Kilowatthour When Generating Electricity With Fossil Fuels? [Internet], Washington, DC: EIA FAQ, Washington, D.C., USA. [cited 2014 June 9]. Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11.

Energy Information Administration. (2014). How Much Coal, Natural Gas, or Petroleum Is Used to Generate A Kilowatthour of Electricity? [Internet], Washington, DC: EIA FAQ, Washington, D.C., USA. [cited 2014 June 9]. Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=6.

Environmental Protection Agency. (2005). Average Carbon Dioxide Emissions from Gasoline and Diesel Fuel, Washington, DC: Publication EPA420-F-05-001. Washington, D.C., USA.

Environmental Protection Agency. (2014). Airport Deicing Effluent Guidelines [Internet], Washington, DC: US EPA, Washington, D.C., USA. [cited 2014 February 6]. Available from: http://water.epa.gov/scitech/wastetech/guide/airport/index.cfm.

Federal Aviation Administration. (2011). Airside use of heated pavement systems, Publication FAA 150/5370-17. Washington, DC: U.S. Department of Transportation. Washington, D.C., USA.

Federal Aviation Administration. (2012). Airport Winter Safety and Operations, *Publication FAA 150/5200-30C*, Washington, DC: U.S. Department of Transportation, Washington, D.C., USA.

Gagnon, L., Belanger, C., and Uchiyama, Y. (2002). Life Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001, Energy Policy, Vol. 30, pp. 1267-1278.

Geest, V.J. and Kiechle, C. (2010). Anaerobic Wastewater Treatment [Internet]. Brewing and Beverage Industry No1, Celle, Germany [cited 2014 June 9]. Available from: http://www.berkefeld.com/berkefeld/ressources/documents/1/23010,EN_VWS_Biothane_Aquantis_Brewing-B.pdf.

Hanson, C.S., Noland, R.B., and Cavale KR. (2012). Life-Cycle Greenhouse Gas Emissions of Materials Used in Road Construction, Transportation Research Record: Journal of the Transportation Research Board, No.2287, Washington, DC: Transportation Research Board of the National Academies, pp. 174-181.

ICAX™. (2007). Mean Annual Air Temperature – MATT [Internet], London, UK. [cited 2014 July 29]. Available from: http://www.icax.co.uk/Mean_Annual_Air_Temperature.html.

Intergovernmental Panel on Climate Change. (2007). Direct Global Warming Potential [Internet], Switzerland: IPCC Fourth Assessment Report: Climate Change, Geneva 2, Switzerland. [cited 2014 July 22]. Available from: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html.

Kecojevic, V. and Komljenovic, D. (2001). Impact of Bulldozer's Engine Load Factor on Fuel Consumption, CO2 Emission and Cost, Am. J. Enviorn. Sci, Vol. 7(2), pp. 125-131.

Kreith, F. and Goswami, D.Y. (2008). Energy Management and Conservation Handbook, CRC Press, Boca Raton, FL, USA.

Loijos, A. (2014). Life Cycle Assessment of Concrete Pavements: Impacts and Opportunities [Internet], US-MA: Master Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA. [cited 2014 July 29]. Available from: http://dspace.mit.edu/bitstream/handle/1721.1/65431/746765257.pdf?sequence=1.

Lu, J., Vechhi, G.A., and Reichler, T. (2007). Expansion Of The Hadley Cell Under Global Warming, Geophysical Research Letters, 34(6), pp. 1-5. [cited 2014 July 29]. Available from: http://onlinelibrary.wiley.com/doi/10.1029/2006GL028443/pdf

Marceau, M., Nisbet, M., and VanGeem, M. (2006). Life Cycle Inventory of Portland Cement Manufacture [Internet], Washington DC: Portland Cement Association, Washington, D.C., USA. [cited 2014 July 29]. Available from: http://www.nrmca.org/taskforce/item_2_talkingpoints/sustainability/sustainability/sn2095b%20-%20cement%20lci%202006.pdf.

Melissa, M.A. (2007). Hybrid Life Cycle Assessment Model for Construction Processes [Internet], US-PA: Doctoral Dissertation, University of Pittsburgh, Pittsburgh, PA, USA. [cited 2014 July 29]. Available from: http://d-scholarship.pitt.edu/8065/1/bilec_July_11_2007_7.pdf.

Mukherjee, A. and Cass, D. (2011). Carbon Footprint for HMA and PCC Pavements [Internet]. Office of Research & Best Practices, US-MI: Michigan Department of Transportation, MI, USA. [cited 2014 July 29]. Available from: http://www.michigan.gov/documents/mdot/MDOT_Research__Report_RC-1553_363800_7.pdf.

National Center for Biotechnology Information. (2014). Potassium Acetate [Internet]. NCBI, U.S. National Library of Medicine, Bethesda, MD, USA. [cited 2014 June 16]. Available from: http://pubchem.ncbi.nlm.nih.gov/summary/summary.cgi?cid=517044.

National Energy Technology Laboratory. (2000). Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant, Pittsburgh, PA: Publication DOE/NETL-403/110509, Pittsburgh, PA, USA.

Ozyurt, O. and Ekinci, D.A. (2011). Experimental Study of Vertical Ground Source Heat Pump Performance Evaluation for Cold Climate in Turkey, Applied Energy, Vol. 88, pp. 1257-1265.

Rafferty, K. (1997). An Information Survival Kit for the Prospective Residential Geothermal Heat Pump Owner [Internet], US-OR: GHC Bulletin. [cited 2014 May 26]. Available from: http://geoheat.oit.edu/bulletin/bull18-,2/art1.pdf.

Scientific Applications International Corporation (SAIC). (2006). Life cycle assessment: principle and practice, US-VA: Environmental Protection Agency, Contract No. 68-C02-067, Tysons Corner, Virginia, U.S.

Spath, P.L., Mann, M.K., and Kerr, D.R. (1999). Life Cycle Assessment of Coal-Fired Power Production [Internet], Golden, CO: NREL/TP-570-25119. [cited 2014 July 29]. Available from: http://www.nrel.gov/docs/fy99osti/25119.pdf.

Subsequent Distribution Office. (2001). Airside Use of Heated Pavement Systems. Publication FAA 150/5370-xx, Washington, DC: U.S. Department of Transportation. Washington, D.C., USA.

Zapata, P. and Gambatese, J.A. (2005). Energy Consumption of Asphalt and Reinforced Concrete, Journal of Infrastructure Systems, Vol. 11(1), pp. 9-20.

CHAPTER 4- AIRPORT APRON HEATED PAVEMENT SYSTEM OPERATION ANALYSIS: ENERGY REQUIREMENT, GREENHOUSE GAS EMISSIONS, AND OPERATING COST ANALYSIS

A paper to be submitted for presentation and publication in ASCE Conference of Geo-Chicago 2016: Sustainability, Energy, and the Geoenvironment

Weibin Shen[1*], Kasthurirangan Gopalakrishnan[*], Halil Ceylan[*], and Sunghwan Kim[*]

Abstract

Traditional snow removal equipment (SRE) is typically used in clearing snow from large areas in airport pavements such as the runways and taxiways. However, their utility in small areas like the airport apron is limited and challenging to airport operators. A relatively new technology called the hydronic heated pavement system (HHPS) can be applied in the apron areas to save airline delay time and reduce man-power. The primary goal of this study is to employ the life cycle assessment (LCA) methodology to evaluate and compare energy consumptions, GHG emissions, and costs from the operations of three different HHPSs: hydronic heated pavement system using geothermal heat pump (HHPS-G), hydronic heated pavement system using electric water heater (HHPS-E), and hydronic heated pavement system using natural gas boiler (HHPS-NG). The system boundaries where the analysis is carried out are defined and established. The consequences of the inventory analysis and impact assessment of both systems are conducted and discussed to provide some actionable insights to the system operators. The LCA results indicate that the operation of HHPS-G for apron snow removal might have the least energy requirements, GHG emissions, and operating costs. Also, the potential sustainability benefits of HHPS-NG is expected to increase as the efficiency of water boiler improves.

---

[1] Primary researcher and author

[*] Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA, 50010

Introduction

Traditional snow removal system usually applies snow removal machines, like snow plow and snow bloom combinations, snow blowers, and deicing chemical sprayers to achieve airfield surface cleaning missions. These mechanical equipment are usually designed for large areas, like runway, in order to increase snow removal efficiency. However, it makes the equipment difficult to operate in a narrow space like the airport apron. Although smaller snow removal machines are used instead to remove snow from apron areas, they are not as efficient as the big equipment used in runway, and more labors and time are required for traditional apron snow removal application. According to all these reasons, using traditional methods to remove snow from apron areas could cause airline delay problems and high operation costs. Because airport apron is the area where aircraft are parked, unloaded or loaded, refueled, or boarded (FAA 2012), many human activities are involved in this area. Also potential risks, like airport crew safety issues, might happen during traditional snow removal applications. In order to prevent airline delay problem and airport crew accident happening during snow removal application, hydronic heated pavement systems are being studied as the alternative strategy to traditional snow removal system applied in apron areas. Previous study suggested hydronic heated pavement system could have great sustainable benefits to be used for apron snow removal applications (Shen et al. 2015).

Hydronic heated pavement system (HHPS) utilizes natural gas boiler or electric water heater to warm up and circulate hot water through embedded pipes in the pavement in order to heat up the pavement and melt the ice. An alternative approach called geothermal heated pavement system (HHPS-G) is using geothermal energy instead for heating. To achieve the heating function, ground source heat pump (GSHP) is utilized to replace boiler or heater. GSHP can supply space heating by accessing heat in the soil (Kreith and Goswami 2001). It is applied in regions that do not have access to high temperature geothermal resources. GSHP takes the heat absorbed in the land from solar energy through the use of a ground heat exchanger. Ground heat exchanger has three types of systems, direct exchange geothermal system, closed loop geothermal system and open loop geothermal system. Considering the relatively lower efficiency, longer and larger pipe requirements and high construction fee of closed loop systems, this paper focuses on direct exchange based HHPS-G. The direct exchange system uses a single loop to circulate fluid in contact with the ground to extract or dissipate heat directly.

In order to understand the energy consumptions, GHG emissions, and operating cost, a life cycle assessment (LCA) method is used in this study. The use of LCA to assess the GHG emissions of different alternative airport heated pavement systems will enable airport owners or operators to study different what-if scenarios, identify airport pavement locations where one or both the systems would have the highest/least environmental impact. A carbon footprint analysis and comparison between HHPS-G and conventional airport runway snow removal system has been studied previously, however, operating cost was not assessed in previous study (Shen et al 2014). Knowing the operating cost could give the system user a more comprehensive view in comparing different alternatives. Technical economic analysis (TEA) is usually applied by researchers to understand the cost of a system or a product in particular system boundary. To help the airport company to choose a more cost-effective heated pavement systems alternative, TEA is used to analyze the cost to operate geothermal and hydronic heated system during snow removal.

The overall goal of this study is to understand and compare the energy consumptions, GHG emissions, and costs of the operations of three alternative hydronic heated pavement systems, HHPS-G, HHPS-E, and HHPS-NG for different snow rate conditions.

Analysis Methodology

Geothermal heated pavement operation system boundary

The system boundary of HHPS-G operation to prevent ice/snow accumulation on apron surface were identified and illustrated in FIG. 1. Energy production stage and system operation stage are included in this study. Energy production stage describes the life cycle of power plant producing electricity which is used for supplying geothermal heat pump and circulating pump operations. A “cradle-to-gate” assessment of energy production facility (power plant) is applied to estimate the GHG emissions from energy production phase. Three different types of power plants are considered in this study, which include coal fired power plant, natural gas power plant, and distillate oil power plant.

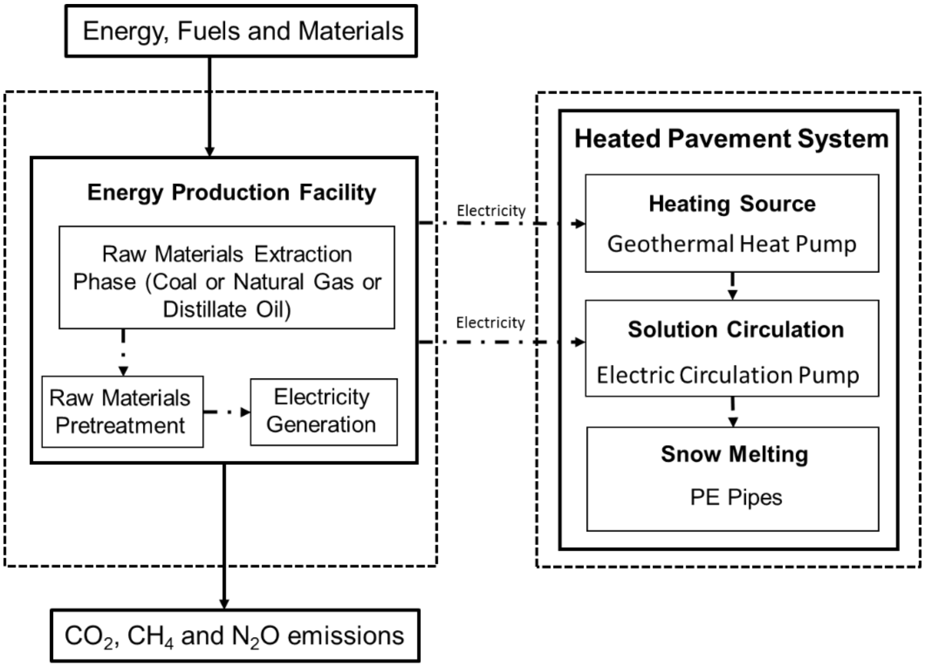
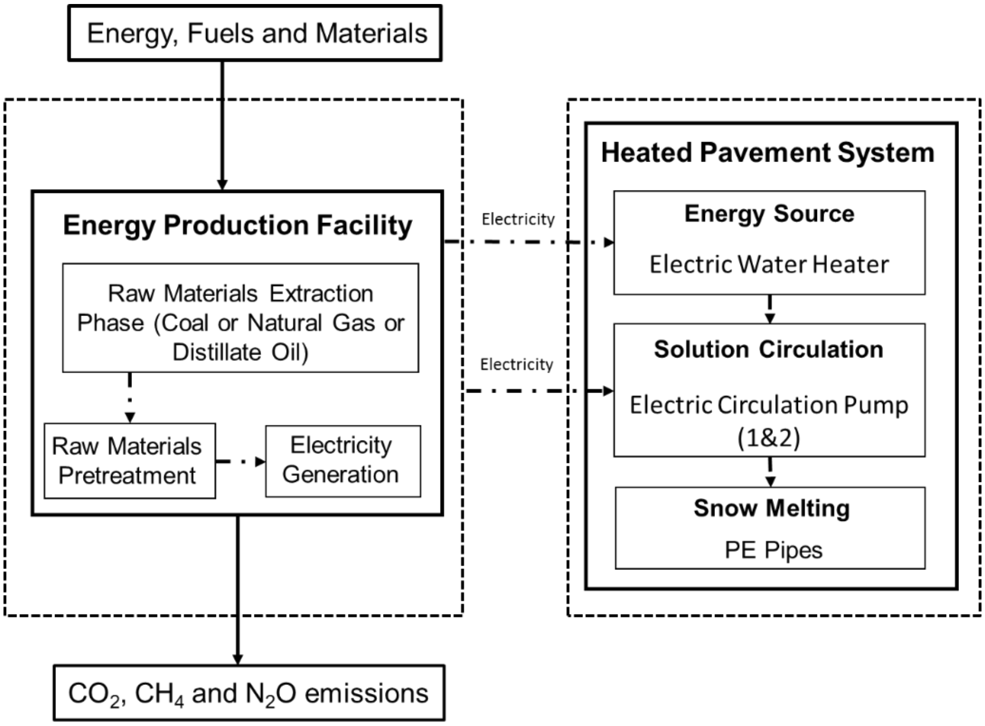


Figure 6. System boundary of geothermal heated pavement system.

Hydronic heated pavement system operation boundary

The system boundaries of HHPS-E and HHPS-NG are identified and illustrated in Figure 7 (a) and (b), respectively. . Similar to the system boundary of HHPS-G, HHPS-E and HHPS-NG system boundaries both include energy production stage and heated pavement system operation stage. Three different types of power plants are analyzed for HHPS-E and HHPS-NG as well. For HHPS-E, energy production stage represents that life cycle phase of power plant which generates electricity for water heater to warm up solution and circulating pump operation. Different from HHPS-G and HHPS-E, HHPS-NG operation energy production stage includes life cycle phase of electricity generation from power plant and life cycle phase of natural gas production facility. Electricity is used to supply circulating pump operation, and natural gas is combusted in natural gas boiler for solution heating as Figure 7 (b) describes.

(a)



(b)

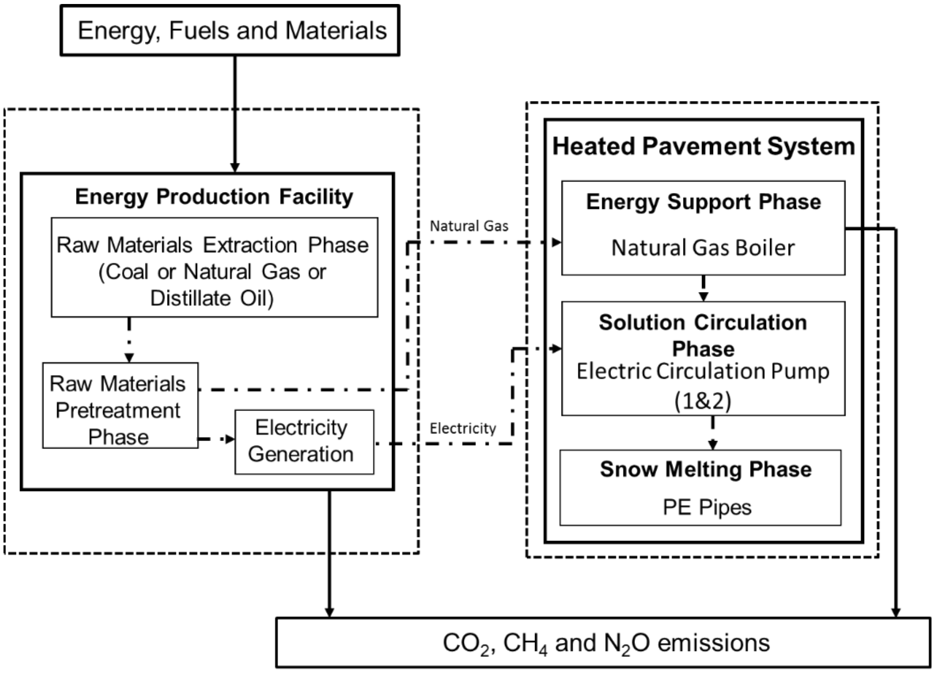


Figure 7. System boundary of hydronic heated pavement system: (a) electric water heater, (b) natural gas boiler.

Heated pavement system models

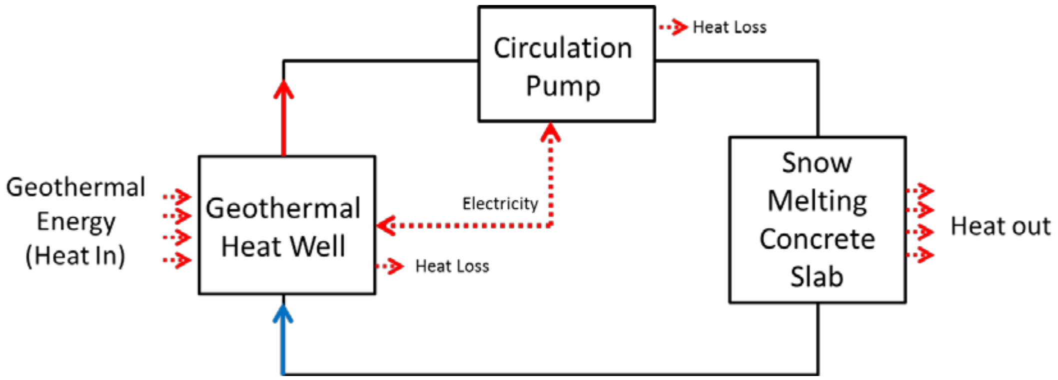
In order to understand the behaviors of both heated pavement systems under different weather conditions, five different snow rates, which were 0.5 in/h, 0.75 in/h, 1 in/h, 1.5 in/h and 2 in/h, at an ambient temperature of 20°F and wind speed of 10 mile per hour were analyzed in this study.

