Final Abstract

Final Report Approved on May 21, 2025

M.L. 2021 Project Abstract

For the Period Ending June 30, 2024

Project Title: Enhanced Thermo-Active Foundations for Space Heating in Minnesota

Project Manager: Alison Hoxie

Affiliation: U of MN - Duluth

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Website: https://www.d.umn.edu/

Funding Source:

Fiscal Year:

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 07a

Appropriation Amount: $312,000

Amount Spent: $297,796

Amount Remaining: $14,204

Sound bite of Project Outcomes and Results

Overall, results from the project exhibit the high potential of solar-enhanced foundation heat exchangers to meet the entire building's energy loads in various Minnesota locations, reducing emissions by up to 70% compared to a natural gas + air conditioning system, without noticeable disturbance of the ground temperature.

Overall Project Outcome and Results

Space heating and hot water account for 60% of building energy use in Minnesota. With natural gas as the dominant source of heating (above 60%), the contribution of buildings to CO_2 emissions is tremendous. Ground source heat pumps (GSHPs) are promising renewable energy technologies for space heating and cooling due to their high efficiency (up to 500%), with great potential for curbing building-related emissions. However, the widespread deployment of GSHP technology has not yet been realized, mainly due to high capital costs and ground thermal imbalance in poorly designed and sized systems. Thermo-active foundation design allows utilizing the building foundation for the heat exchanger of the GSHP, thereby reducing the initial costs.

This project presents the results of investigations into the energy, economic, and emissions performance of horizontal foundation heat exchangers—i.e., serpentine and Slinky™ foundation heat exchangers—and vertical foundation heat exchangers, also called energy piles—i.e., u-tube and a novel offset pile heat exchanger. Overall, results from the project show the potential of solar-enhanced foundation heat exchangers to meet building energy loads in single-family Minnesota houses. The results of the analysis show that, compared to natural gas-fired systems with air conditioning, the payback period of these systems is about 14 to 15 years, while it is 10 to 11 years when compared with electric resistance heating.

In terms of emissions, our analysis suggests that solar-enhanced thermo-active foundation GSHPs can reduce emissions by up to 70% compared to a natural gas and air conditioning system—i.e., from about 9,200 to 2,030 kg CO_2 for the system with the lowest CO_2 emissions.

Project Results Use and Dissemination

The ENRTF funding for this project has resulted in 8 publications (conference and journal papers) in total. Three M.Sc. students, Prem Agarwal, Jordan Gruenes (M.Sc. University of Minnesota Duluth) and Amirhossein Darbandi (M.Sc. University of Calgary), have graduated with the support of this funding. One of the papers presented at ASTFE's conference receive the Best Research Paper Award, awarded to the 5 best research papers among the over 300 papers presented at the 9th Thermal and Fluids Engineering Conference, American Society of Thermal and Fluids Engineers (ASTFE), Oregon State University, OR, USA, April 21-24, 2024.

Environment and Natural Resources Trust Fund

M.L. 2021 Approved Final Report

General Information

Date: September 22, 2025

ID Number: 2021-010

Staff Lead: Noah Fribley

Project Title: Enhanced Thermo-Active Foundations for Space Heating in Minnesota

Project Budget: $312,000

Project Manager Information

Name: Alison Hoxie

Organization: U of MN - Duluth

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Project Reporting

Final Report Approved: May 21, 2025

Reporting Status: Project Completed

Date of Last Action: May 21, 2025

Project Completion: June 30, 2024

Legal Information

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 07a

Appropriation Language: $312,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota, Duluth, to design and optimize cost-competitive thermally enhanced heat exchanger systems for use in building foundations to improve energy efficiency and conservation of natural resources in Minnesota's cold climate.

Appropriation End Date: June 30, 2024

Narrative

Project Summary: This project primarily involves the design and optimization of cost-competitive, thermally enhanced and compact heat exchanger systems for deep thermo-active building foundations for Minnesota's space heating and cooling industry

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

Globally, buildings contribute about 40% of the total carbon dioxide emissions and use about 36% of the total energy supplied. In Minnesota, about 78% of the total energy bill goes to providing space heating and domestic hot water supply owing to the state's cold climate.

To reduce energy consumption in buildings, ground source heat pumps (GSHPs) are increasingly being considered given their ability to provide energy efficiently compared to conventional systems. They give about 25-45% energy savings compared to air source heat pumps and about 75% energy savings compared to electric resistance heating. Despite these benefits, several challenges have hindered widespread utilization of these systems. These include higher upfront costs, lack of drilling space in densely populated areas and performance degradation in cases where building heating and cooling loads vary significantly leading to ground thermal imbalance.

The use of thermo-active building foundations, where heat exchangers are embedded in the foundation structure has emerged as an excellent means to reduce drilling costs and space requirements for GSHPs. However, compared to conventional systems, limited studies have reported the performance of thermo-active foundations in the US climates. Moreover, these systems are shallower than conventional ones, thus requiring compact and optimized heat exchangers.

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

This study involves the design and optimization of thermally enhanced heat exchanger systems for thermo-active foundations for Minnesota's cold climate. When incorporated in building foundation structures, capital costs of GSHPs will significantly reduce, leading to increased uptake of the technology. Specific emphasis will be on pile and caisson foundations which present considerable lengths for energy transfer to and from the ground and are not space intensive.

Moreover, we will consider the influence of different heat exchanger configurations and several backfill materials on long-term system performance. Furthermore, we will engineer optimal configurations for the incorporation of phase change material for energy storage to alleviate thermal imbalance, while optimizing the cost of these systems. Using latent thermal energy storage minimizes ground thermal imbalance and improves the long-term performance of the system.

Detailed determination of building energy loads for proper sizing of heat exchangers will be undertaken. This requires the use of site specific climatic data to cater for temperature variation throughout the different seasons. Moreover, ground temperature variation affects heat transfer and long-term performance. As such, for the developed systems, the long-term coefficients of performance will be established by coupling building energy modeling and finite element analysis using TRNSYS and COMSOL.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

Successful completion of the project will provide designs of optimal configurations of enhanced heat exchangers for deep thermo-active foundations, demonstrate the influence of building energy loads on long-term system performance in Minnesota's cold climate and establish the energy saving potential and the resulting emission reductions from these systems. Moreover, a detailed economic analysis will be undertaken to establish the cost competitiveness of the developed solutions. Adoption of these systems for space heating and cooling will lead to reduced use of natural gas and biomass for space heating resulting in the conservation and preservation of Minnesota's natural resources.

Project Location

What is the best scale for describing where your work will take place?

Statewide

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

In the Future

Activities and Milestones

Activity 1: Determination of building energy loads and ground temperature profiles for different locations in different regions of Minnesota

Activity Budget: $103,460

Activity Description:

The performance of a ground source heat pump system is influenced by the deep ground temperatures as well as the nature of the building energy loads. The building energy loads and the ground temperature are dependent on the local climatic conditions of the system's location. In this task, we will select representative sites to be used in the evaluation of system performance. At least 25 counties representing diverse regions in the state will be considered. Moreover, we will select counties representing Northern Minnesota, North Eastern Minnesota, North Western Minnesota, Western Minnesota, South Western Minnesota, Southern Minnesota, South Eastern Minnesota, Eastern Minnesota and Central Minnesota. One site from each county will be considered.

For the selected sites, climatic data will be collected from different sources including the Minnesota State Climatology Office, the National Weather Services, the U.S. Climate data and others. This data will be organized and analyzed for use in the energy modelling studies. Then, models for determining the building heating and cooling loads for each site will be developed in the transient system simulation (TRNSYS) software.