The airport heated pavement systems in this study are applied in the MD-87 aircraft (short to medium range airliner) gate area, which is about 19,000 ft^2 (Robert et al 2010). Both of the heated pavement designs were based on Viega Snow Melting System Installation Manual (Viega 2003). The pipe line design for both geothermal and hydronic heated pavement systems used ¾ inch cross-linked polyethylene (PEX) pipe, whose circuit length is 400 ft, and total 71 circuits are required. A 40% by volume of propylene glycol solution is used as a heated medium in both systems to prevent pipe line frozen, and it is circulated in a flow rate of 8.3 gallons per minute (gpm). The total flow rate of the system is 591 gpm and pressure drop is about 125 ft of head, and a glandless circulating pump with 60% to 80% efficiency (Wilo 2009) can be used to circulate fluid in the systems. In this study, 70% efficiency circulating pumps were analyzed for both heated pavement systems.

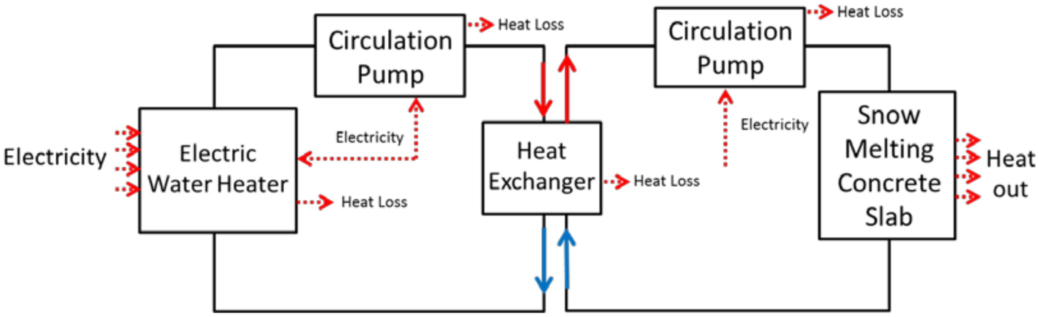
The models of three approaches are demonstrated in Figure 8 (a), (b), and (c) in respectively. The heating energy of geothermal heated pavement system is extracted from the ground by applying electrically geothermal heat pumps. Based on geothermal heat pumps key product criteria, the coefficient of performance (COP) of an efficient direct geo-exchange heat pumps is 3.6 (Energy Star 2012). However, geothermal heat pump coefficient of performance is highly depended on the sufficiency of geothermal energy of the location. It has been studied that COP can be as low as 2.4 (The Canadian Renewable Energy Network 2002). In this study, a low and high COP of ground source heat pump was analyzed to understand the behaviors of HHPS-G under different geothermal situations.

Hydronic heated pavement system applications can be classified by different energy sources. Electric water heater and natural gas boiler for heating in HHPS are analyzed respectively. Typical water heaters in the U.S. are electric resistance or atmospheric natural gas tank water heaters. Electric water heaters typically have efficiency of about 90%, while natural gas boiler will be rated about 60% (American Council for an Energy-Efficient Economy 2012). A heat exchanger is required in the HHPS-E and HHPS-NG, because propylene glycol is used as antifreeze to prevent heat transfer medium freezing, and propylene glycol solution cannot be directly heated by the furnace. Therefore, the HHPS can be divided into two subsystems, a water-heating system and a pavement-heating system. The water-heating system uses a natural gas furnace to heat up water and circulates heated water through a 70% efficiency heat exchanger using a circulating pump. 40% by volume of propylene glycol solution extracts heat from the water heating system through the heat exchanger and it is circulated under the concrete slab surface by the circulating pump to heat the pavement surface.

(a)



(b)



(c)

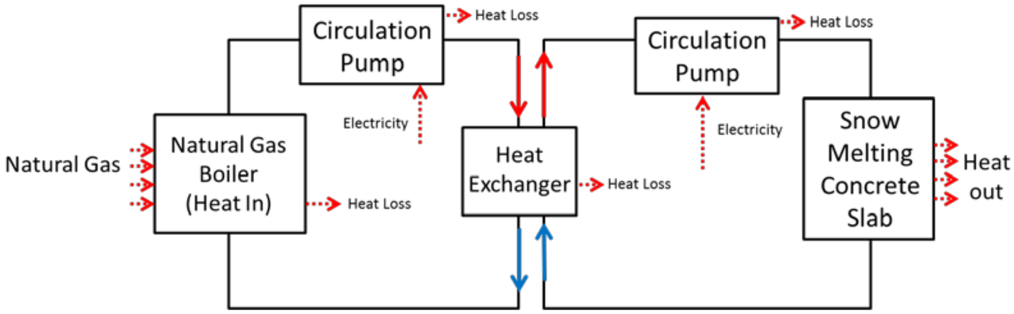


Figure 8. Airport gate area snow removal system models: (a) geothermal heated pavement system, (b) hydronic heated pavement system with electric water heater, (c) hydronic heated pavement system with natural gas boiler.

As Figure 8 presents, electricity and natural gas are two main energies used to operate system in melting snow. Based on U.S. Energy Information Administration, commercial electricity price by the end of December 2014 is 0.1 \$/kWh and natural gas price is 8.52 \$/1000 ft^3, and operating costs of different systems could be understood by multiplying the energy consumption. Three kinds of fossil fuel power plants were assessed to understand the GHG emissions from power plant supported by different energy sources.

Analysis equations

In order to understand the heat (qo) required for melting snow by using a heated pavement system, the following Equation (1) was can be applied (Chapman 1952):

$$qo = qs + qm + Ar(qe + qh) \tag{1}$$

in which, qs = sensible heat transferred to the snow (Btu/h·ft^2), qm = heat of fusion (Btu/h·ft^2), Ar = ratio of snow-free area to total area (dimensionless), qe = heat of evaporation (Btu/h·ft^2), qh = heat transfer by convection and (Btu/h·ft^2).

To calculate the energy demand for circulating pump, the following equation for required water horsepower (WHP) in HP was applied:

$$WHP = \frac{Q \times H \times SG}{3960 \times n} \tag{2}$$

in which, WHP = water horsepower (HP), Q = flow rate (gpm), H = total head (ft), SG = specific gravity of heated solution (1 of water and 1.034 of 40% propylene glycol), n = pump efficiency (%).

Energy consumption (E) in kWh of geothermal heat pump is calculated by the equation shown below:

$$E = \frac{qo}{COP} \tag{3}$$

where E = electric energy requirement (kW), q_o = heat required to melt snow (kW), COP = coefficient of performance.

Analysis Results

Energy consumption of system operation

0.5 in/h, 0.75 in/h, 1 in/h, 1.5 in/h and 2 in/h of different snow rate conditions can be calculated using Equations (1). The resulting energy requirements for snow melting under different snow rates are therefore 161 Btu/h·ft^2, 180 Btu/h·ft^2, 207 Btu/h·ft^2, 250 Btu/h·ft^2 and 301 Btu/h·ft^2 by applying 20% back and edge heat losses (ASHRAE 2003).

Applying values of circulating solution flow rate and total head drop, 591 gpm and 125 ft of head, energy requirement for a circulating pump is about 19 hp by using Equation 2.

Based on the assumptions and energy balance under the system boundaries, total energy consumptions of operating different heated pavement systems for different snow rate conditions are shown in Table 6.

Table 6. Total energy consumption of HHPS-G and HHPS (kWh/h) for different snow rate conditions

Snow removal System	Snow Rate (in/h)	Total Energy Consumption (kWh/h)	
		Coefficient of Performance	
		2.4	3.6
Geothermal Heated Pavement System	2.00	717	486
	1.50	599	407
	1.00	501	342
	0.75	438	300
	0.50	393	270
Hydronic Heated Pavement System with Electric Water Heater	2.00	2,709	
	1.50	2,256	
	1.00	1,880	
	0.75	1,638	
	0.50	1,465	
Hydronic Heated Pavement System with Natural Gas Boiler	2.00	4,040	
	1.50	3,360	
	1.00	2,796	
	0.75	2,434	
	0.50	2,175	

Note. [1]Minimum Coefficient of Performance (COP) = 2.4, [2]Maximim COP = 3.6

As Table 6 demonstrates, more energy is required for geothermal heat pump operation under high snow rate or low COP condition. Geothermal heat pump COP is highly related to soil conditions and the heat pump appliance, so ground-heating conditions should be evaluated before applying HHPS-G. Although COP of HHPS-G can be as low as 2.4, it still requires much less energy to keep apron area snow free under same snow rate compared to HHPS. Because electric water heater has a higher efficiency for water heating, less energy is required for HHPS-E operation than HHPS-NG operation.

Greenhouse gas emission from system operation

Emission factor analysis

Three different types of fossil fuel power plants are considered: coal, natural gas and distillate oil. The phases of 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. GHG emissions of the different life phases of a coal power plant are shown in Table 7.

Table 7. GHG emission factor of coal-fired power plant

Life Cycles of Coal Power Plant	GHG Emission Factor (kgCO$_2$eq/kWh)	Percentage (%)
Surface mining[1]	0.013	1.35
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

Note: [1]Illinois No. 6 coal as an example; electricity demand: 0.0143 kWh/kg of coal; diesel oil demand: 269 m^3/MMT of coal; transportation of diesel oil GHG emission: 2.7 kgCO$_2$eq/L; 0.54 kg coal/kWh electricity produced (Spath et al 1999) (CDM-Executive Board 2001) (EIA 2014).
[2]Jig washing is the technique used in this LCA (Spath 1999).
[3]Distance from mining to power plant: 48 km; GHG emission: 0.01 kgCO$_2$eq/t·km (Chen et al 2013).
[4]Data from US Energy Information Administration EIA-1605 is used (EIA 2007).

Natural gas-fired power plant life cycle includes natural gas extraction, natural gas pretreatment and transportation, and grid electricity production (NETL 2000). GHG emissions of different life cycle phases of natural gas-fired power plant are shown in Table 2.

Since the fuel-fired power plant GHG emissions factor is highly site-specific, a reasonable value based on a previous study of 0.778 kgCO$_2$eq/kWh was assumed (Gagnon et al 2002). To confirm the applicability and use of this factor, it was compared with the US Energy Information Administration (EIA) database (EIA 2014).

In conclusion, a coal (bituminous) fired power plant has a GHG emission factor of 0.96 kgCO$_2$eq/kWh, a natural gas-fired power plant has a GHG emission factor of 0.42 kgCO$_2$eq/kWh, and a distillate oil (No.2) power plant has a GHG emission factor of 0.778 $kgCO_2eq/kWh$. Based on the information provided by U.S. Energy Information Administration (EIA 2014), among these three types of power plant, 58% utilize coal as energy source, 40% use natural gas, and only 2% use distillate oil to generate electricity (EIA 2014).

Natural gas combustion emission factor is 0.181 $kgCO_2eq/kWh$ (EIA 2014), and natural gas facility has an emission factor of 0.004 $kgCO_2eq/kWh$ for natural gas production which is shown in Table 3. So the total emission factor of natural boiler operation is 0.185 $kgCO_2eq/kWh$.

System operation

Energy source used for operating HHPS-G is electricity and GHG emissions from the system are released from the power generation facility as Figure 6 shows. Thus, the sum of the GHG releases from the energy production phase has been calculated as the total GHG emissions from HHPS-G life cycle, which is shown in Figure 7.

Heating source of HHPS-E is supplied by electric water heater, and HHPS-NG is using natural gas boiler for heating. For HHPS-E operation life cycle, electricity is used for water heating and solution circulating pump energy supply. Similar to the GHG emissions from HHPS-G life cycle, there is no GHG directly released from system operation. Thus, the sum of the GHG releases from the energy production phase has been calculated as the total GHG emissions from HHPS with electric water heater. For HHPS-NG operation life cycle, GHG releases from both power plant where electricity is generated and natural gas combustion inside boiler system. So, GHG is released from both energy production phase and operation phase of HHPS-NG operation life cycle. Based on various energy source power plant and different weather conditions, the GHG emissions of HHPS-G and HHPS airport gate area snow removal applications are shown in Table 8.

Table 8. GHG emissions from HHPS-G, HHPS-E, and HHPS-NG (kgCO$_2$/h) of different energy sources under different snow rate conditions

Snow removal System	Snow Rate (in/h)	GHG Emissions (Coal Power Plant kgCO$_2$/h)		GHG Emissions (Natural Gas Power Plant kgCO$_2$/h)		GHG Emissions (Distillate Oil Power Plant kgCO$_2$/h)	
		Coefficient of Performance					
		2.4	3.6	2.4	3.6	2.4	3.6
Geothermal Heated Pavement System	2	690	467	303	205	558	378
	1.5	576	392	253	172	466	317
	1	482	329	211	144	390	266
	0.75	421	288	185	127	341	233
	0.5	378	260	166	114	306	210
Hydronic Heated Pavement System with Electric Water Heater	2	2,598		1,140		2,100	
	1.5	2,162		949		1,748	
	1	1,800		790		1,455	
	0.75	1,568		688		1,267	
	0.5	1,402		615		1,133	
Hydronic Heated Pavement System with Natural Gas Boiler	2	777		757		771	
	1.5	651		631		644	
	1	547		526		540	
	0.75	479		459		472	
	0.5	431		411		424	

Note. [1]Minimum Coefficient of Performance (COP) = 2.4, [2]Maximim COP = 3.6

Table 8 demonstrates that during the increasing of snow rate, more GHG is released from the operation of heated pavement system. Because different energy sources has different emission factors, amount three kinds of fossil fuel power plant, system operation utilized natural gas power plant for electricity support has lower GHG emissions than using the electricity generated from both coal and oil power plant.

HHPS-G has lower GHG emissions than HHPS-E and HHPS-NG for lowest and highest COP conditions in this study. Between HHPS-E and HHPS-NG, HHPS-NG has much lower GHG emissions.

Operating cost

Since the goal of this study is to understand the performance of heated pavement systems applied in airport gate area in removing snow and to help airport owners or operators study different what-if scenarios and to identify airport pavement locations where one or both the systems would have the highest/least environmental impact and operation cost, the system boundaries for both HHPS-G and HHPS in this study include the energy production phase and operation phase. Also according to the lack of practical data and the variety of design approaches, the only difference between the economic behaviors of both heated pavement systems is assumed to be energy cost.

Based on Energy Information Administration (EIA), 2014 Iowa commercial electricity prize is 0.105 \$/kWh (EIA 2014), and natural gas price is about 0.0167\$/kWh (EIA 2014). By using TEA to estimate the operating costs of HHPS-G and HHPS with electric water heater and HHPS with natural gas boiler in removing snow under same snow rate conditions, both HHPS-G and HHPS cost analysis are shown in Table 9.

Table 9. Operating cost of HHPS-G and HHPS

Snow removal System	Snow Rate (in/h)	Operating Cost ($/h)	
		Coefficient of Performance	
		2.4	3.6
Geothermal Heated Pavement System	2	75	51
	1.5	63	43
	1	53	36
	0.75	46	31
	0.5	41	28
Hydronic Heated Pavement System with Electric Water Heater	2	283	
	1.5	236	
	1	196	
	0.75	171	
	0.5	153	
Hydronic Heated Pavement System with Natural Gas Boiler	2	67	
	1.5	56	
	1	47	
	0.75	40	
	0.5	36	

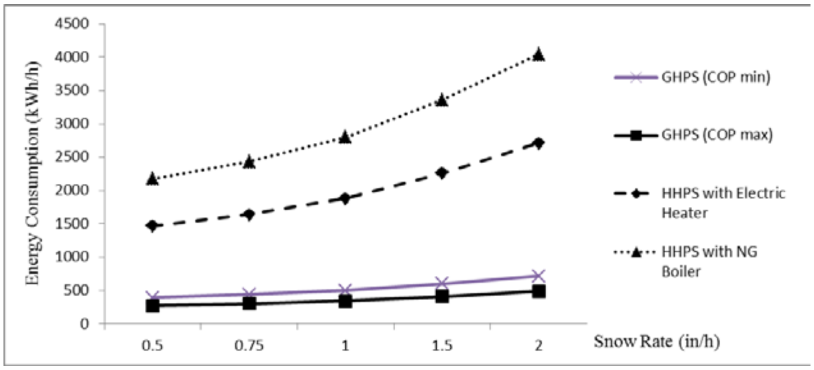
Note. [1]Minimum Coefficient of Performance (COP) = 2.4, [2]Maximim COP = 3.6

Discussions

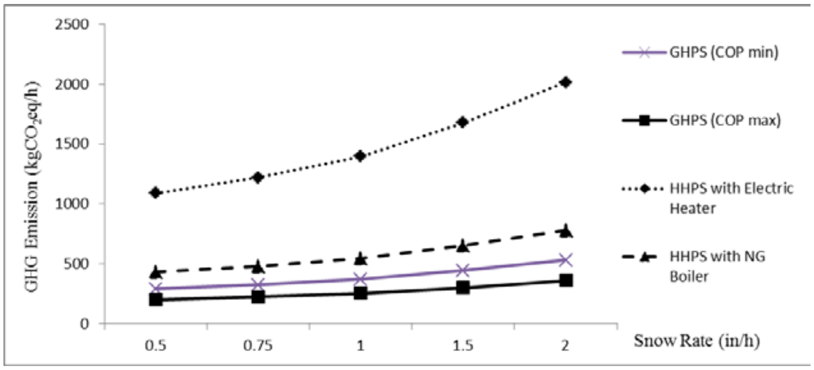
Three alternative heated pavement system operations in airport apron have been analyzed to evaluate the sustainability of such systems. As the analyses for different snow removal system operations demonstrate, several different factors such as snow rates and system efficiencies could affect the sustainability of system operations, and these factors vary among the three types of system operations. Energy consumption, GHG emissions have been compared to estimate which system for removing snow is most sustainable based on the system boundaries and models in this study. Figure 9 below describes the impact of snow rate on energy consumptions, GHG emissions and operating cost of both heated pavement systems. When ambient temperature and wind speed are stable, more energy is required for heated pavement system operations to keep the airport apron out of snow during the increasing of snow rate.

According to the differences of various energy based power plant emission factors. Electricity generated from a natural gas power plant has the least GHG emission factor among three kinds of energy source power plant, which is demonstrated in Table 8. In Figure 9, total GHG emissions from both heated pavement systems are multiplied by different power plant ratio. Since GHG emissions and operating cost are determined by energy consumptions, there would be more GHG emissions and higher operating cost while energy consumptions increase. That is why more GHG will be released and higher cost needs to be paid during snow rate increases as Figure 9 (b) and (c) show.

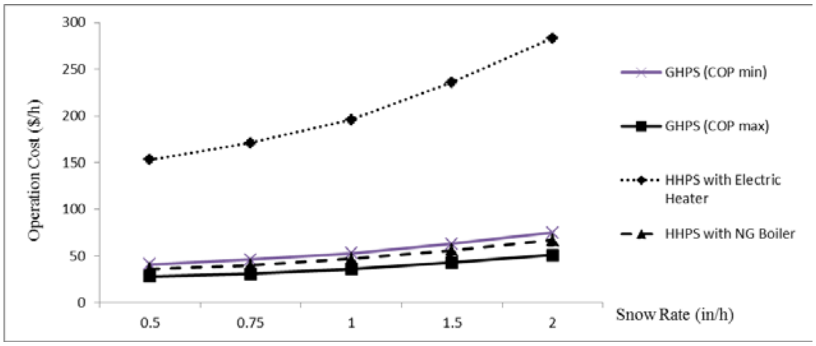
(a)



(b)



(c)



Note. COP is coefficient of performance

Figure 9. (a) Energy consumptions, (b) GHG emissions and (c) energy cost of HHPS-G and HHPS with electric water heater and HHPS with natural gas boiler under 5 different snow fall conditions.