Activity Milestones:

Description	Approximate Completion Date
Selection of different locations within the state for use in building energy modelling and transient system analysis studies	September 30, 2021
Development of soil thermal property and ground temperature variation models for the selected sites	November 30, 2021
Development of building models in TRNBuild for use in the determination of building loads	December 31, 2021
Determination of building energy loads for the selected sites using TRNSYS	June 30, 2022

Activity 2: Development, evaluation and optimization of thermally enhanced heat exchanger configurations for thermo-active building foundations in cold climates

Activity Budget: $139,100

Activity Description:

To properly design and size heat exchanger for thermo-active building foundations, a survey of the different deep foundations used in Minnesota will be undertaken. We will particularly look for the available diameters and depths of the pile and drilled caisson foundations. Furthermore, a survey of available heat exchanger designs for ground source heat pump systems will be done to be used for benchmarking performance of the developed concepts. With this information, at least three different designs of heat exchangers for thermo-active foundations for cold climates will be developed, evaluated and the best configurations optimized for further study. First law and second laws of thermodynamics with entropy generation minimization will be used to determine optimal configurations. Furthermore, optimal ways for incorporation of latent thermal energy storage (LTES) will be engineered and evaluated. It should be noted that this study does not intend to design building foundations, but heat exchanger systems that can be incorporated in already existing designs of foundation structures.

Activity Milestones:

Description	Approximate Completion Date
Development, evaluation and selection of thermally enhanced heat exchanger concepts for thermo-active foundations.	June 30, 2023

Development of numerical models of different concepts and evaluation of the potential enhancements with LTES	August 31, 2023
Development of a field scale system model to investigate long-term system performance with/without LTES	December 31, 2023

Activity 3: Evaluation of long-term system performance and techno-economic assessment of the developed heat exchanger systems

Activity Budget: $69,440

Activity Description:
Knowledge of the long-term performance of the system is essential in ensuring reliability and determining whether the system will continue to perform as expected. Here, the performance of the developed heat exchanger systems in a thermo-active foundation will be evaluated over 4 year, 10 year and 25 year periods. The coefficient of performance of the system over time will be evaluated to establish: (i) any performance enhancements or degradation, (iii) the energy usage and resulting carbon dioxide emission reductions, and (iii) the overall value of the technology by looking at benefits (savings) and costs - the Net Present Value (NPV) of such an investment will be determined. Moreover, the influence of latent energy storage on ground thermal imbalance will be investigated and any improvements in performance quantified and compared with a system having no latent thermal energy storage.

Activity Milestones:

Description	Approximate Completion Date
Determination of energy savings and emission reduction potential of the developed systems	April 30, 2024
Numerical simulation and determination of the long-term performance of the developed enhanced thermo-active foundations.	April 30, 2024
Development of a techno-economic assessment model to evaluate feasibility and profitability of different configurations	June 30, 2024

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Aggrey Mwesigy	University of Alberta	Collaborator	Yes

Dissemination

Describe your plans for dissemination, presentation, documentation, or sharing of data, results, samples, physical collections, and other products and how they will follow ENRTF Acknowledgement Requirements and Guidelines.
We will share our results with stakeholders in the Heating Ventilation and Air Conditioning (HVAC) industry, more specifically those in the design and installation and of ground source heat pump systems. Our plan is to present our findings at the Minnesota Geothermal Heat Pump Association's conference reaching local industry and experts and also at relevant national conferences such as the American Society of Mechanical Engineers' Energy and Sustainability conference and the International Ground Source Heat Pumps Association (IGSHPA) annual conference. Moreover, will also prepare and submit our work to independent peer-reviewed scientific journals for publication. In addition, we will also reach out to local industry to establish potential collaboration and eventually work towards securing funding for field testing of the developed technology to demonstrate its technical and financial viability to interested users.

During the dissemination of study findings, The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the
trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENTRF Acknowledgment Guidelines

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?
Results from the study will be shared with stakeholders in industry and professionals in the Heating, Ventilation, Air Conditioning and refrigeration (HVAC&R) discipline. With the results obtained from this study, we anticipate partnering with industry to write a grant proposal to be submitted to the U.S. Department of Energy for field scale experimentation and demonstration of performance of the optimized heat exchanger configurations for thermo-active foundations. Such experiments will enable us to validate the long-term performance of the system which is essential in assuring potential clients of the performance and reliability of the technology.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount	$ Amount Spent	$ Amount Remaining
Personnel										
2 Undergraduate research assistants		Two U of M undergraduate research assistants (5 hrs/week, 0.125 FTE each year for 2 years i.e. 25% for two students). Conducting numerical studies and assisting with the survey of building foundations and review of heat exchangers for GSHPs			0%	0.75		$10,013	-	-
1 MSc Research Assistant		1 U of M MSc student working of determination of energy loads using Transient System Simulation (TRNSYS) software and numerical modeling using COMSOL. Full time for two years and two summer periods (0.5 FTE, 19.9% fringe benefits: 50% of time per year and 25% for the summer months)			19.9%	1.25		$84,031	-	-
Postdoctoral Fellow		Assisting the PI with project administration and performing numerical modelling studies in both TRNSYS and COMSOL. Includes two periods of summer appointment. ($50000 base salary for 0.7 FTE and 20.2% fringe benefits)			20.2%	1.75		$135,283	-	-
Principal investigator, Hoxie		Project administration, student advising and development of numerical models in COMSOL. $14,145/yr (74% salary, 26% fringe). 50% paid effort during summer months x 3 yrs.			26%	0.27		$29,568	-	-
							Sub Total	**$258,895**	**$251,910**	**$6,985**
Contracts and Services										
Aggrey Mwesigy	Subaward	Dr Mwesigy will hire a graduate student at the University of Calgary, to assist in modeling and heat exchanger design				0.5		$28,400	$28,400	-

							Sub Total	**$28,400**	**$28,400**	**-**
Equipment, Tools, and Supplies										
	Tools and Supplies	TRNSYS software	TRNSYS is a transient thermal system simulation software, it will be used for the determination of building loads, which is essential for the prediction of the performance of a ground source heat pump					$4,530	$2,516	$2,014
	Tools and Supplies	1 COMSOL Multiphysics Floating Network Licence. Initial licence cost and subscription for two years	COMSOL Multiphysics will be used for most of the numerical simulations. It will be use for both steady state and transient simulations studies to determine ground temperature variation and the coefficient of performance over a period of 10 years. We were able to use Transys from another source. Therefore we did not need to purchase it. Instead we added one more module to the Comsol package. Therefore the Comsol was slightly more expensive then originally budgeted for.					$7,965	$7,965	-
							Sub Total	**$12,495**	**$10,481**	**$2,014**
Capital Expenditures										
		Computer	The computer is necessary to run the softwares requested for this project	X				$7,005	$7,005	-
							Sub Total	**$7,005**	**$7,005**	**-**

Acquisitions and Stewardship										
							Sub Total	**-**	**-**	**-**
Travel In Minnesota										
	Miles/ Meals/ Lodging	During the course or the project, we will establish connections with industry. Visits are anticipated as the project progresses	Meeting potential industry partners in the state and collaborating travel to sites where installation of geothermal heat pump systems might be taking place. Also presentation of findings to potential industrial partners					$1,605	-	$1,605
	Conference Registration Miles/ Meals/ Lodging	Minnesota Geothermal Heat Pump Association Conference for one person every year. Conference registration, meals and transport at a cost of 1000 per person per year	I am in the process of registering as a member of the Minnesota Geothermal Heat Pump Association, the largest geothermal assembly of installers, designers and educators in Minnesota, as a group we plan to be attending the annual conference and present our findings and learning from the contractors					$3,600	-	$3,600
							Sub Total	**$5,205**	**-**	**$5,205**
Travel Outside Minnesota										
							Sub Total	**-**	**-**	**-**
Printing and Publication										
							Sub Total	**-**	**-**	**-**
Other Expenses										
							Sub Total	**-**	**-**	**-**

							Grand Total	$312,000	$297,796	$14,204

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request
Capital Expenditures		Computer	The purchase of this computer has been previously approved by LCCMR. The final cost of the computer came in over by 5 dollars. **Additional Explanation :** The useful life of this computer will be spent running the TRNSYS and COSMOS software to obtain results for the project.