Since GSHP has a higher coefficient of performance than the efficiency of electric water heater or natural gas boiler, using GSHP as energy source can save a lot of energy in snow removal. Applied in the same area of apron under same climate condition, HHPS-G requires about 10 times less energy than HHPS with electric water heater and 6 times less than HHPS with natural gas boiler under different snow rate conditions. Also HHPS-G generates less GHG compared to HHPS according to the low energy consumption. As Figure 8 demonstrates, HHPS-G has a lower energy demand, GHG emissions and operating cost than HHPS.

Because heating system efficiency has a significant impact on energy requirement, and natural gas boiler has a relatively lower efficiency compared to electric water heater, HHPS with natural gas boiler requires more energy input to melt same amount of snow. As Figure 10 shows, although HHPS with natural gas boiler has a highest energy requirement, its GHG emission is about 3 times less than HHPS with electric water heater. Also, since the price of natural gas is about 3 times less than electricity, the operating cost of HHPS with natural gas boiler is about 2 times lower than the cost of HHPS with electric water heater.

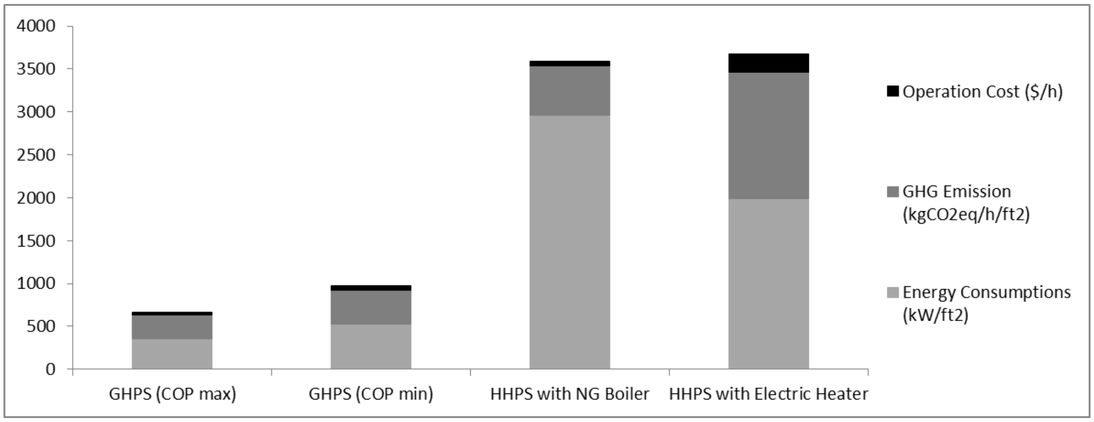


Figure 10. Energy requirements and GHG emissions of HHPS-G and HHPS with electric water heater and HHPS with natural gas boiler for different snow rate conditions.

Although HHPS-G has much less energy consumptions, GHG emissions and operating cost compared to the HHPS, it is highly depended on the location where there is sufficient geothermal energy supply. As the Figure 9 (c) shows, HHPS-G with 2.4 COP has a higher operation cost than HHPS with natural gas boiler. According to the low GHG emissions and operating cost of natural gas boiler, HHPS could be a low environmental impact as an alternative of HHPS-G. However, it requires much more energy than HHPS-G. Instead of using the natural gas boiler, natural gas furnace which has a higher efficiency has been used in many applications. Therefore, HHPS with natural gas furnace could have a potential to be a low energy consumption and low environmental impact system for snow removal.

Conclusion and Recommendations

Heated pavement systems is able to solve the ineffective apron snow removal problems caused by traditional snow removal strategy. With the specific goal of carrying out a comparative assessment of the energy requirement, GHG emissions, and operating cost of three different hydronic heated pavement systems, HHPS-G, HHPS-E, and HHPS-NG, several simplifying assumptions were made due to lack of publically available data. The overall findings (pertaining to the scope and specific assumptions made in this study) and future recommendations are summarized below.

Findings

- HHPS-G with a coefficient of performance (COP) as low as 2.4 still results in less energy consumption, fewer GHG emissions, and lower operation costs than other two types of hydronic heated pavement systems under the same snow rate conditions.
- Snow rate determines energy requirement, GHG emissions and operating costs of HHPS-G and HHPS. While the snow rate is higher, the heated pavement systems require more energy which causes more GHG emissions and higher operating cost.
- Energy source determines GHG emission. Although HHPS-NG operation requires more energy, it has lower global warming potentials and operation cost than HHPS-E operation for different snow rate conditions. From an environmental impact perspective, using natural gas for water heating, with a relatively low emission factor, has the potential to replace electricity as a more environmentally friendly energy source.
- If the efficiency of natural gas boiler energy extraction is improved, hydronic heated pavement system using natural gas boiler could reduce energy requirement, GHG emissions and save more costs. HHPS-NG can have a better viability from the environmental and economic perspectives, and it can be a better alternative for place where there is not enough geothermal energy.

Recommendations

- The entire life cycle of a heated pavement system, including construction and maintenance stages and a more comprehensive life cycle of traditional snow removal systems, could be assessed to provide more informed information.
- The system equipment sizing and choice of energy source can be critical in enabling geothermal heated pavement systems and hydronic heated pavement systems more environmental friendly.
- Traditional snow removal approaches and other types of heated pavement system, like using electrically heated pavement system for apron snow removal instead of using hydronic heated pavement system, can be studied.

References

American Council for an Energy-Efficient Economy. (2012). Water Heating. (cited on Jan 14th 2015). Available from: http://www.aceee.org/consumer/water-heating

American Society of Heating, Refrigerating and Air-Conditioning Research. (2003). ASHRAE Handbook: HVAC Applications IP Edition. *Atlanta: ASHRAE Engineers, Inc*. Atlanta, GA, USA.

Board on Atmospheric Sciences and Climate (BASC). (2011). Division on Earth and Life Studies (DELS) and National Research Council. America's Climate Choices. Washington, DC: The National Academies Press.

CDM-Executive Board. (2001). Clean Development Mechanism Project Design Document Form. Bonn, Germany: CDM-SSC-PDD Version 03. (cited on Jul 14th 2014). Available from: http://www.dnv.com/focus/climate_change/Upload/DNV_Vers%C3%A3o%20Ingl%C3%AAs_PDD%2001_Ecobio_20mar.pdf

Chapman WP. Design of snow melting systems. Heating and Ventilating, (April): 95 and (November):88; 1952.

Chen, G., Chen, B., Zhou, H., Dai, P. (2013). Life Cycle Carbon Emission Flow Analysis for Electricity Supply System: A Case Study of China. Energy Policy. Vol. 61, 1276-1284

Energy Information Administration. (2007). Electricity Emission Factors. Publication EIA-1605, OMB No. 1905-0194. Washington, DC, USA.

Energy Information Administration. (2014). How Much Carbon Dioxide is Produced per Kilowatthour When Generating Electricity with Fossil Fuels? (cited on Jul 14th 2014). Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11.

Energy Information Administration. (2014). How Much Coal, Natural Gas, or Petroleum Is Used to Generate a Kilowatthour of Electricity?" (cited on Jun 14th 2014). Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=6.

Energy Information Administration. (2014). Natural Gas Weekly Update. Washington, DC. (cited on Nov 2nd 2014). Available from: http://www.eia.gov/naturalgas/weekly/.

Energy Information Administration. (2014). Table 5.6.A. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. (cited on Nov 2nd 2014). Available from: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

Energy Information Administration. (2014). What Is U.S. Electricity Generation by Energy Source? Washington, DC. (cited on Nov 2nd 2014) Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

Energy Star. (2012). Geothermal Heat Pumps Key Product Criteria. Washington, DC. (cited on Jan 14th 2015). Available from: https://www.energystar.gov/index.cfm?c=geo_heat.pr_crit_geo_heat_pumps

Environmental Protection Agency. (2014). Emission Factors for Greenhouse Gas Inventories. (cited on Oct 19th 2014). Available from: http://www.epa.gov/climateleadership/documents/emission-factors.pdfJ

Federal Aviation Administration. (20121996). Airport Winter Safety and Operations Surface Movement Guidance and Control System. Publication FAA 150/5200-30C120-57A. Washington, DC: U.S. Department of Transportation.

Gagnon, L., Belanger, C., Uchiyama, Y. (2002). Life Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001. Energy Policy. Vol. 30, 1267-1278.

Intergovernmental Panel on Climate Change. (2015). Direct Global Warming Potential. Switzerland: IPCC Fifth Assessment Report: Climate Change 2013: The Physical Science Basis. (cited on Feb 19th 2015) Available from: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter01_FINAL.pdf.

Kreith, F., Goswami, D.Y. (2001). Energy Management and Conservation Handbook. *CRC Press*. Boca Raton, FL, USA.

National Energy Technology Laboratory. (2000). Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant. Publication DOE/NETL-403/110509. Pittsburgh, PA, USA.

PexUniverse.com. (2009). PEX Tubing Technical Specifications and General Installation Recommendations. (cited on Aug 18th 2014) Available from: http://www.pexuniverse.com/pex-tubing-technical-specs.

Robert, H., Francis, M., Villiam, S., Seth, Y. (2010). Planning and Design of Airport, Fifth Edition. Technology & Engineering. *Granite Hill Publishers.* U.S.

Shen, W., Gopalakrishnan, K., Kim, S., and Halil, C. (2014). Carbon Footprint Analysis of Geothermal Heated Airport Pavements. TRB 94th Annual Meeting Compendium of Papers, 15-4790. (cited on Jan 16th 2015). Available from: http://amonline.trb.org/trb57535-2015-1.1793793/t003-1.1821686/596-1.1821777/15-4790-1.1821821/15-4790-1.1957012?qr=1

Shen, W., Gopalakrishnan, K., Kim, S., and Halil, C. (2015). Assessment of Greenhouse Gas Emissions from Geothermal Heated Airport Pavement System. Accepted and will be published in IJPRT.

Spath, P.L., Mann, M.K., Kerr, D.R. (1999). Life Cycle Assessment of Coal-Fired Power Production. Golden, CO: NREL/TP-570-25119. (cited on Jul 14th 2014). Available from: http://www.nrel.gov/docs/fy99osti/25119.pdf

Subsequent Distribution Office. (2001). Airside Use of Heated Pavement Systems. Publication FAA 150/5370-17. Washington, DC: U.S. Department of Transportation.

The Canadian Renewable Energy Network. (2002). Commercial Earth Energy Systems: A Buyer's Guide. Natural Resources Canada. (cited on Nov 20th 2014). Available from: http://publications.gc.ca/collections/Collection/M92-251-2002E.pdf

Viega. (2003). S-no-Ice® Snow Melting System Installation Manual. Wichita, KS, USA. (cited on Nov 2nd 2014). Available from: http://www.viega.us/cps/rde/xbcr/en-us/Viega_S-no-ice_Snow_Melting_System.pdf

Wilo. (2009). Circulating Pumps. (cited on Jul 29th 2014) Available from: http://www.majo.rs/page_files/page_97/A1-Glandless%20Pumps%20-%202009.pdf.

CHAPTER 5- LIFE CYCLE ASSESSMENT OF HEATED APRON PAVEMENT SYSTEM OPERATION

A paper to be submitted for presentation on 2016 Transportation Research Board (TRB) 95th Annual Meeting and publication in Transportation Research Record: Journal of the TRB

Weibin Shen[1*], Halil Ceylan[*], Kasthurirangan Gopalakrishnan[*], Sunghwan Kim[*], Peter C. Taylor[*], and Chris Robert Rehmann[*]

Abstract

Although snow removing efficiency and economic benefits of heated pavement systems (HPS) have been assessed by previous studies, their environmental impact is not well known. Airport facilities offering public or private services need to evaluate the energy consumption and global warming potential of different types of snow and ice removal systems. The operations of hydronic heated pavement system using geothermal energy, hydronic heated pavement system using natural gas furnace, electrically heated pavement system, and traditional snow removal system (TSRS) are estimated and compared in this study using the hybrid life cycle assessment methodology. Based on the system models assessed in this study, HPS application in the apron area seems to be a viable option from an energy or environmental perspective to achieve ice/snow free pavement surfaces without using mechanical or chemical methods. TSRS methods typically require a higher energy demand and they produce more greenhouse gas (GHG) emissions compared to HPS during the operation phase, under the conditions and assumptions considered in this study. Also, heated pavement system operations require less energy and have less GHG emissions during a snow event with a small snow rate and a long snow period.

---

[1] Primary researcher and author

[*] Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA, 50010

Introduction

Typical mechanical equipment for snow and ice removal are usually designed for large areas, like runway, in order to increase efficiency. However, it makes the equipment difficult to operate in a narrow space like the airport apron. Although smaller snow and ice removal machines can be used instead to remove snow and ice in apron areas, they are not as efficient as the big equipment used in runway and require more labors and time. All these issues on traditional snow and ice removal methods could cause airline delay problems, high operation costs and airport crew accident happening during snow and ice removal activities. In order to prevent these problems, heated pavement systems are being studied as the alternative strategy to traditional snow and ice removal system applied in apron areas (Ceylan 2015). The study recently reported by Shen et al. (Shen et al 2015) suggested hydronic heated pavement system, as one type of heated pavement systems, could have sustainable benefits to be used for apron snow and ice removal applications.

The primary goal of this study is to provide a more comprehensive understanding of different snow and ice removal system operation not only from an energy consumption perspective but also from an environmental impact aspect, and to help the airport snow and ice removal system user make a more informed decision. The secondary goal is to find out the inventories or steps which contribute the most burdens for each snow and ice removal system operation in order to provide guidance to minimize system energy usage and environmental impacts. Energy consumption and global warming potential effects of four different kinds of snow and ice removal systems applied in airport apron to remove same amount of snow under different snow fall conditions are evaluated and compared to achieve the goals. These systems are hydronic heated pavement system using geothermal energy (HHPS-G), hydronic heated pavement system using natural gas furnace (HHPS-NG), electrically heated pavement system (EHPS), and traditional snow and ice removal system (TSRS).

As the very first life cycle assessment (LCA) study on different types of heated pavement system application as alternative apron snow and ice removal strategy, this study gives a general overview of the life cycle phases in different apron snow and ice removal strategies. Since heated pavement systems are relatively new technologies for airport snow and ice removal application, the detailed information related to its construction and maintenance (frequency, energy consumption, etc.) that are required to conduct a full-fledged LCA study are not available (Shen et al 2015). Therefore, the scope of this study is only to focus on the impacts of snow and ice removal operation phase and related life cycle stages.

For the sake of simplicity, system boundaries of four different snow and ice removal systems only include sectors which are defined as processes of snow and ice removal operation. Snow and ice removal system can be generally classified into four sub-system processes: power generation, material production, snow and ice removal application, and waste treatment. Therefore, the operation system boundary in this study includes these four sectors. A “well to gate” assessment for power generation facility was applied to understand the greenhouse gas (GHG) emission from power production phase. The product upstream has a relative large ratio of impact in a product life cycle. An economic input-output life cycle assessment (EIO-LCA) on-line model was applied in material production stage, and its system boundary was defined in the 2002 US Benchmark version of the EIO LCA model (Weber et al 2015).

Life cycle inventories are significantly related to the system boundary (SAIC 2006). Because this study is to evaluate the energy consumption and global warming potential of different airport apron snow and ice removal system operations, inventories that contribute efforts (e.g., increasing thermal conductivity or preventing heat lost) to snow and ice removal and their upstream stage life cycle (e.g., raw material extraction) are assessed. Life cycle inventories of the systems for snow removing were collected through previous studies, government official documents or company manual scripts and defined in following sections.

Methodology

Types of heated pavement systems

Hydronic heated pavement systems generally use fossil-fuel heaters, like natural gas water boilers/furnaces or electric water heaters, as energy sources for warming up the propylene glycol solution usually used as a heat-transfer medium, and circulating it inside a cross-linked polyethylene (PEX) tube under the pavement (FAA 2011).

Generally speaking, a natural gas boiler has an efficiency of 60% and an electric water heater has an efficiency of 90% (ACEEE 2015). However, systems utilizing natural gas combustion for heating could be more sustainable than systems using electricity, because natural gas combustion has a much lower greenhouse gas emission factor than electricity generation does. Natural gas furnaces are also considered to have higher efficiencies than traditional gas boilers (Energy. Gov 2015). From the aspect of sustainability, a natural gas furnace was evaluated as the heating source for HHPS-NG in this study.

New technology can be innovative in combination with using renewable energy to reduce energy cost and environmental impact. Geothermal power is one of the sustainable energy technologies commonly used for electricity generation, and it was also evaluated in a previous study as a heating source for hydronic heated pavement system for bridge snow-melting applications (Xie and Whiteley 2007).

The difference between HHPS-G and normal HHPS is that HHPS-G does not utilize fossil fuels or electricity for heating but instead uses a ground-source heat pump (GSHP) to extract geothermal energy to warm up a hot solution and circulate it through embedded pipes in the pavement using a circulating pump to heat up the pavement and melt the ice. GSHP can also supply space heating by accessing heat in the soil (Kreith and Goswami 2008). It is commonly applied in regions without access to high temperature geothermal resources. GSHP takes the heat absorbed in the land from solar energy using a ground heat exchanger. There are three types of ground heat exchanger systems, a direct exchange geothermal system, a closed loop geothermal system, and an open loop geothermal system. Considering the relatively lower efficiency, longer and larger pipe requirements and high construction cost of both closed-loop and open-loop systems (MNGHPA 2009), this study focuses on use of direct exchange based HHPS-G. The direct-exchange system uses a single loop to circulate fluid in contact with the ground to directly extract or dissipate heat.

In contrast to HHPS-G and HHPS-NG using heated solution as a heat-transfer media, an electronically heated pavement system (EHPS) utilizes electric radiant heat from heated wires/panels to directly warm up the concrete pavement surface (FAA 2011). Another difference of EHPS is that, rather than using buried PEX tubes in the concrete, polyacrylonitrile (PAN) based carbon fiber is added during the Portland cement concrete mixing process to transform the normal concrete into conductive concrete (Hymers 1980). Conductive concrete pavement is designed for increasing electrical conductivity of the slab to reduce energy consumption.

LCA for apron snow removal systems

As a technique for assessing the environmental and potential impacts associated with a product, process, or system, 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 (EPA 2014). A hybrid LCA, including both a process-based LCA and an IO-LCA, can be adopted to analyze and compare 4 different types of snow-removal systems. A process-based LCA provides detailed information with respect to the assessment of specific processes and is considered an effective methodology for system/product comparisons (Melissa 2007). IO-LCA utilizes economic transactions for a particular product to trace out the energy requirements and environmental impacts of its production. According to ISO (International Organization for Standardization), a LCA is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040 1997).

In this study, four different snow-removal systems, HHPS-G, HHPS-NG, EHPS and TSRS, are individually analyzed. Each system is designed for a short to medium range airliner apron area of 19,000 ft^2 (Aircraft Technical Data & Specifications 2015). The systems are analyzed at 20°F air temperature, 10 mile per hour (mph) wind speed, and under 0.5 in/h, 0.75 in/h, 1 in/h, 1.5 in/h and 2 in/h snowfall rate conditions. Based on the lifetime of general concrete pavement, heated pavement systems are assumed to be designed for a 20-year life (CTC & Associates LLC WisDOT RD&T Program 2004). Modelling equations utilized in the analysis are firstly summarized in the following subsection for further discussions.

Modelling equations

Pavement idling energy consumption

In this study, a heated pavement surface must heat up to 32°F, and the energy consumption (q_i) is given by a pavement idling equation:

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

in which 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).

Snow melting energy consumption

After concrete slab surface is heated to 32°F, heated pavement systems utilize heat to melt snow, in order to understand the heat (q_o) required for melting snow by using heated pavement system, the following Equation 2 was applied (Chapman 1952):

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

in which, 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 (dimensionless), 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:

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

where, s = rate of snowfall (inches of water equivalent per hour), D = density of water equivalent of snow (62.4 lb/ft^3), $c_{p,ice}$ = specific heat of snow (0.5 Btu/lb/°F), $c_{p,water}$ = specific heat of water

(1 Btu/lb/°F), t_s = melting temperature (32°F), t_f = liquid film temperature (33°F), t_a = ambient temperature (20°F), and c_1 = conversion factor (12 in/ft).

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

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

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

The heat of evaporation (qe) 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 (14.7 lb/ft^3), h_m = mass transfer coefficient of concrete slab (1.7 ft/h), W_f = humidity ratio of saturated air at film surface temperature at 33°F (0.003947 lb_{vapor}/lb_{air}), W_a = humidity ratio of ambient air at 20°F (lb_{vapor}/lb_{air}), and h_{fg} = heat of evaporation at the film temperature at 33°F (1074.64 Btu/lb).

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

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

where, hc = convection heat transfer coefficient for turbulent flow (2.85 Btu/h·ft^2·°F), δ = Stephan-Boltzmann constant (0.17×10^{-8} Btu/h·ft^2·°R^4), ε_s = emittance of wet slab (0.9), T_f = liquid film temperature (492.67°R), T_{MR} = mean radiant temperature of surroundings (479.67°R).

Geothermal heat pump operating energy demand

Energy consumption (E) in MJ/h of geothermal heat pump is calculated by the Equation 7, the equation shown below (Mix 2006):

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

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

Hydronic system flow rate

Flow rate calculation is based on the equation below Equation 8 (Viega 2015):

$$Q = \frac{q_0}{Cp \cdot \Delta T} \cdot (1 + M) \tag{8}$$

where, Q = flow rate (gpm), q_o = heat required to melt snow (Btu/h), Cp = heat capacity of water (8.3 Btu/gallon·°F), ΔT = temperature drop (°F), M = flow rate increase multiplier (8.5% for 40% by volume glycol mixture)

Circulating pump operating energy demand

To calculate the energy demand for circulating pump, the following Equation 9 for required water horsepower (WHP) in HP was applied (Viega 2015):

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

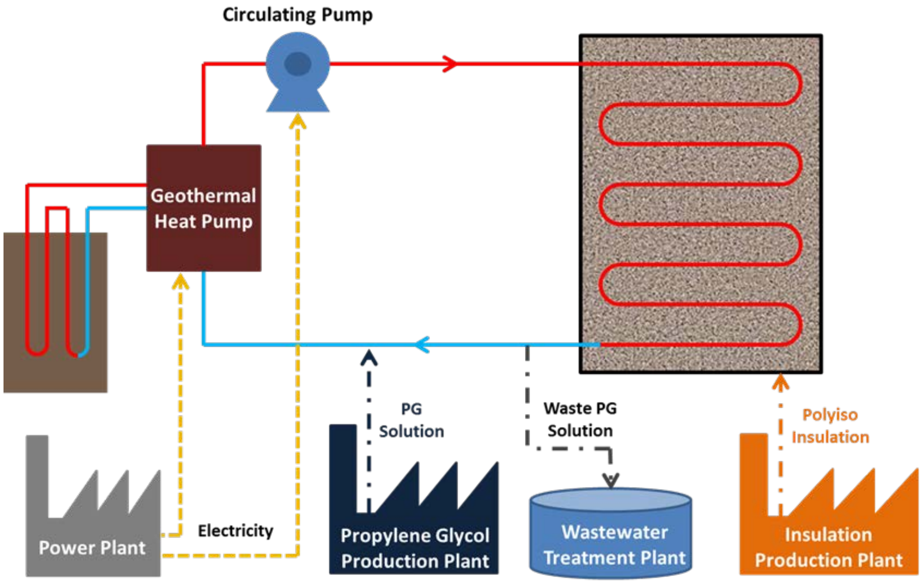
in which, WHP = water horsepower (HP), Q = flow rate (gpm), H = total head (ft), SG = specific gravity of heated solution (1 of water and 1.034 of 40% propylene glycol), n = pump efficiency (%).

Case 1: Operation of Hydronic Heated Pavement System Using Geothermal Energy

HHPS-G operation system boundary

HHPS-G utilizes geothermal energy as a heating source to warm up antifreeze solution circulating under the pavement in order to keep the concrete slab surface without snow. Based on the methodology, the HHPS-G operation life cycle can be divided into 4 sub-life cycles, which are power-generation life cycle, a snow-removal operation life cycle, a material-production life cycle (antifreeze and insulation layer production life cycle), and an antifreeze-wastewater treatment life cycle. The HHPS-G operation flow chart and system boundary of the HHPS-G operation life cycle is shown in Figure 11 below.

(a)



(b)

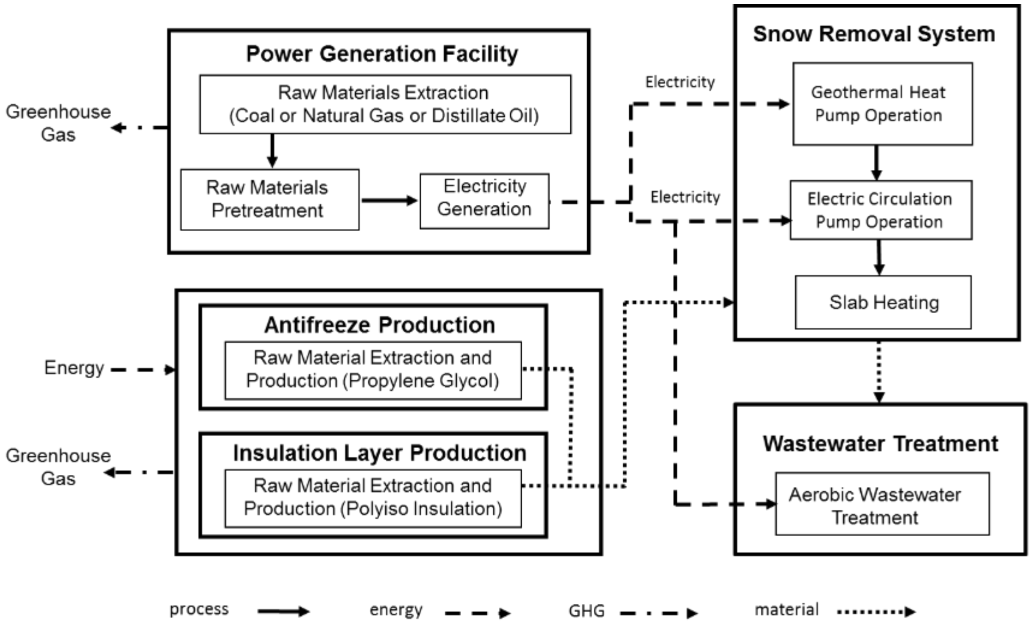


Figure 11. (a) HHPS-G operation flow chart; (b) System boundary of HHPS-G operation

HHPS-G operation model

A HHPS-G uses a direct exchange ground source heat pump (GSHP) to extract geothermal energy from the ground to warm hot solution flowing through embedded pipes in the pavement in order to heat up the pavement and melt the ice. Energy required for snow melting is calculated by applying equations (1) to (6). Based on geothermal heat pumps key product criteria, the coefficient of performance (COP) of a direct ground exchange heat pump can be as high as 3.6 (Energy Star 2015). To understand the behavior of HHPS-G applied in different geothermal conditions, the COP of geothermal heat pump is assumed to be 2, 2.5, 3 and 3.6 in this study. Energy consumption of heat pump can be calculated by coordinating with Eequation (7).

System design is based on the energy requirement for snow melting (Viega 2015). The heaviest snow fall in this study is 2 in/h, therefore, systems at least need to be feasibly operational under 2 in/h snow rate conditions. Based on the operational energy requirement for snow melting under 2 in/h snow rate, PEX pipe spacing in concrete is assumed to be 9 inches in order to support enough energy. Tubing length has a multiplier of 1.5 ft/ft^2, therefore so 28,500 ft of PEX tube is required to be installed under a 19,000 ft^2 apron area. Piping circuit length is designed to be 400 ft and a total of 71 circuits are is required. HHPS-G circulates 40% by volume of propylene glycol solution in ¾ inch cross-linked polyethylene (PEX) pipe. Dependent on the design for 2 in/h snow rate condition, the solution circulating flow rate is can be calculated through using equation (8) to obtain and a flow rate is 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. A glandless circulating pump with 50% to 70% efficiency (Wilo 2013) can be used, and so 60% efficiency circulating pumps are applied in the systems in this situation.

Because 40% by volume of propylene glycol solution has a very similar density to water, the unit volume of solution in ¾ inch pipe is about 0.018 gal/ft, and a total of 513 gallon of solution is required for HHPS-G operation. The price of propylene glycol is about 1.6 $/kg, so by using IO-LCA software GREET, the energy to produce 1 kg propylene glycol requires is 27.57 kWh energy and will release 6.46 kgCO_2eq. The solution needs to must be checked and replaced every year (Raypak, Inc 2015), and the waste solution can be discharged and treated in a municipal wastewater treatment plant.

A Polyiso insulation layer is installed on the bottom and edge of top 4 inches of the concrete slab to prevent heat loss, and the back and edge heat loss of the heated pavement systems is assumed to be 0% (Viega 2015). Based on the description of life cycle inventory assessment, a 1.5 inch thick layer of Polyiso insulation with a 9.8 of thermal resistance RIP (US unit, using Inch-Pound measures) was assumed to be used in the heated pavement system whose life time with a lifetime is about which is the same as a that of normal concrete pavement life time. 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 (NSF International 2015).

HHPS-G operation energy consumptions

A heated-pavement system applies hydronic heat or radiant heat through conductive media to melt snow. To evaluate how much energy is needed to operate each heated pavement system, the energy requirement for concrete pavement idling and snow melting should first be analyzed. Because of the insulation installed in top 4 inches of concrete of each heated pavement system, zero back and edge losses were assumed. The top 4-inch concrete pavement is considered to be idled in this study. Normal concrete has a density of 150 lb/ft^3 (Washington DOT 2015) and a specific heat of 0.2 Btu/lb·°F (Lamond and Pielert 2006). A heated-pavement system warms the slab surface to a certain temperature to melt snow. At 32°F, snow is able to melt with extra energy input, so the strategy of using a heated-pavement system idling operation in this study maintains a pavement surface temperature as 32°F.

The energy consumption for different snow rate conditions, 0.5 in/h, 0.75 in/h, 1 in/h, 1.5 in/h and 2 in/h, is calculated by using Equation (1) through (5). The resulting energy requirements for snow melting under different snow rates are therefore 134 Btu/h·ft^2, 153 Btu/h·ft^2, 173 Btu/h·ft^2, 211 Btu/h·ft^2 and 251 Btu/h·ft^2. Based on Equation (1), to warm up 19,000 ft^2 of slab surface from 20°F to 32°F requires 2405 MJ. The functional unit is time-based in this study, and allocating energy consumption of pavement idling depends on the snow periods, assumed to be 1 h, 4h, 8 h, and 12 h.

The energy used for operating a geothermal heated pavement includes the energy used for geothermal heat pump and circulating pump operation, antifreeze solution production, insulation production, and solution waste treatment. Energy consumption of geothermal heat pumps with different coefficients of performance are calculated by applying Equation (7) with the results based on different snow rates shown in Table 10 below.

Table 10. Energy consumptions of geothermal heat pump for different snow periods and rates

Snow Period (h)	Snow Rate (in/h)	Energy Consumptions of Geothermal Heat Pump (MJ/h)			
		Coefficient of Performance (COP)			
		2	2.5	3	3.6
1	0.5	3,058	2,657	2,387	2,165
	0.75	3,219	2,786	2,497	2,256
	1	3,444	2,965	2,647	2,382
	1.5	3,797	3,247	2,883	2,578
	2	4,221	3,587	3,165	2,813
4	0.5	2,269	1,868	1,598	1,376
	0.75	2,430	1,997	1,708	1,467
	1	2,655	2,176	1,858	1,593
	1.5	3,008	2,458	2,094	1,789
	2	3,432	2,798	2,376	2,024
8	0.5	2,138	1,737	1,467	1,245
	0.75	2,299	1,866	1,577	1,336
	1	2,524	2,045	1,727	1,462
	1.5	2,877	2,327	1,963	1,658
	2	3,301	2,667	2,245	1,893
12	0.5	2,131	1,730	1,460	1,238
	0.75	2,292	1,859	1,570	1,329
	1	2,517	2,038	1,720	1,455
	1.5	2,870	2,320	1,956	1,651
	2	3,294	2,660	2,238	1,886

Note. Equation (1) - (6) are used for energy consumption of geothermal heat pump calculation

As the Table 10 demonstrates, more energy is required for geothermal heat pump operation under high snow rate or low COP condition. Geothermal heat pump COP is highly related to soil conditions and the heat pump appliance, so ground-heating conditions should be evaluated before applying HHPS-G. Because some areas don't have sufficient geothermal energy, HHPS-G requires relatively high energy consumption to support heating or else the system might not function. Table 10 also shows that when the snow period is longer, energy consumption of the heated pavement system operations is less.

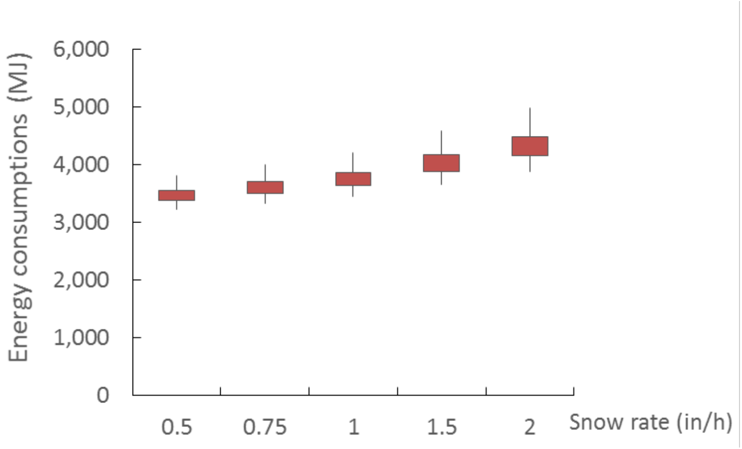
Using Equation (8), the total flow rate of an HHPS-G system is calculated as 490 gpm and a 125 ft pressure drop is determined based on a Viega manual script. Since a 60% efficient horsepower circulating pump is selected, the energy circulating pump demand is calculated as 26 hp using Equation (9).

The area of the apron is assessed to be 19,000 ft^2, and its length and width are 146 ft and 130 ft, respectively. The back and the top 10-inch edge of the apron are covered by an insulation layer to prevent heat loss and save energy, and the total required insulation layer area is about 19,184 ft^2. As the HHPS-G model shows, the insulation layer production requires 8.66 MJ/ft^2 of energy, so a total of 46,148 kW is consumed to produce 19,184 ft^2 insulation layers. Because the insulating layer lifetime is assumed the same as the pavement design lifetime, i.e., 20 years, energy consumption per hour of insulation layer production allocated is about 0.94 MJ/h.

As the HHPS-G operation model shows, 808 kg of antifreeze (propylene glycol) is used for one year. Since the functional unit in this study is per hour, inventories are converted into hour-based values and the propylene glycol demand is 90 g/h. Input-output LCA is conducted in analyzing antifreeze production stage using software GREET (GREET 2013), and the energy required for producing 90 g/h of propylene glycol is 9 MJ/h.

Propylene glycol has a COD content of about 1.68 kg/kg and the result must be allocated on an hourly basis. 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/kgCOD (Geest and Kiechle 2010), so the energy consumption of antifreeze waste treatment is 0.54 MJ/h. In summary, the total energy consumption of HHPS-G operation under different snow rates and an average snow period of 6 h and total energy consumption of HHPS-G operation for different snow periods at average snow rates are shown in Figure 12 (a) and (b) below.

(a)



(b)

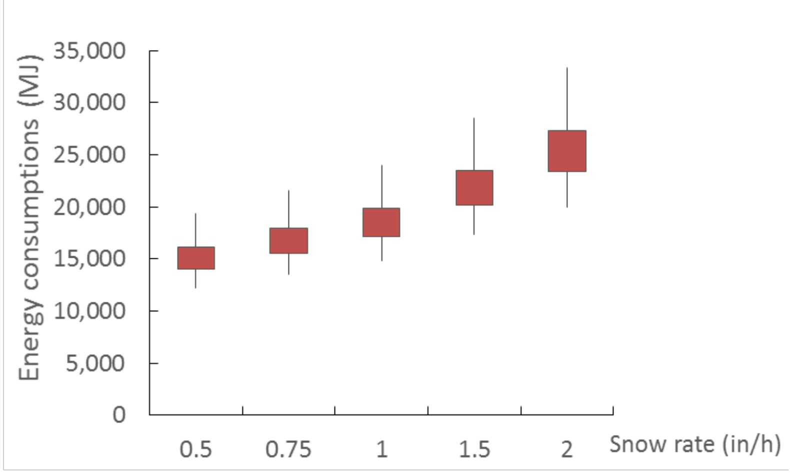


Figure 12. (a) Energy consumptions of HHPS-G operation life cycle against snow rates with 1 h snow period; (b) Energy consumptions of HHPS-G operation life cycle against snow rates 12 h snow period

As the Figure 12 (a) demonstrates, the coefficient of performance 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 12 (b) shows the influence of the COP geothermal heat pump.

HHPS-G operation GHG emissions

GHG emission factors of electricity, natural gas and diesel oil

Three different types of fossil fuel power plants are considered: coal, natural gas and distillate oil. The phases of 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. GHG emissions of the different life phases of a coal power plant are shown in Table 7.

A natural gas-fired power plant life cycle includes natural gas extraction, natural gas pretreatment and transportation, and grid electricity production (NGCC 2000). GHG emissions for different life cycle phases of a natural gas-fired power plant are shown in Table 2.

Since the fuel-fired power plant GHG emissions factor is highly site-specific, a reasonable value based on a previous study of 0.778 kgCO$_2$eq/kWh was assumed (Gagnon et al 2002). To confirm the applicability and use of this factor, it was compared with the US Energy Information Administration (EIA) database (EIA 2015).

In conclusion, a coal (bituminous) fired power plant has a GHG emission factor of 0.96 kgCO$_2$eq/kWh, a natural gas-fired power plant has a GHG emission factor of 0.42 kgCO$_2$eq/kWh, and a distillate oil (No.2) power plant has a GHG emission factor of 0.778 kgCO$_2$eq/kWh. Based on the information provided by U.S. Energy Information Administration (EIA 2015), among these three types of power plant, 58% utilize coal as energy source, 40% use natural gas, and only 2% use distillate oil to generate electricity.

As Table 2 demonstrates, natural gas extraction, pretreatment, and transportation has a GHG emission factor of 4.4×10^{-3} $kgCO_2eq/kWh$ electricity, and producing 1kWh electricity required 7.86 ft^3 natural gas (EIA 2015) whose heat value is about 1000 Btu/ft^3 (Engineering Tool Box 2015). Thus, the natural gas production emission factor is 5.6×10^{-4} $kgCO_2eq/ft^3$. Based on IPCC, the GHG emission of natural gas combustion is 0.18 $kgCO_2eq/kWh$.

The GHG emission from diesel oil extraction and pretreatment is about 0.19 $kgCO_2eq/kWh$ (Shen et al 2014) and 0.27 $kgCO_2eq/kWh$ (Alternative Fuels Data Center 2014) from diesel oil combustion. To sum up, GHG emission factors of different fossil fuel applications are shown in Table 11 below.

Table 11. GHG emission factors of electricity, natural gas and diesel oil

Fossil Fuel Application Emission Factors		**Value ($kgCO_2eq/kWh$)**
Electricity emission factor	Coal power plant	0.96
	Natural gas power plant	0.42
	Distillate oil power plant	0.78
Natural gas combustion emission factor[1]		0.18
Diesel oil combustion emission factor[2]		0.46

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

GHG emission analysis

A HHPS-G utilizes electricity to operate a geothermal heat pump and a circulating pump for extracting geothermal energy and circulating heated propylene glycol antifreeze solution, and their energy requirements are shown in Table 10 above. There is thus no direct GHG released from both pumping operations; the GHG emissions are actually from the energy production stage. By applying GHG emission factors from different types of power plants and percentages of each power application in the US, GHG emissions from the electrical power production used for the operations of the geothermal heat pump and the circulating pump are shown in Table 12 below.