Non ENRTF Funds

Category	Specific Source	Use	Status	$ Amount	$ Amount Spent	$ Amount Remaining
State						
			State Sub Total	**-**	**-**	**-**
Non-State						
In-Kind	University of Minnesota Unrecovered indirect costs at 55% Modified total direct costs	This is the unrecovered indirect cost amount contributed to the running of the project by the University of Minnesota	Secured	$184,331	-	$184,331
			Non State Sub Total	**$184,331**	**-**	**$184,331**
			Funds Total	**$184,331**	**-**	**$184,331**

Attachments

Required Attachments

Visual Component

File: c1b76fa9-b3d.pdf

Alternate Text for Visual Component

The attached visual shows how the ground source heat pump system maintains thermal comfort in winter and summer by exchanging heat with the ground. The second visual shows a helical steel type pile thermo-active foundation and the incorporated u-loop heat exchanger. Different enhanced heat exchanger configurations will be developed, optimized and compared with this conventional type....

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Approved Research Addendum	07d7c324-56e.docx
Background Check Certification	a27c986e-c33.pdf
Paper 1	e35a79e1-d7e.pdf
Paper 2	6ea8cec0-3d0.pdf
Paper 3	ab2edeca-8b5.pdf
Paper 4	cc32577e-8a4.pdf
Paper 5	9a9c12c7-1eb.pdf

Difference between Proposal and Work Plan

Describe changes from Proposal to Work Plan Stage

Revision No.1

The main differences between the proposal and workplan are in the budget items. The budget has been revised to be inline with the recommended funding: The personnel costs have been revised by eliminating summer funding for the postdoc, reducing the amount from $61, 584 to $135,100, one undergraduate researcher will be hired now instead of two bringing the cost down from $18,984 to $9,891 and the PI from $59,677 to $57,939. The cost of software has also been changed and fewer essential libraries will now be purchased. COMSOL reduced from $21,185 to $14,000, TRNSYS from $11,000 to $5,500. Travel costs have been reduced from $9000 to $4000. A section on dissemination was added. Milestone 1 under activity 2 has also been deleted, this will be part of the literature review and not a milestone.

Revision No.2

Corrections have been made to the budget to have the benefits and the description the same. The values for the budget have not changed from the figures of the previous revision. We have now indicated the potential for patents from the study. We have specified at least 25 counties representing different regions to be considered for activity 1 and at least three heat exchanger configurations for activity 2.

Additional Acknowledgements and Conditions:

The following are acknowledgements and conditions beyond those already included in the above workplan:

Do you understand and acknowledge the ENRTF repayment requirements if the use of capital equipment changes?

Yes

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

Yes, I understand the UMN Policy on travel applies.

Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?

Yes

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

Yes

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

No

Does your project include original, hypothesis-driven research?

Yes

Does the organization have a fiscal agent for this project?