Table 12. 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 ($kgCO_2eq/h$)**			
		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

[1] COP=coefficient of performance

GHG emission factor of 1.5 inch thick insulation layer is about 0.39 $kgCO_2eq/ft^2$ (NSF International 2015). A total of 19,184 ft^2 insulation layers are required and the total GHG released from insulation layer production is about 7,482 $kgCO_2eq$. Because the insulation lifetime is assumed to be 20 years, the GHG emission result is converted into an hour-based value of 0.043 $kgCO_2eq/h$.

40% by volume of propylene glycol antifreeze is used in HHPS-G, and the GHG emission factor of antifreeze production is 6.46 kgCO_2eq/kg chemicals based on GREET (Sripple 2001). Converting the usage of propylene glycol to an hourly basis results in an hourly requirement of 0.09 kg antifreeze per hour. Therefore, the total GHG emissions from antifreeze production are allocated as 0.6 kgCO_2eq/h.

Waste 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. 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 US, GHG emissions from the electrical power production used for wastewater treatment are found to be 0.1 kgCO_2eq/h.

Similar to the energy consumption behavior, HHPS-G operation GHG emissions depend on snow rate conditions and COP of the geothermal heat pump mainly based on the model and assumptions made in this study. In conclusion, taking a snow period of 12 h as an example, the total GHG emissions from HHPS-G operation are shown in Figure 13 (a) and (b) below.

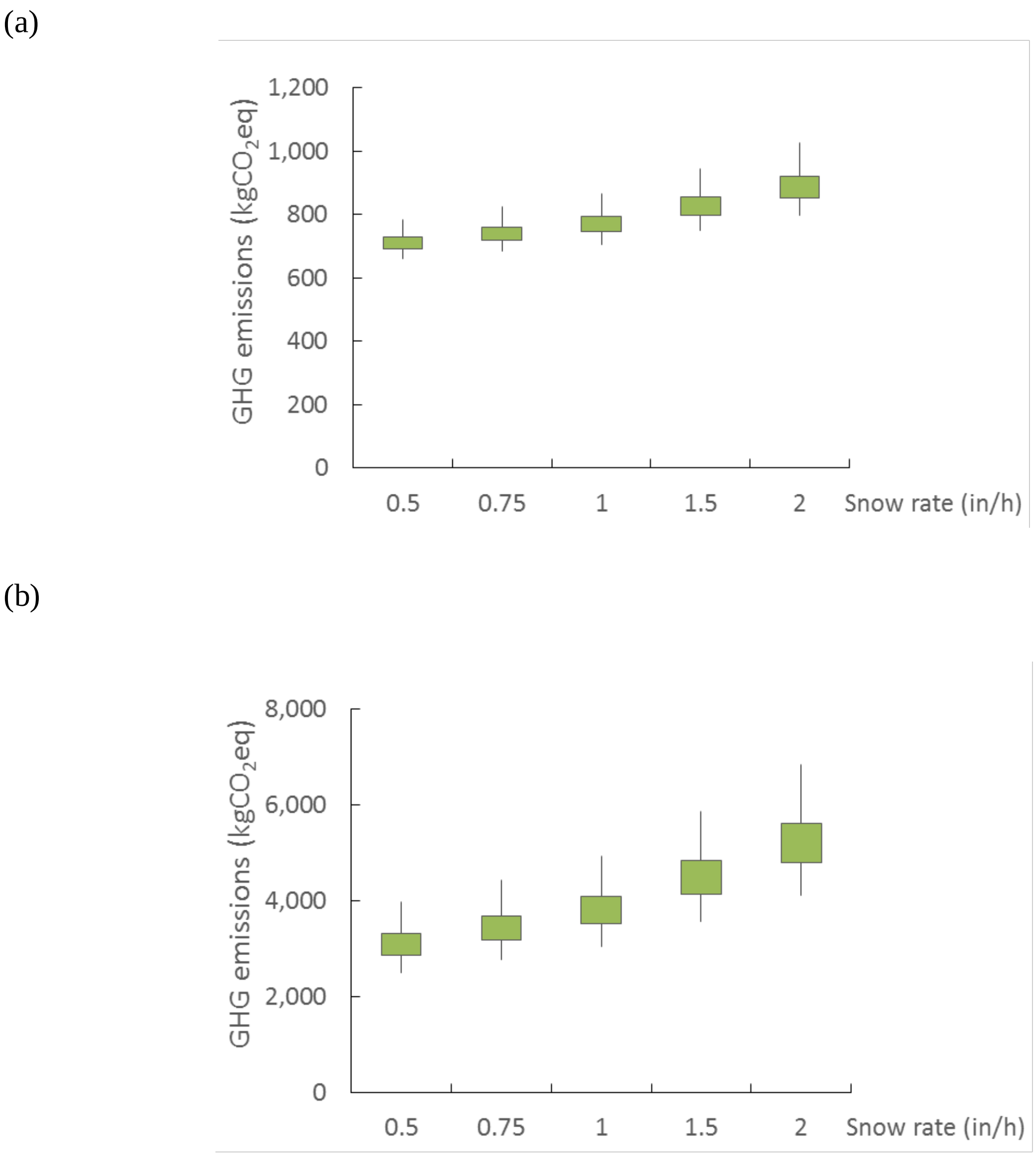


Figure 13. (a) GHG emissions from HHPS-G operation life cycle against different snow rate with 1 h snow period; (b) GHG emissions from HHPS-G operation life cycle against different snow rate with 12 h snow period

Compared with the energy consumption situation, GHG emissions follow a similar trend of energy demand for different snow rates as shown in Figure 12. It was found that GHG emissions from HHPS-G operation were determined by the energy. As Figure 13 demonstrates, the coefficient of performance determines the GHG emissions of the heat pump operation, and geothermal heat pump operation contributes most of the GHG emissions in a HHPS-G operation life cycle.

Case 2: Operation of Hydronic Heated Pavement System Using Natural Gas Furnace

HHPS-NG operation system boundary

Similarly to the HHPS-G operation LCA, the HHPS operation LCA includes both product LCA and process LCA. Based on the modeling and assumptions, the HHPS-NG operation life cycle can be divided into 4 sub-life cycles: the power generation life cycle, the snow-removal operation life cycle, the material-production life cycle (antifreeze and insulation layer production life cycle), and the antifreeze wastewater treatment life cycle. The only difference assumed between the HHPS and the HHPS-G is that the HHPS utilizes a fossil fuel heater as a heating source to warm up the antifreeze solution. The HHPS system boundary is similar to the boundary of the HHPS-G, and the HHPS operation flow chart and system boundary are shown in Figure 14.

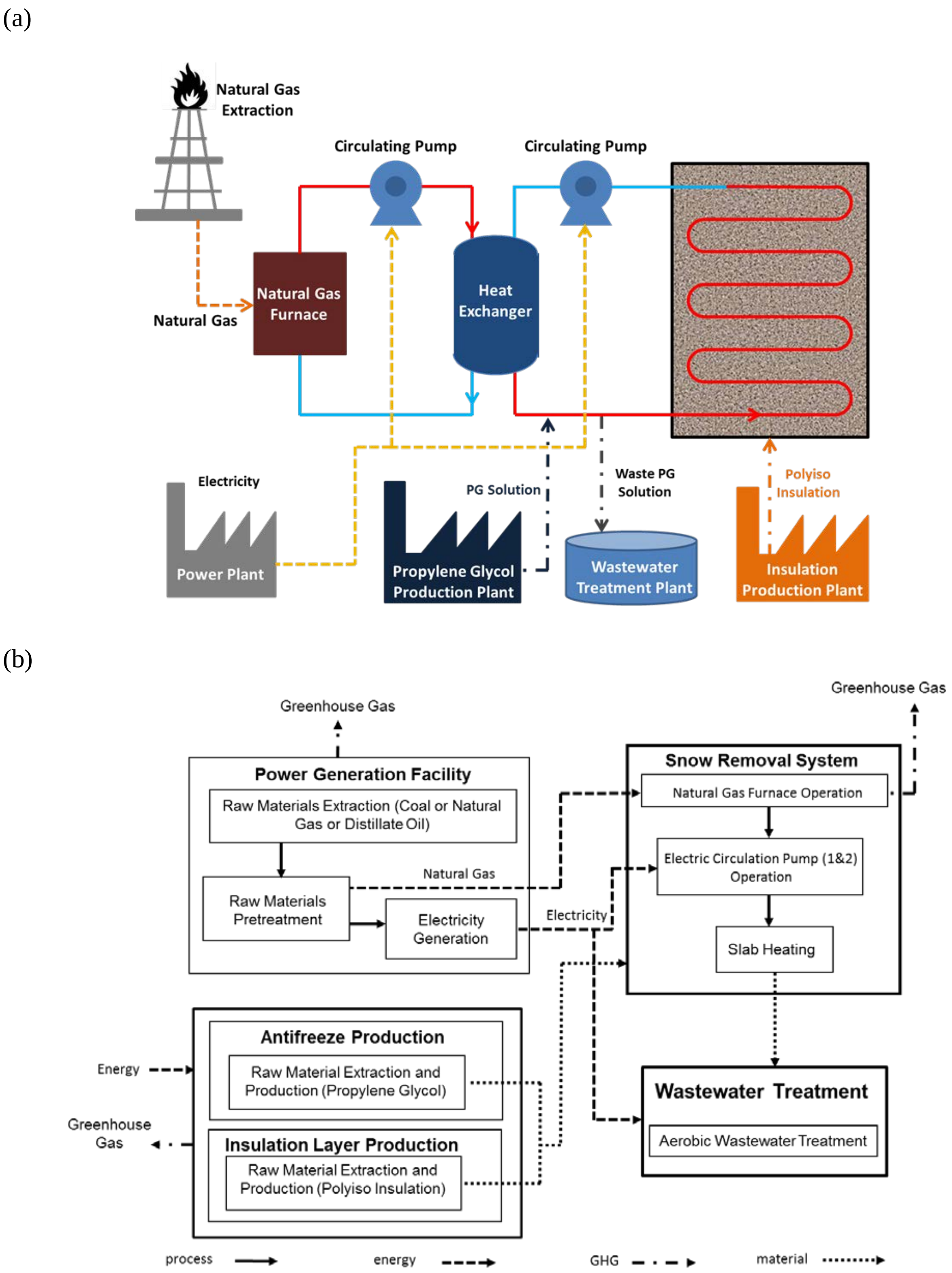


Figure 14. (a) HHPS-NG operation flow chart; (b) System boundary of HHPS-NG operation

HHPS-NG operation model

Studies have shown that a HHPS with a 60% efficient natural gas boiler has the potential to achieve fewer GHG emissions when the efficiency of the heating technique is improved (American Council for An Energy-Efficient Economy 2012). Thus, a natural-gas furnace with a 90% efficiency, considered to have higher efficiency than a traditional gas boiler, is applied in the HHPS. A heat exchanger is required in the HHPS because propylene glycol is used as antifreeze to prevent heat transfer medium freezing, and propylene glycol solution cannot be directly heated by the furnace. Therefore, the HHPS can be divided into two subsystems, a water-heating system and a pavement-heating system. The water-heating system uses a natural gas furnace to heat up water and circulates heated water through a 70% efficiency heat exchanger using a circulating pump. 40% by volume of propylene glycol solution extracts heat from the water heating system through the heat exchanger and it is circulated under the concrete slab surface by the circulating pump to heat the pavement surface. As demonstrated by the model and boundary of HHPS operation shown in Figure 14, the difference between the HHPS and the HHPS-G is that two circulating pumps and a heat exchanger are required in the HHPS, and there are direct GHG emissions at the snow-removal system stage. However, the system design of HHPS is generally similar to HHPS-G, according to the “Vigea Heated Pavement Design Manual Script” (Viega 2015). 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, propylene glycol solution usage, and solution waste treatment will be the same as for the HHPS-G.

HHPS-NG operation energy consumptions

As shown for the HHPS-G, a warming of the 19,000 ft^2 slab surface from 20°F to 32°F requires a 2405 MJ/snow period. Based on the snow periods evaluated in this study, energy consumption for idling are 2405 MJ/h, 601 MJ/h, 301 MJ/h, and 200 MJ/h. Because of insulation installation in the HHPS, zero back and edge losses were assumed to apply in the snow melting heat calculation. Different snow rate conditions for 0.5 in/h, 0.75 in/h, 1 in/h, 1.5 in/h, and 2 in/h were calculated by using Equations (1) through (6), and energy requirements for snow melting under different snow rates were 134 Btu/h·ft^2, 153 Btu/h·ft^2, 173 Btu/h·ft^2, 211 Btu/h·ft^2, and 251 Btu/h·ft2. Energy required for melting snow is presented in Table 13 below.

Table 13. Energy consumptions of natural gas furnace for different snow rates

Snow Rate (in/h)	Snow Melting Energy Requirement (Btu/h)	Snow Melting Energy Requirement through Heat Exchanger (Btu/h)	Natural Gas Furnace Energy Consumption for Snow Melting (MBtu/h)
2	4,769	6,813	7,570
1.5	3,958	5,654	6,282
1	3,284	4,692	5,213
0.75	2,851	4,073	4,526
0.5	2,542	3,631	4,035

Note. Equation (2) - (6) are used for energy consumption of natural gas furnace

As Table 13 shows, shows, energy demand in natural gas furnace will be higher than the energy required for snow melting, because of the heat loss from gas furnace itself and heat exchanger.

The total flow rate of the HHPS system is calculated using Equation (8) as 490 gpm, and a 125 ft pressure drop is determined based on the Viega manual script. A 60% efficient horsepower circulating pump is selected. Therefore, the energy demand of one circulating pump is calculated as 26 hp using Equation (9). Because circulating pumps are required in both water and pavement heating systems, total energy consumption for both circulating pumps is 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 will be the same as shown for the HHPS-G above. In conclusion, the total energy consumption for HHPS-NG operation is given in Table 14.

Table 14. Energy consumptions of HHPS-NG operation life cycle for different snow periods and rates

Snow period (h)	Snow Rate (in/h)	Energy Consumption of HHPS with Natural Gas Furnace (MJ/h)	Total Energy Consumption of HHPS with Natural Gas Furnace (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. Equation (1) - (6), (8), and (9) are used for energy consumption calculation

Because system energy requirement is determined by snow rate, energy consumption of HHPS operation increases during the increasing of snow fall. Comparing Table 13 with Table 14 shows that most of the energy for system operation is used when a natural gas furnace is the heating source.

HHPS-NG operation GHG emissions

GHG emission factors are shown in Table 11. HHPS uses a natural gas furnace to heat up water and an electric circulating pump circulates heated water and propylene glycol antifreeze solution in two subsystems. Because natural gas is combusted as a heating source, there is direct GHG released from the natural gas furnace. As in the HHPS-G, GHG emissions from the electric circulating pump are from 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 15 below.

Table 15. 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 Power Plant	2.0	482
	Natural Gas Power Plant	2.0	442
	Distillate Oil Power Plant	2.0	469

As the GHG emissions analysis done for HHPS-G operation shows, GHG emissions are highly related to the energy sources which have different emission factors. In Table 15, it can be seen that total GHG emissions from natural gas combustion and electrical power production used for the circulating pump operations varied only slightly when circulating pumps use electrical power generated from different fossil fuels.

Depending on the system boundary and model described, GHG emissions from insulation layer production, propylene glycol production and antifreeze wastewater treatment will as for

HHPS-G. The total GHG emissions from HHPS-NG operation after applying the GHG emission factors and percentages of the different types of power plants in the US is shown in Table 16 below.

Table 16. GHG emissions from HHPS-NG operation life cycle for different snow periods and 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	2,240
	1.5	495	1,980
	1.0	433	1,732
	0.75	401	1,604
	0.5	370	1,480
8	2.0	498	3,984
	1.5	434	3,472
	1.0	372	2,976
	0.75	339	2,712
	0.5	308	2,464
12	2.0	478	5,736
	1.5	413	4,956
	1.0	351	4,212
	0.75	319	3,828
	0.5	288	3,456

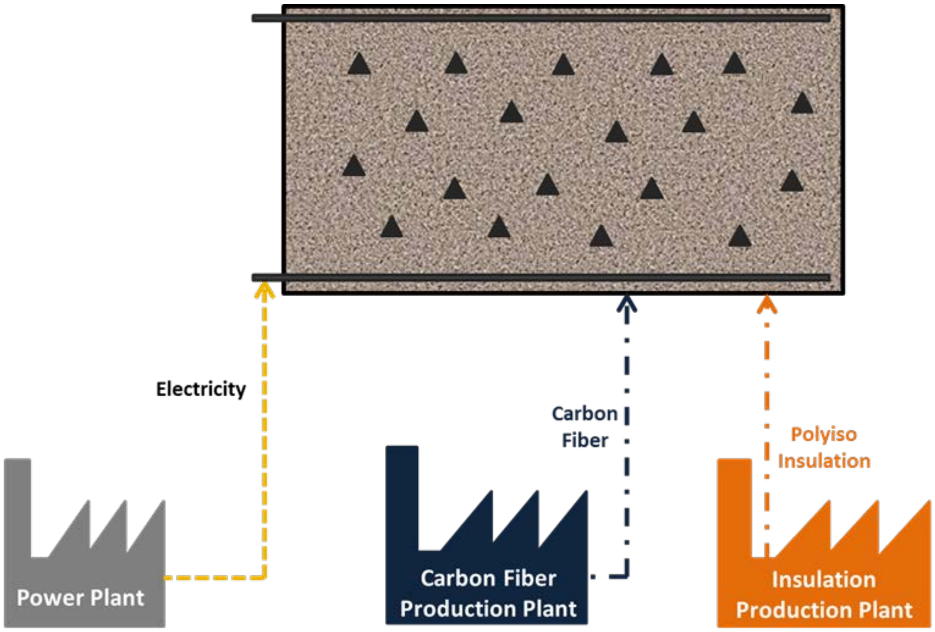
Because GHG emissions are significantly related to energy consumption, HHPS-NG operation GHG emissions are depended on snow rate conditions and snow period as well.

Case 3: Operation of Electrically Heated Pavement System

EHPS operation system boundary

An electrically-heated pavement system utilizes electric mats or cables to transform electricity into radiant heat for pavement heating. EHPS operation life cycle can be divided into 3 sub-life cycles, a power-generation life cycle, a snow-removal operation life cycle, and a material-production life cycle (carbon fiber and insulation layer production life cycle). The EHPS operation system boundary is similar to the other heated pavement system boundaries, the only difference for the EHPS boundary is that it does not include the wastewater treatment stage. An EHPS operation flow chart and system boundary are shown in Figure 15 below.

(a)



(b)

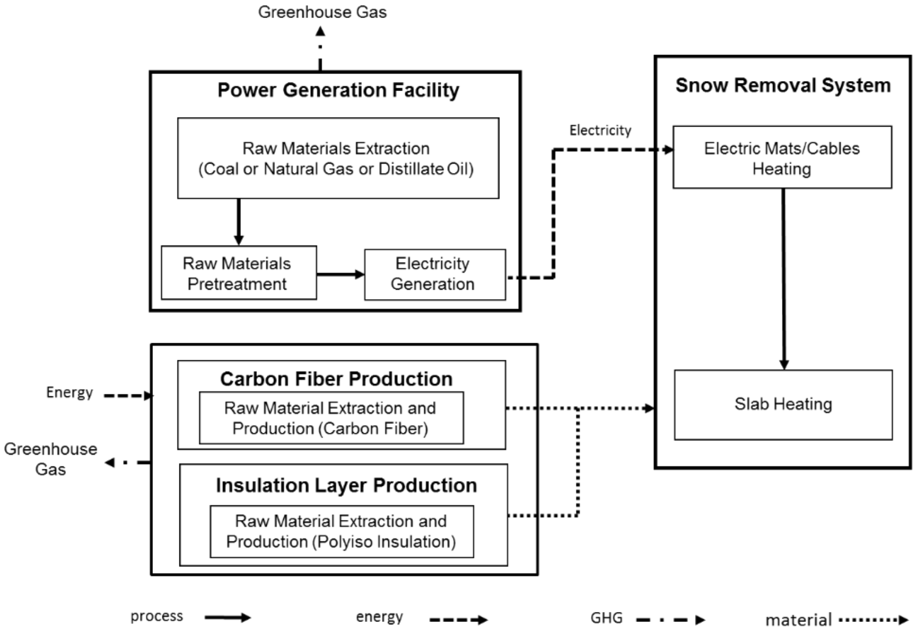


Figure 15. (a) EHPS operation flow chart; (b) System boundary of EHPS operation

EHPS operation model

A 4-ft-long, 3-ft-wide, and 4 inch thick electronically heated pavement slab was tested in part of on-going study (Ceylan 2015) in Iowa State University (ISU) to evaluate its energy efficiency. The electrical input was 950W, and edge and bottom insulation layers were installed to prevent heat lost through those surfaces. 0.8% carbon fiber was mixed in the concrete to increase its conductivity (Ceylan 2015). The result was that it took 20 min to warm the 12 ft^2 slab from 20°F to 32°F, so energy consumption for conductive concrete pavement idling was 0.07 MJ/ft^2.

For 146 ft long, 130 ft wide, and 4 in thickness of the apron pavement analyzed in this study, total apron pavement concrete volume is 7813 ft^3. So, 62.5 ft^3 of the total volume of active carbon for EHPS are calculated by using 0.8% of carbon fiber by volume of 1 ft^3 of concrete. Carbon fiber has a density of 1.55 g/cm^3 (Clearwater Composites, LLC 2015),), 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, so the lifetime of carbon fiber is assumed to also be 20 years. Allocating carbon fiber usage on an hourly basis, 16 g/h of carbon is required. Based on a previous study, carbon fiber production life cycle has an energy consumption factor of 704 MJ/kg and 31 kgCO2eq/kg of GHG emission factor (Das 2011).

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

EHPS operation energy consumptions

As in the other heated-pavement systems, energy required for snow melting is calculated by Equations (1) through (5) and adding an 1803 MJ/snow period to determine the power input for system operation. Since electricity only is used for heating in EHPS operation, the energy consumption of the electrical heating cable under different snow rate conditions is shown in Table 17 below.

Table 17. Electrical heating energy consumptions for different snow periods and rates

Snow period (h)	Snow Rate (in/h)	Energy Requirement of Electrical Heating (MJ/h)
1	2.0	6,833
	1.5	6,034
	1.0	5,266
	0.75	4,866
	0.5	4,482
4	2.0	5,481
	1.5	4,682
	1.0	3,914
	0.75	3,515
	0.5	3,131
8	2.0	5,255
	1.5	4,456
	1.0	3,688
	0.75	3,288
	0.5	2,905
12	2.0	5,180
	1.5	4,381
	1.0	3,614
	0.75	3,214
	0.5	2,830

Note. Equation (1) - (6) are used for energy consumption of electrically heating

Like the other two heated pavement systems, EHPS energy consumption is significantly relied upon under different snow rate conditions. A higher snow rate requires more energy consumption for snow melting.

As described by the system model, carbon fiber usage converted to an hourly basis is about 16 g/h and carbon fiber production is assumed to have a 704 MJ/kg of energy requirement rate based on a previous study, so energy consumption of carbon fiber production for EHPS is 11 MJ/h.

The insulation layer design for EHPS will be the same as for HHPS-G and HHPS-NG, so the energy demand will also be the same. In summary, the total EHPS operation energy consumptions for different snow rates are shown in Table 18.

Table 18. Energy consumptions of EHPS operation life cycle for different snow periods and 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. Equation (1) - (6) are used for energy consumption calculation

Table 18 and Table 17 show that most of the energy consumed in an EHPS operation life cycle is used for heating, the same as for the other two heated-pavement system analyzed.

EHPS operation GHG emissions

For electrical heating, GHG is released during the power generation stage. By applying the GHG emission factors from different types of power plants and percentages for each power application in the US, GHG emissions from electrical power production used for electrical heating have been determined and are shown in Table 19 below.

Table 19. GHG emissions from power generation (electrical heating) for different snow periods and rates

Snow period (h)	Snow Rate (in/h)	GHG Emissions ($kgCO_2eq/h$)
1	2.0	1,409
	1.5	1,244
	1.0	1,086
	0.75	1,004
	0.5	924
4	2.0	1,131
	1.5	966
	1.0	808
	0.75	725
	0.5	646
8	2.0	1,084
	1.5	920
	1.0	761
	0.75	679
	0.5	600
12	2.0	1,069
	1.5	904
	1.0	746
	0.75	663
	0.5	584

16 g/h carbon fiber usage for EHPS operation is calculated and a 31 $kgCO_2eq/kg$ GHG emission factor is taken from a previous study. GHG emissions from insulation layer production will be the same as for HHPS-G and HHPS-NG, so GHG emissions from carbon fiber production and insulation layer production are 0.48-$kgCO_2eq/h$ and 0.043 $kgCO_2eq$. Total GHG emissions from EHPS operation is shown in Table 20.

Table 20. GHG emissions from EHPS operation life cycle for different snow periods and rates

Snow period (h)	Snow Rate (in/h)	GHG Emissions (kgCO$_2$eq/h)	Total GHG Emissions (kgCO$_2$eq)
1	2.0	1,410	1,410
	1.5	1,245	1,245
	1.0	1,087	1,087
	0.75	1,005	1,005
	0.5	925	925
4	2.0	1,132	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	1,085	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	1,070	12,840
	1.5	905	10,860
	1.0	747	8,964
	0.75	664	7,968
	0.5	585	7,020

Compared with the results in Table 19, most of the GHG emissions are related to the heating stage from the EHPS operation life cycle.

Case 4: Operation of Traditional Snow Removal System

TSRS operation system boundary

Traditional snow removal systems use mechanical equipment like snow plows or snow blooms to remove snow first and then apply de-icing chemicals on the pavement to prevent snow formation. The chemically polluted water is subsequently treated in municipal wastewater treatment plant. Therefore, life cycles of de-icing chemical production, power generation, snow removal operations and wastewater treatment should be included. Figure 16 shows the TSRS flow chart and system boundary that differs from that of heated pavement systems.

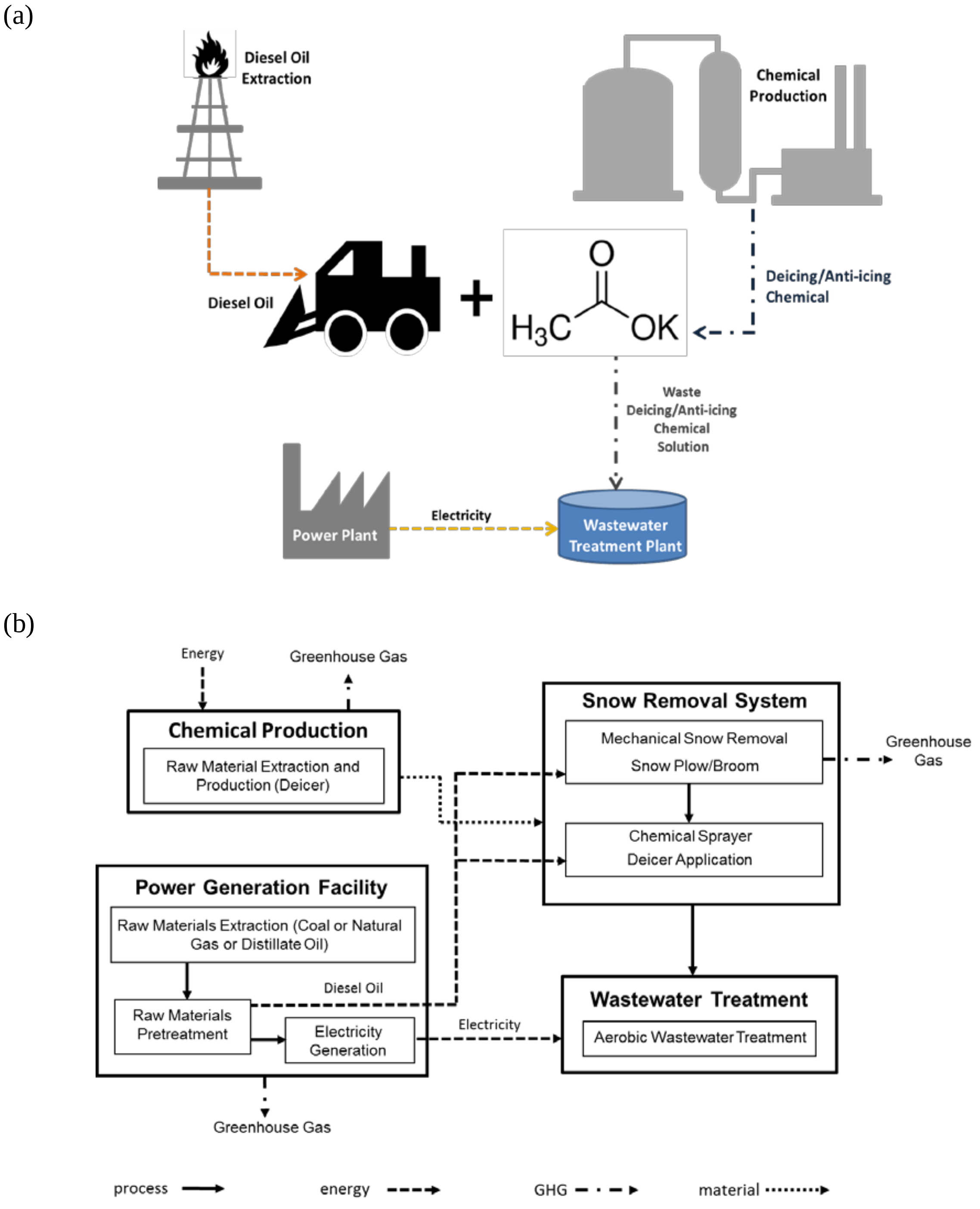


Figure 16. (a) TSRS operation flow chart; (b) System boundary of TSRS operation

TSRS operation model

Potassium acetate, sodium acetate, and propylene glycol are the chemicals commonly used in airport pavement de-icing (EPA 2012). A 50% by weight potassium acetate solution, a 60% by weight propylene glycol solution, and a sodium acetate solid de-icer are assessed in this study. These three chemicals are applied at levels of 75 g/m^2 (SnowMelt 2015), 65 g/m^2 (FAA 1992), and 50 g/m^2 (Cryotech NAAC® 2008), respectively. Because the amount of chemical for a de-icing application is based on air temperature, and the air temperature is constant under different snow rate conditions, de-icer usage is the same for all snow rates. Among these three chemicals, 67% of airports in U.S. use potassium acetate, 11% use propylene glycol and 22% use sodium acetate. De-icing chemicals are sprayed on the pavement once per hour.

A multifunctional vehicle 1104D-E44TA, with a diesel engine requiring 97 kW and a transmission power demand of 68 kW (RPM Tech 2015), is used for spraying the de-icing chemical on the 19,000 ft^2 apron pavement to prevent ice adhesion. One hour after the application of the chemical, the multifunctional vehicle is converted into a snowplow to remove snow from the apron area. Considering that the apron area is relatively small, the total operating time of the vehicle, including chemical spraying and snow plowing, is assumed to be 10 minutes.

Because a de-icing chemical is used in the TSRS, a wastewater treatment process is required. In general, most of the airport pavement runoff is treated in municipal wastewater treatment plant using an aerobic treatment.

TSRS operation energy consumptions

The strategy for TSRS is to spray de-icing 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 diesel raw material production and diesel oil combustion for the snow removal operation is 99 MJ/h.

Three kinds of deicing chemicals, potassium acetate, propylene glycol, and sodium acetate, were analyzed. Software such as GREET and on-line software Economy Input-Output Life Cycle Assessment (EIO-LCA) were used to calculate the energy consumption of de-icer 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 propylene glycol, 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, 193 kg/h, and 88 kg/h. Therefore, to produce certain amounts of chemicals, the energy consumptions are 8,374 MJ/h, 7,258 MJ/h, and 5,584 MJ/h, respectively. According to a United States Environmental Protection Agency report (EPA 2012), 67% of airports in the U.S. use potassium acetate, 11% use propylene glycol, and 22% use sodium acetate.

Based on a previous study, the chemical oxygen demand (COD) of the different chemicals are 1,050 g/kg for potassium acetate, 1,680 g/kg for propylene glycol, and 1,010 g/kg for sodium acetate (University of South Carolina 2008). Thus, the total COD of de-icing wastewater is 139 kg for potassium acetate, 193 kg for propylene glycol, 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 (Geest and Kiechle 2010). The energy required for a wastewater plant to treat different kinds of de-icing wastewater would thus be 500 MJ/h, 695 MJ/h, and 320 MJ/h in namely.

Because the operational strategy of TSRS is to use mechanical equipment to clear accumulated snow before applying chemical de-icer, operational time of mechanical equipment and de-icer usage for 19,000 ft^2 apron area are not affected by snow rate, as shown for the model in this study . Energy consumption of TSRS operation therefore does not change with increasing snow rate. By applying the percentage of de-icer usage in the energy calculation, the total energy consumption of TSRS operation for a 19,000 ft^2 apron is found to be 8,359 MJ/h, and the results for different snow periods are shown in Table 21.

Table 21. Energy consumptions of TSRS 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

TSRS operation GHG emissions

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

GREET and EIO-LCA software was used for the life cycle analysis of the de-icing chemical production. The GHG emission factor was 3.82 kgCO_2eq/kg for potassium acetate, 6.46 kgCO_2eq/kg for propylene glycol, and 2.73 kgCO_2eq/kg chemical for sodium acetate. Calculating the usage of the chemicals for a 19,000 ft^2 apron, the GHG released from potassium is 506 kgCO_2eq/h from acetate production, 742 kgCO_2eq/h from propylene glycol production, and 241 kgCO_2eq/h from sodium acetate manufacturing.

The wastewater treatment stage in TSRS is the same as for GHPS and HHPS. 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 treating a given amount of will release 129 $kgCO_2eq/h$ for potassium acetate waste water treatment, 104 $kgCO_2eq/h$ for propylene glycol wastewater treatment, and 56 $kgCO_2eq/h$ sodium for acetate wastewater treatment.

By multiplying the percentages of different chemical usages, the average GHG emission from TSRS airport apron snow removal under different snow rate conditions is found to be 585 $kgCO_2eq/h$. GHG emissions for different snow periods, as shown in Table 22 below.

Table 22. GHG emissions from TSRS operation life cycle for different snow periods

Snow Period (h)	Total GHG Emissions ($kgCO_2eq$)
1	585
4	2,341
8	4,682
12	7,023

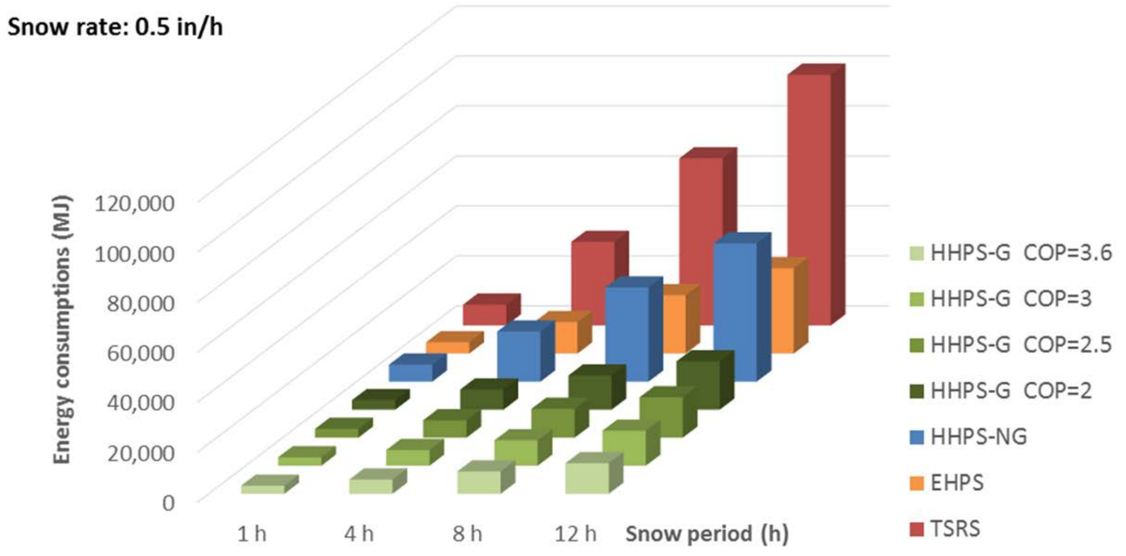
Comparisons of Cases

Four case studies of operations of traditional snow removal systems and three alternative heated pavement systems have been analyzed to evaluate the sustainability of such systems. As the analyses for different snow removal system operations demonstrate, energy consumption conditions and environmental impact are influenced by several different factors such as snow rates, snow period, and system efficiency, and these factors vary among the four types of system operations. Energy consumption and GHG emissions have also been compared to estimate which system for removing snow is most sustainable.

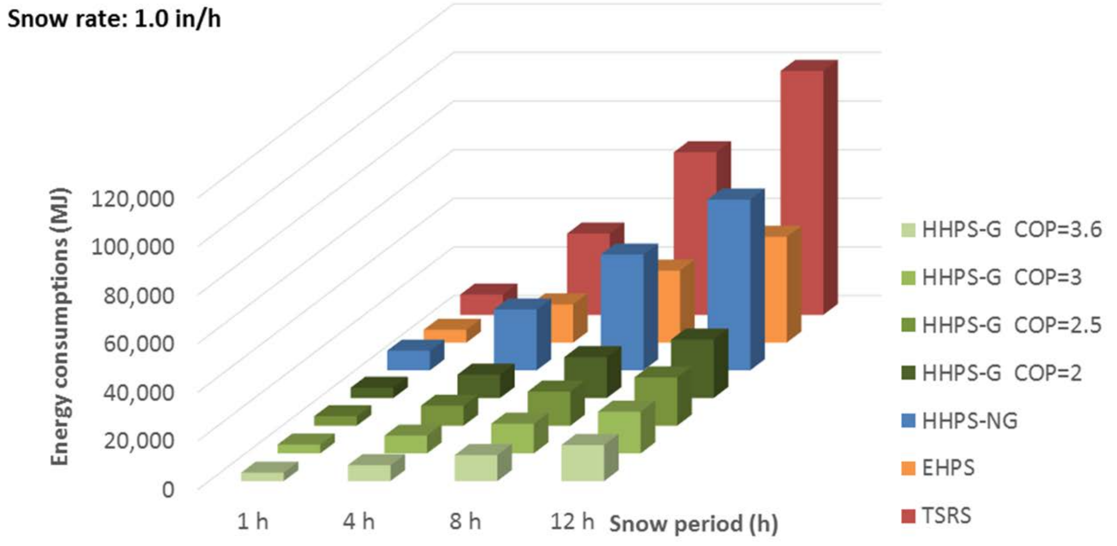
Energy consumptions comparison

The equations and models of system operations used in this study show that snow rate and snow period have significant effects on energy consumption. To compare four different system operations, energy consumptions for different snow periods, 1 h, 4 h, 8 h, and 12 h, and snow rates of 0.5 in/h, 1 in/h, and 2 in/h conditions are summarized in Figure 17 (a) (b) (c) below.

(a)



(b)



(c)

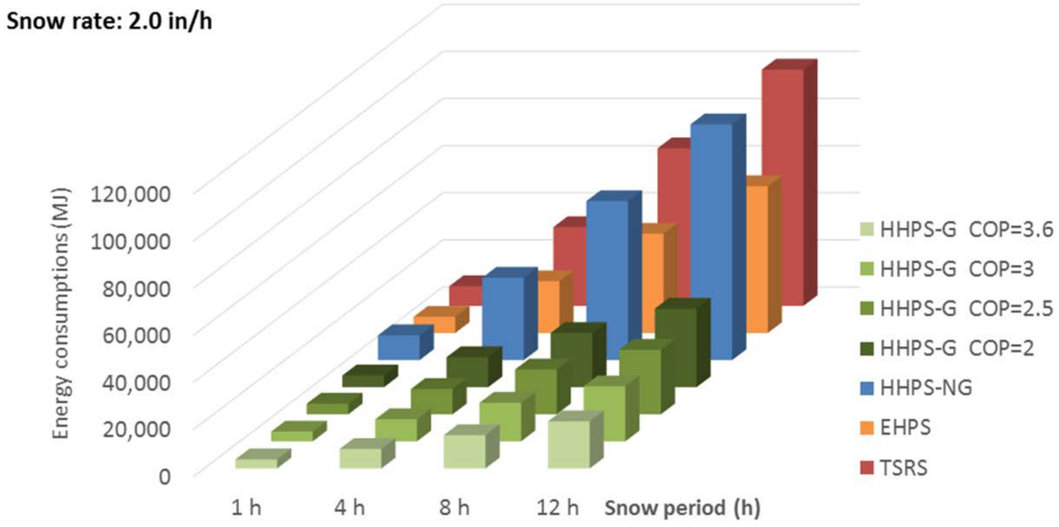


Figure 17. (a) Energy consumptions of snow removal system operations against different snow period under 0.5 in/h snow rate; (b) Energy consumptions of snow removal system operations against different snow period under 1 in/h snow rate; (c) Energy consumptions of snow removal system operations against different snow period under 2 in/h snow rate

As snow period becomes longer, energy consumption of all snow and ice removal system operations increase. Among snow and ice removal systems, TSRS will require more energy for snow and ice removal operation than heated pavement system operations when snow period become longer. As snow rate increases, energy consumption of heated pavement system operations increases but one of TSRS does not. Considering that energy consumption of heated pavement system operations will increase when snowfall rate increases, energy consumption of a HHPS-NG operation might be more than for TSRS when the snow rate exceeds 2 in/h (See Figure 17 (c)) but energy consumption of the other heated pavement system operations will be less under various snow rates.

Although heated pavement systems are obviously expected to require energy to heat the pavement surface to remove snow, it is surprising to find that more energy is consumed in TSRS operation life cycle as Figure 17 (a) and (b) demonstrates. Also, among the 3 kinds of different heated pavement system operations, the HHPS-NG operation has a higher energy consumption compared to energy consumption of HHPS-G and EHPS operations. To understand the inventories causing such differences, the energy consumption contributions of different inventories in different systems have been analyzed and are summarized in Table 23.

Table 23. 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]	TSRS[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 stage, antifreeze production stage, and antifreeze waste treatment stage.
[4] Other includes insulation layer production and carbon fiber production stage.
[5] Other includes diesel oil for mechanical equipment operation.

Most of the energy used in a TSRS operation is related to de-icing chemical production. A huge amount of de-icing chemicals are required for a 19,000 ft^2 apron area, and the energy demand for de-icer manufacture is relatively high. This results in a higher energy consumption for the TSRS operation life cycle than for the heated pavement systems that do not require de-icing materials. Therefore, if an airport company is conducting an “Airport Sustainability Planning” program and wishes to reduce their energy consumption during snow removal, using less de-icer is an effective way to reduce much of the energy demand.

More than 99% of the total energy consumed in heated pavement system operation is used for heating, as shown in Table 23. Due to differences in system models and equipment used for heated pavement systems, energy consumption may vary. Taking HHPS-NG as an example, the system utilizes a 90% efficient natural gas furnace, a 60% efficient circulating pump, and a 70%

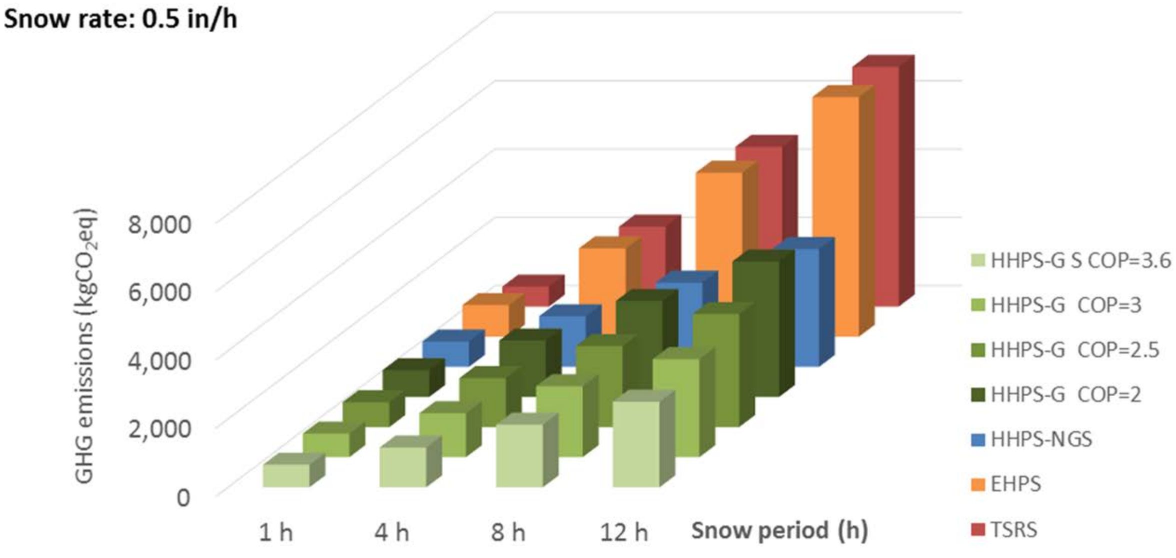
efficient heat exchanger. Compared to the other two system models, the HHPS-NG exhibits more heat loss during the heating process, so the HHPS-NG operation requires the most energy consumption among the three different kinds of heated pavement systems.

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

GHG emissions comparison

Based on the system boundaries, models, and assumptions made in this study, GHG emissions are determined by the energy consumption of snow and ice removal system operation and compared under various snow period and rate conditions in Figure 18.

(a)



(b)

(c)

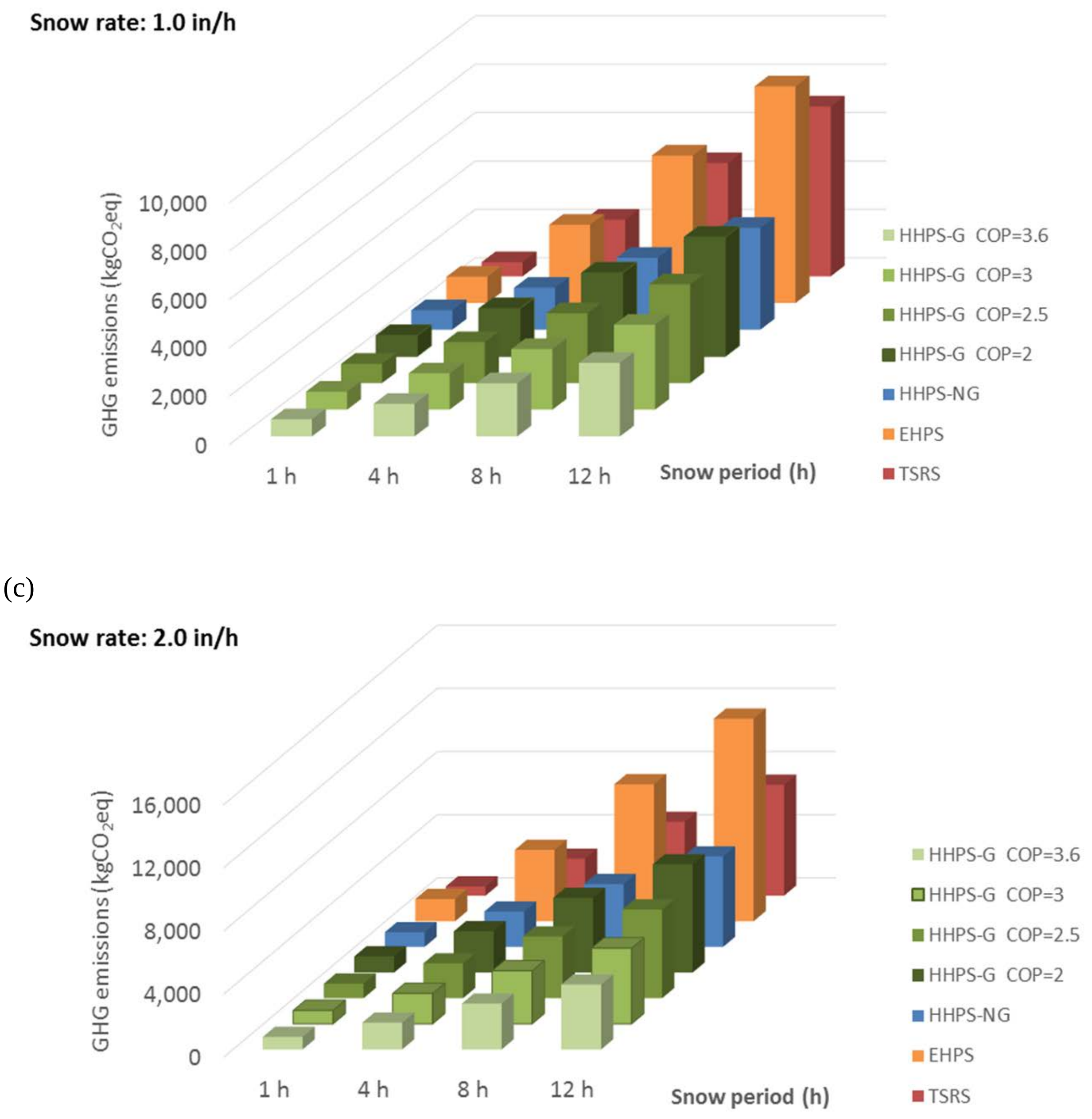


Figure 18. (a) GHG emissions from snow removal system operations against different snow period under 0.5 in/h snow rate; (b) GHG emissions from snow removal system operations against different snow period under 1 in/h snow rate; (c) GHG emissions from snow removal system operations against different snow period under 2 in/h snow rate

GHG emissions are dictated by energy consumption as shown by the models in this study, so GHG emissions from system operations increase by the increase of snow periods. The increase of snow rates results in more GHG emissions from the heated pavement system operations requiring more energy but has little effect on TSRS operation. Considering GHG emissions changes under different snow period and rate conditions, three types of heated pavement system operations will has less GHG emissions than TSRS applied in apron snow and ice removal under 0.5 in/h snow rate conditions when the snow period is greater than 9 hours.

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

To identify the inventory releasing the most GHG in each system operation, GHG emission contributions from different life cycle inventories of snow removal systems were analyzed and the results are summarized in Table 24.

Table 24. Operation GHG emissions of different inventories in different snow removal systems

GHG Emission (%)	HHPS-G (COP max)[1]	HHPS-G (COP min)[2]	HHPS-NG[3]	EHPS[4]	TSRS[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

1-3Other includes insulation layer production stage, antifreeze production stage, and antifreeze waste treatment stage.
4Other includes insulation layer production and carbon fiber production stage.
5Other includes diesel oil for mechanical equipment operation.

Table 24 shows that most of the GHG emissions result from heating energy production in heated pavement systems and de-icer production in TSRS. Since GHG emissions are significantly positively correlated to energy consumption, the more energy used, the more GHG will be released, as shown in Table 23 and Table 24. Using a similar strategy to reduce energy consumption of snow removal operation, using less de-icer can be a significant way to significantly reduce GHG emissions in TSRS, and using a heated pavement system instead of de-icing chemical application has potential for reducing GHG emissions. Also, for longer snow periods, less GHG per hour are released from heated pavement system operations as shown in Figure 18 (a) shows.

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 hour snowfall conditions, operations of heated pavement systems produce less energy consumption and GHG emissions than a TSRS operation.

Conclusions and Recommendations

Ineffective snow and ice removal activities can result in airline delays, employee injuries, and potential environmental risks from overuse of de-icers or anti-icers (FAA 2010). 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 must seek more sustainable systems able to replace conventional snow removal system (FAA 2010). This study was carried out with the specific goal of applying a hybrid LCA approach for evaluating energy consumption and GHG emissions from the operations of HHPS-G, HHPS-NG, and HHPS-E., The findings and future recommendations of the study are summarized below.

Findings

- Heated pavement system apron application is a viable option from an energy or environmental perspective for automatically achieving pavement surfaces free of ice/snow without using mechanical or chemical methods.
- De-icing chemical production requires a high energy demand and produces GHG emissions over a TSRS operation life cycle. Using heated pavement systems instead of de-icers thus enables effective snow removal with reduced energy consumption and GHG emissions.
- Energy demand and GHG emissions from operation of heated pavement systems are significantly determined by snowfall rate and snow period.
- Compared to TSRS, heated pavement system operations have a greater advantage during a snow event with a small snow rate and a long snow period.
- Energy production (i.e., electrical power generation) and energy consumption phases (i.e., natural gas combustion) for heating require the most energy and contribute the most GHG emissions in a heated pavement system operation life cycle.

- HHPS-G using geothermal heat pumps with a COP higher than 2.5 results in less energy consumption and fewer GHG emissions than other types of snow removal systems under the same snow rate conditions. From an environmental impact perspective, hydronic heated pavement system using natural gas furnace, with high heating efficiency and a relatively low emission factor, has the potential to be used as a sustainable snow removal system for places where do not have a good geothermal condition.

Although this study only focused on the operation phase of both heated pavement systems and traditional snow removal systems, it provides a decision maker or airport manager a more informed view of operating heated pavement systems in removing snow in terms of energy saving and global warming potential 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, so the study's results should be regarded as only a qualitative view, and more comprehensive assessments that include broader system boundaries are required for future study.

Recommendations

- Based on the assumptions for system boundaries defined in this study, most of the energy is used for heating and causes high GHG emissions. Thus, heating source efficiency and coefficient of performance are critical in heated pavement systems if they are to be more energy-efficient and environmentally-friendly.
- Future studies may focus on different weather conditions, different de-icing chemical usage strategies, and other potential factors that might influence energy consumption and GHG emissions from different types of snow removal systems.

- The entire life cycle of a heated pavement system, including construction and maintenance stages and a more comprehensive life cycle of traditional snow removal systems, could be assessed to provide more informed information.
- Previous studies have suggested that the use of de-icer chemicals on airport pavement surfaces tends to cause and/or accelerate distress and lead to more frequent repairs (Shi, et al.). Studying the full life cycles of snow removal systems may reveal an increase in the energy spent during the pavement maintenance phase, so it will be interesting to study the life cycles of both snow removal systems from this perspective.

References

Airliners. (2015). Aircraft Technical Data & Specifications. [cited by 2015 Feb 28th]. Retrieved from http://www.airliners.net/aircraft-data/

Alternative Fuels Data Center. (2014). Fuel Properties Comparison. Washington, DC: U.S. Department of Energy. [cited by 2015 Feb 28th]. Retrieved from http://www.afdc.energy.gov/fuels/fuel_properties.php

American Council for An Energy-Efficient Economy. (2012). Water Heating. Washington, DC: [cited by 2015 Jan 03rd]. Retrieved from http://www.aceee.org/consumer/water-heating

Amsler, D. E. (2014). Snow and Ice Control 2014. *Publication CLRP No. 13-04*. Cornell Local Roads Program, New York LTAP Center, NY, 2014. [cited by 2015 Feb 14th]. Retrieved from http://www.clrp.cornell.edu/workshops/manuals/snow_and_ice_control.pdf

CDM-Executive Board. (2014). Clean Development Mechanism Project Design Document Form. *CDM-SSC-PDD Version 03*. Bonn, Germany. [cited by 2015 Mar 4th]. Retrieved from http://www.dnv.com/focus/climate_change/Upload/DNV_Vers%C3%A3o%20Ingl%C3%AAs_PDD%2001_Ecobio_20mar.pdf.

Ceylan, H. (2015). FAA PEGASAS COE Project 1: Heated Airport Pavements. FAA PEGASAS COE 3nd Annual Meeting, Purdue University, West Lafayette, Indiana, May 27-28.

Chapman, W.P. (1952). Design of snow melting systems. *Heating and Ventilating*, (April): 95 and (November):88.

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

Clearwater Composites, LLC. (2015). Properties of Carbon Fiber. Duluth, MN, USA. [cited by 2015 Feb 18th]. Retrieved from http://www.clearwatercomposites.com/resources/Properties-of-carbon-fiber

Cryotech NAAC®. (2008). Solid Commercial Deicer. Fort Madison, IA, USA. [cited by 2015 Feb 16th]. Retrieved from http://www.cryotech.com/websites/cryotech/images/docs/products/commercial/MKT900_-_NAAC_Commercial_Fact_Sheet.pdf

CTC & Associates LLC WisDOT RD&T Program. (2004). Pavement Service Life-rev.2. *Transportation Synthesis Report*. Wisconsin Department of Transportation. [cited by 2015 Feb 26th]. Retrieved from ftp://ftp.mdt.mt.gov/research/LIBRARY/TSRPAVEMENTSERVICELIFE2WITHATTACHMENTS.PDF

Das, S. (2011). Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites. *Int J Life Cycle Assess* 16: 268-282.

EIA. (2007). Electricity Emission Factors. *Washington, DC: Energy Information Administration*. Publication EIA-1605, OMB No. 1905-0194.

EIA. (2015). How Much Carbon Dioxide Is Produced Per Kilowatthour When Generating Electricity with Fossil Fuels? *Washington, DC: Energy Information Administration FAQ*. [cited by 2015 Feb 24th]. Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

EIA. (2015). How Much Coal, Natural Gas, or Petroleum Is Used to Generate A Kilowatthour of Electricity? *Washington, DC: Publication EIA FAQ*. [cited by 2015 Feb 20th]. Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=8

EIA. (2015). How Much Coal, Natural Gas, or Petroleum Is Used to Generate A Kilowatthour Of Electricity? *Washington, DC: Energy Information Administration FAQ*. [cited by 2015 Feb 25th]. Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=6.

EIA. (2015). What Is U.S. Electricity Generation by Energy Source? *Washington, DC: Publication EIA FAQ*. [cited by 2015 Feb 24th]. Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

Energy Star. (2015). Geothermal Heat Pumps Key Product Criteria. Washington, DC, USA. [cited by 2015 Feb 25th]. Retrieved from https://www.energystar.gov/index.cfm?c=geo_heat.pr_crit_geo_heat_pumps

Energy. Gov. (2015). Furnaces and Boiler. *U.S. Department of Energy*. Washington, DC, USA. [cited by 2015 Feb 25th]. Retrieved from http://energy.gov/energysaver/articles/furnaces-and-boilers

Engineering Tool Box. (2015). Fuel Gases-Heating Values. [cited by 2015 Mar 6th]. Retrieved from http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html

EPA. (2012). Technical Development Document for the Final Effluent Limitations Guidelines and New Source Performance Standards for the Airport. *Washington, DC: United States Environmental Protection Agency*. EPA-821-R-12-005. Washington, DC, USA. [cited by 2015 Mar 4th]. Retrieved from http://water.epa.gov/scitech/wastetech/guide/airport/upload/Technical-Development-Document-for-the-Final-Effluent-Limitations-Guidelines-and-New-Source-Performance-Standards-for-the-Airport-Deicing-Category.pdf

FAA. (1992). Airport Snow and Ice Control Equipment. *Publication FAA 150/5220-20A. U.S. Department of Transportation*, Washington, DC: Federal Aviation Administration. [cited by 2015 Mar 7th]. Retrieved from http://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5220-20A.pdf

FAA. (~~2011~~2010). Airside Use of Heated Pavement Systems. *Washington, DC: Federal Aviation Administration*. Publication FAA 150/5370-17. U.S. Department of Transportation.

Gagnon, L., Belanger, C., and Uchiyama, Y. (2002). Life Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001. *Energy Policy*, Vol. 30, p. 1267-1278.

Geest, V. J., and Kiechle, C. (2010). Anaerobic Wastewater Treatment. *Brewing and Beverage Industry No1*. [cited by 2015 Feb 17th]. Retrieved from http://www.berkefeld.com/berkefeld/ressources/documents/1/23010,EN_VWS_Biothane_Aquantis_Brewing-B.pdf

Greenhouse Gases, (2013). Regulated Emissions, and Energy Use in Transportation (GREET) Model, version 1. *Input Fuel Specifications*. Argonne National Laboratory. Chicago, IL.

Hymers W. (1980). Electrically Conductive Concrete. *Rosemont, IL: Concrete Construction*. [cited by 2015 Mar 13th]. Retrieved from http://concreteconstruction.net/Images/Electrically%20Conductive%20Concrete_tcm45-340789.pdf

Kreith, F., and Goswami, D.Y. (2008). *Energy Management and Conservation Handbook*. Boca Raton, FL: CRC Press.

Lamond, J.F., and Pielert, J.H. (2006). *Significance of Tests and Properties of Concrete and Concrete-making Materials*. ASTM International, West Conshohocken, PA, USA.

Melissa, M.A. (2007). Hybrid Life Cycle Assessment Model for Construction Processes. *US-PA: Doctoral Dissertation*, University of Pittsburgh. [cited by 2015 Mar 29th]. Retrieved from http://d-scholarship.pitt.edu/8065/1/bilec_July_11_2007_7.pdf.

MeltSnow. (2015). Acetates. Franklin, MA. [cited by 2015 Mar 28th]. Retrieved from http://meltsnow.com/products/acetates/

Mix, J. (2006). HVAC Efficiency Definition. *Carrier Corporation*. [cited by 2015 Mar 28th]. Retrieved from http://www.usair-eng.com/pdfs/efficiency-definitions.pdf

MNGHPA. (2009). Geothermal Loop Options. *Brooklyn Center, MN: Minnesota Geothermal Heat Pump Association*. [cited by 2015 Mar 29th]. Retrieved from http://minnesotageothermalheatpumpassociation.com/geothermal/earth-loop-options/

National Energy Technology Laboratory. (2000). *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant*. Pittsburgh, PA: Publication DOE/NETL-403/110509.

NSF International. (2015). Polyiso Wall Insulation Boards. *Polyisocyanurate Insulation Manufactures Association (PIMA)*. [cited by 2015 Mar 25th]. Retrieved from http://c.ymcdn.com/sites/www.polyiso.org/resource/resmgr/Health_&_Environment/PIMA_EPD_Wall_Final_Publicat.pdf

Raypak, Inc. (2015). Anti-Freeze in Hydronic Systems. Oxnard, CA. [cited by 2015 Mar 24th]. Retrieved from http://www.raypak.com/support/tech_corner/anti_freeze

Risk Reduction Engineering Laboratory. (1993). Life Cycle Assessment: Inventory Guidelines and Principles. *U.S. Environmental Protection Agency*. EPA/600/SR-92/245. Cincinnati, OH, USA. [cited by 2015 Mar 19th]. Retrieved from http://nepis.epa.gov/Exe/ZyPDF.cgi/30003W9K.PDF?Dockey=30003W9K.PDF

RPM Tech. (2015). The Cameleon®: A Multifunctional Vehicle. Canada. [cited by 2015 Mar 21st]. Retrieved from http://grouperpmtech.com/en/municipal-vehicle.aspx

Scientific Applications International Corporation (SAIC). (2006). Life Cycle Assessment: Principles and Practice. U.S. Environmental Protection Agency. Contract No. 68-C02-067. Cincinnati, OH, USA. [cited by 2015 Mar 28th]. Retrieved from http://www.epa.gov/nrmrl/std/lca/pdfs/chapter1_frontmatter_lca101.pdfEPA. (2014). Life Cycle Assessment (LCA). *Washington, DC: United States Environmental Protection Agency*. [cited by 2015 Mar 16th]. Retrieved from http://www.epa.gov/nrmrl/std/lca/lca.html

Shen, W., Gopalakrishnan, K., Kim, S., and Ceylan, H. (2014). Greenhouse Gas Emission Analysis for Heated Pavement System. *The 2014 FAA Worldwide Airport Technology Transfer Conference*, Galloway, NJ, USA. [cited by 2015 Feb 28th]. Retrieved from http://www.airporttech.tc.faa.gov/att2014/Papers/P10065%20-%20Shen%20et%20al.pdf

Shen, W., Gopalakrishnan, K., Kim, S., and Ceylan, H. (2015). Carbon Footprint Analysis of Geothermal Heated Airport Pavements. *Transportation Research Board 94th Annual Meeting*. TRB Paper 15-4790.

Shi, X., Akin, M., Pan, T., Fay, L., Liu, Y., and Yang, Z. (2009). Deicer Impacts on Pavement Materials: Introduction and Recent Developments. The Open Civil Engineering Journal. 3: 16-27. [cited by 2015 Jun 2nd]. Retrieved from http://www.coe.montana.edu/me/faculty/Shi/DeicerPavementReview.pdf

Spath, P.L., Mann, M.K., and Kerr, D.R. (1999). Life Cycle Assessment of Coal-Fired Power Production. Golden, CO: NREL/TP-570-25119. NREL Life Cycle Assessment. [cited by 2015 Mar 21st]. Retrieved from http://www.nrel.gov/docs/fy99osti/25119.pdf.

Suh, S., Lenzen, M., Treloar, GJ., Hondo, H., Horvath, A., Huppes, G., and Jolliet, O. (2004). System Boundary Selection in Life Cycle Inventories Using Hybrid Approaches. *Environ. Sci. Technol* 38: 657-664.

University of South Carolina. (2008). Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand. *Airport Cooperation Research Program: Transportation Research Board*. [cited by 2015 Mar 13th]. Retrieved from http://onlinepubs.trb.org/onlinepubs/acrp/acrp_webdoc_003.pdf

Viega. (2015). S-no-Ice® Snow Melting System Installation Manual. *IM-SNO-01/05*. Wichita, KS, USA. [cited by 2015 Feb 15th]. Retrieved from http://www.viega.us/xbcr/en-us/Viega_S-no-ice_Snow_Melting_System.pdf

Washington State Department of Transportation. (2015). Metrics International System of Units. Olympia, WA, USA. [cited by 2015 Apr 28th]. Retrieved from http://www.wsdot.wa.gov/reference/metrics/factors.htm

Weber, C., Matthews, D., Venkatesh, A., Costello, C., and Matthews, H.S. (2010). The 2002 US Benchmark Version of the Economic Input-Output Life Cycle Assessment (EIO-LCA) Model. *Theory and Method behind EIO-LCA*. [cited by 2015 Mar 17th]. Retrieved from http://www.eiolca.net/docs/full-document-2002-042310.pdf

Wilo. (2013). Circulating Pumps. Dortmund, Germany. [cited by 2015 Feb 25th]. Retrieved from http://www.majo.rs/page_files/page_97/A1-Glandless%20Pumps%20-%202009.pdf

Xie, F., and Whiteley. J.R. (2007). Model Predictive Control of A Geothermally Heated Bridge Deck. *American Control Conference*. New York City, USA.

CHAPTER 6-CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Few studies have been done on evaluating the environmental impacts of airport snow removal system life cycles, especially the global warming potentials. Therefore, it is significant to develop a life cycle assessment model in order to help airports decide a more sustainable snow removal strategy. A set of three different studies was conducted to develop sustainability assessment framework for evaluating airfield heated pavements by using life-cycle assessment (LCA). The specific objectives and the conclusions drawn from key findings of each study are summarized in following subsections.

Assessment of greenhouse gas emissions from geothermal heated airport pavement system

The objective of this study presented in Chapter 3 is to evaluate the viability of geothermal heated pavement systems (or called hydronic heated pavement system using geothermal heat pump) as alternative substitute for traditional snow removal strategy to maintain airport runway snow free condition from a sustainable perspective. Based on the findings of this study, the following conclusions can be drawn:

- Geothermal heated pavement systems (GHPS or HHPS-G) have slightly lower GHG emissions than traditional snow removal systems (TSRS) applied for airport runway snow removal.
- According to the limitedly available information of airport snow removal life cycle assessment, this study shows operation phase contributes most differences between the life cycles of GHPS and TSRS, instead of construction phase.

- GHPS show more benefits to be used for removing snow from airport gate areas (or aprons). It not only has less environmental impacts, but also overcomes a number of problems associated with removing snow from gate areas using mechanical equipment, environmental pollution caused by use of chemicals, and safety issues involving snow-clearing ground crews on cold winter days.

Airport apron heated pavement system operation analysis: energy requirement, greenhouse gas emissions, and operating cost analysis

Based on the previous study shown in Chapter 3, Chapter 4 focus on analyzing the operation phases of hydronic pavement systems applied for apron snow removal. The objective of this study is to approach a more advanced life cycle assessment for hydronic heated apron pavement system operations. Energy consumptions, GHG emissions, and operation costs of 3 different types of hydronic heated pavement system, which use geothermal heat pump (HHPS-G), electric water heater (HHPS-E), or natural gas boiler (HHPS-NG), are analyzed and compared in order to achieve the goal of this study. Based on the findings of this study, the following conclusions can be drawn:

- Operation of HHPS-G with a low COP as 2.4 still considers more sustainable (less energy consumption, fewer GHG emissions, and lower operation costs) than other two types of hydronic heated pavement systems under weather conditions.
- From an environmental impact perspective, using natural gas for water heating, with a relatively low emission factor, has the potential to substitute for electricity as a more environmentally friendly energy source for hydronic heated pavement system operation.
- If efficiency of natural gas boiler energy extraction was improved, using natural gas as the energy source for heating would be able to reduce energy requirement, GHG emissions

and save more costs. Therefore HHPS-NG can be a better alternative for place where there is not enough geothermal energy.

Life cycle assessment of heated apron pavement system operation

The objective of this study presented in Chapter 4 is to develop a more comprehensive life cycle assessment (LCA) for evaluating energy consumptions and GHG emissions from different kinds of apron snow removal system operations. In order to help airport make a more informed decision in selecting more sustainable snow removal strategy for apron areas. Operations of hydronic heated pavement system using geothermal heat pump (HHPS-G), hydronic heated pavement using natural gas furnace (HHPS-NG), electrically heated pavement system, and traditional snow removal system (TSRS) are evaluated and compared by using a hybrid LCA. Based on the findings of this study, the following conclusions can be drawn:

- Heated pavement system apron application is viable from an energy or environmental perspective for automatically clearing ice/snow without using mechanical or chemical approaches.
- Energy production (i.e., electrical power generation) and energy consumption phases (i.e., natural gas combustion) for heating consume the most energy and contribute the most GHG emissions in a heated pavement system operation life cycle.
- HHPS-G using geothermal heat pumps with a COP higher than 2.5 results in less energy consumption and fewer GHG emissions than other types of snow removal systems under the same weather conditions.

- Hydronic heated pavement system using natural gas furnace, with high heating efficiency and a relatively low emission factor, has the potential to be a sustainable snow removal system for places where do not have a good geothermal condition.

State of the Art and Contribution to Engineering Practices

- Theoretical and experimental results of energy demand for snow melting and pavement idling are utilized in the hybrid life cycle model in this research to duplicate the actual behavior of heated pavement system (HPS).
- Energy consumptions, environmental impacts, and sustainability of HPS and traditional snow removal system (TSRS) life cycles are able to be quantified.
- Different types of airport snow removal systems can be compared from energy-saving and environmental perspectives.
- Environmental footprint of every life cycle inventories under the system boundary are tracked. Guidance could be given to improve sustainability of HPS by improving HPS life cycle phases which were identified to contribute most environmental impacts.
- This research gave evidences to show that using deicing/anti-icing chemicals for snow removal is not sustainable, and HPS as potential alternatives are able to overcome this problem.
- As the very first LCA of HPS for airport snow removal applications, life cycles inventories of HPS which are still lack of sufficient data are acknowledged and the gaps for future studies are provided.

- This research proves that facility efficiency and energy sources are two critical factors which determine sustainability of HPS. Therefore, heating techniques could be improved and renewable energies can be used for HPS operation in order to achieve more sustainable.
- When comprehensive life cycle assessment models are developed, the more accurate theoretical data can be gotten to duplicate the actual environmental impacts of different airport snow removal strategies.
- Airports can use these full-developed models to help themselves achieve "Airport Sustainability Planning" (i.e. reducing GHG emissions) by choosing the most sustainable snow removal strategy.

Recommendations

Although this research is able to quantify the environmental impacts of different airfield snow removal systems, it needs to be stressed that the life cycle theoretical models in these studies used to analyze energy consumption, GHG emissions, or operation costs are still under development. Therefore, more comprehensive assessments which include broader system boundary are required for future study.

Not only heated pavement systems, but also airfield traditional snow removal systems have rarely be studied, a great amount of required data to conduct a full-fledged LCA and TEA are not available. For example, maintenance phase of snow removal systems has not been studied yet. However, it has been studied that the use of deicer chemicals on airfield surfaces tend to cause and/or accelerate distresses leading to more frequent repairs (Shi et al 2009). When studying the whole life cycles of snow removal systems, this may increase the energy spent during the pavement maintenance phase. Therefore, it will be interesting to study the life cycle of both snow removal systems from this perspective. If more data becomes available, a detailed LCA and TEA could be conducted to gain further insights into the sustainability benefits and impacts associated with the use of heated pavement systems.

Because heated pavement system applied for heating airport paved surfaces is a relatively new technology, future studies may focus on different parameters associated with the behaviors of snow removal systems. For example, weather conditions, different deicing chemical usage strategies, and other potential factors that might influence energy consumptions and GHG emissions from different snow removal systems. Also, a sensitive analysis can be conducted for heated pavement systems by analyzing the varieties of system equipment sizing and choices of energy sources.

Reference

Shi, X., Akin, M., Pan, T., Fay, L., Liu, Y., and Yang, Z. (2009). Deicer Impacts on Pavement Materials: Introduction and Recent Developments. The Open Civil Engineering Journal. 3: 16-27. [cited by 2015 Jun 2nd]. Retrieved from http://www.coe.montana.edu/me/faculty/Shi/DeicerPavementReview.pdf

APPENDIX. LIFE CYCLE ASSESSMENT CALCULATION EXAMPLE

Take operation of hydronic heated pavement system using geothermal heat pump with a 3-COP for a1 in/h snow rate and 4 h snow period condition as an example.

Assumptions

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 coefficient of performance	3
Operation time (Snow period)	4 h
Concentration of antifreeze	40%
Temperature drop	30°F
GHPS & HHPS piping style	Parallel
Pressure drop	Only consider pressure drop in pipe
Efficiency of circulating pump	60%
Antifreeze life time	One year

Greenhouse Gas (GHG) Emission Factors

- 0.96 kgCO$_2$eq/kWh for coal (bituminous) fired power plant
- 0.42 kgCO$_2$eq/kWh for natural gas-fired power plant
- 0.778 kgCO$_2$eq/kWh for distillate oil (No.2) 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$_2$eq/kWh for natural gas production
- 0.181 kgCO$_2$eq/kWh for natural gas combustion
- 0.27 kgCO$_2$eq/kWh for diesel oil combustion
- 0.19 kgCO$_2$eq/kWh for diesel oil production

Energy Demand for Idling and Snow Melting Descriptions

Energy consumption of pavement idling (20°F to 32°F):

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

- 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).

Heat required for melting snow:

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

- 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 (dimensionless),
- q_e = heat of evaporation (Btu/h·ft^2),
- q_h = heat transfer by convection and (Btu/h·ft^2).

The sensible heat (qs) to bring the 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

- s = 0.1 = rate of snowfall (inches of water equivalent per hour)
- cp,ice = 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 lbs/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)

The heat of fusion (q_m) to melt the snow:

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

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

The heat of evaporation (qe):

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

- $P_{dry\ air} = 14.696$ = 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)

The heat of fusion (q_m) to melt the snow:

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

- h_c = convection heat transfer coefficient for turbulent flow (2.85 Btu/h·ft^2·°R^4)
- $\sigma = 0.1712\times10^{-8}$ = Stephan-Boltzmann constant (Btu/h·ft^2·°R^4)
- $\varepsilon_s = 0.9$ = emittance of wet slab

- T_f = 462.67 = liquid film temperature (°R)
- T_{MR} = 479.67 = mean radiant temperature of surroundings (°R)

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 hour operation time)

Total energy demand for operating geothermal heat pump:

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

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

GHG emissions from power plant generating electricity for geothermal heat pump operation:

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

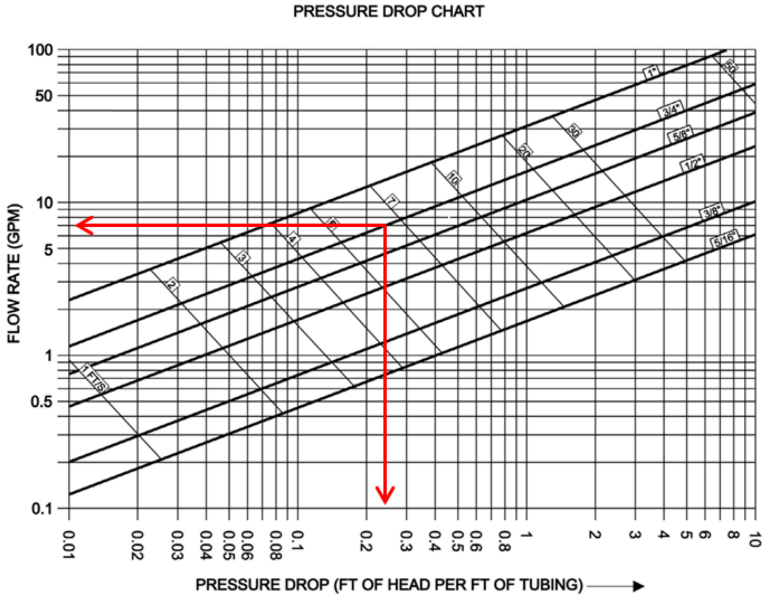
---

Piping Design & Circulating Pump Descriptions

(Viega Snow Melting System Installation Manual)

- ¾ 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 ft^2 × 1.5 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



(Pressure drop of ¾ inch pipe)

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

<u>Total energy for circulating pump operation:</u>

WHP = $\frac{Q\times H\times SG}{3960\times n}$ = 26 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),
- n = pump efficiency (60%).

Total GHG emissions from power plant generating electricity for circulating pump operation:

$(26\times0.96\times58\%+26\times0.42\times40\%+26\times0.778\times2\%)\times0.75$ kW/HP = 19 $kgCO_2/h$

Antifreeze Usage Descriptions

(Viega Snow Melting System Installation Manual)

- Antifreeze solution life time is assumed to be: 1 year
- Antifreeze: propylene glycol (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 propylene glycol: 513 Gal × 40% = 205 Gal
- Density of propylene glycol 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 kg
- Energy consumption factor: 27.57 kWh/kgPG
- GHG emission factor: 6.46 $kgCO_2/kgPG$

Total energy for PG production:

$\frac{27.57\times808}{365\times24}\times3.6$ MJ/kWh= 9MJ/h

Total GHG emissions from PG production:

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

Wastewater Treatment Descriptions

(Greest, J. V., Kiechle, C. 2010. "Anaerobic Wastewater Treatment Biogas Production from Brewery Wastewater")

- 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

Total energy for anti-freeze solution wastewater treatment:

$\frac{808\times1}{24\times365}\times3.6$ MJ/kWh = 0.54 MJ/h

Total GHG emissions from power plant generating electricity for anti-freeze solution wastewater treatment:

$(0.54\times0.96\times58\%+0.54\times0.42\times40\%+0.54\times0.778\times2\%)\times0.2778$ kWh/MJ = 0.1 $kgCO_2/h$

Insulation Layer Descriptions

(PIMA, Polyiso Wall Insulation Boards)

- 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 $ft^2+2\times(146\ ft+130\ ft)\times4\ in\times0.083\ ft/in = 19{,}184\ ft^2$
- Energy consumption factor: 8.66 MJ/ft^2
- GHG emission factor: 0.39 $kgCO_2eq/ft^2$

Total energy for insulation layer production:

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

Total GHG emissions from insulation layer production:

$$\frac{19184\times 0.39}{20\times 365\times 24} = 0.043\ \text{kgCO}_2\text{eq/h}$$