No

Work Plan Amendments

Amendment ID	Request Type	Changes made on the following pages	Explanation & justification for Amendment Request (word limit 75)	Date Submitted	Approved	Date of LCCMR Action
1	Amendment Request	• General Information • Budget - Capital, Equipment, Tools, and Supplies	The original budget requested funds to purchase a software. We thought our department had a computer that could run the software. However, we just realized we don't have the appropriate equipment. Coincidentally, the software cost was less than anticipated. We propose using $7,000 of the savings from that purchase to buy a computer that will enable us to run the software. The useful life of the computer will be spent running this software.	May 9, 2022	Yes	May 10, 2022
2	Amendment Request	• Budget - Capital, Equipment, Tools, and Supplies	The computer we bought came in 5 dollars over the expected amount. In addition we are planning to purchase a simpler Transys software package so that we could add an extra module to the Comsol Software package. Therefore we moved some of the amount budgeted for transys to cover the additional 965 dollars needed for Comsol.	July 13, 2022	Yes	July 13, 2022
3	Amendment Request	• Budget • Budget - Personnel	Move funding from PI salary and fringe to Post-Doc. Recently was called to my attention that post-docs in our SCSE college are paid $55,000 per year. Therefore, I am requesting an increase in salary for our post doc by $10,000 and the corresponding fringe for years 2 and 3 (average over 2 years is $5,000 salary increase).	February 9, 2023	Yes	February 16, 2023

Status Update Reporting

Final Status Update August 14, 2024

Date Submitted: May 21, 2025

Date Approved: May 21, 2025

Overall Update
The project comprised three activities: (i) determining building energy loads and ground temperature profiles for different locations in different regions; (ii) developing, evaluating, and optimizing thermally enhanced heat exchanger configurations for thermo-active foundations; and (iv) evaluating the long-term system performance and techno-economic assessment of the developed heat exchanger configurations.
In activity, 1building energy loads and soil thermal properties for representative locations across the state were determined for use in the subsequent analysis. For activity 2, preliminary studies indicated that the higher heating loads than cooling loads in Minnesota make the use of non-enhanced foundation heat exchangers not feasible. Further, preliminary investigations with latent thermal energy storage did not yield substation improvements in performance. Therefore, coupling foundation heat exchangers with solar thermal energy was considered as the feasible alternative for such a cold climate. Studies of solar-enhanced foundation heat exchangers for three representative locations – Winona, Duluth, and International Falls have been completed. For activity 3, the long-term performance studies have been conducted for a 5-year period to determine the evolution of heat pump's entering water temperatures and ground temperature. These were conducted in parallel with studies in activity 3.

Activity 1
This acPer LCCMR staff guidance, due to system logic, this is place holder text to allow the submission of required reporting.tivity was previously marked complete.
(This activity marked as complete as of this status update)

Activity 2
As per our last update in November 2023, preliminary investigations of the use of latent thermal energy storage did not show significant potential in cold climates. Thus, the studies related to this activity focused on enhancing foundation heat exchangers and pile systems with solar thermal energy. The studies focused on solar enhancement of these systems are now complete for three locations in Minnesota. These locations are deemed to have a diversity of building energy loads: International Falls, Duluth, and Winona.

Both horizontal foundation heat exchanger configurations coupled with the secondary recovery solar loop and the vertical system with two independent U-loop heat exchangers (one for the heat pump and one for the solar thermal recharging loop) have shown promising improvements in terms of heat pump efficiency (coefficient of performance), prevention of heat pump shutdown caused by low entering fluid temperature, shortening the soil freezing period, and solving the thermal imbalance problem. Completed studies on both serpentine and slinky configurations confirm that extending the heat exchanger length to the backyard or wrapping it around the basement is necessary to meet the heating loads.
All three milestones for activity 2 with solar thermal enhancement instead of LTES are now

complete.
(This activity marked as complete as of this status update)

Activity 3
Long-term performance studies have been conducted on the developed foundation heat exchanger concepts. For the serpentine foundation heat exchangers, studies covering a 5-year
period for Duluth, International Falls, and Winona were conducted. The long-term studies are computationally expensive, taking weeks to complete, as such, only a study period of 5 years was considered sufficient for such studies. From these studies, the percentage of the time when soil freezing is expected, the energy consumption, and the emissions reduction potential of the optimal configuration that extends the piping to the backyard have been determined. Similar studies have been conducted for the Slinky TM , horizontal foundation heat exchangers with and without solar enhancement as well as helical pile foundation heat exchangers with and without solar enhancement.
(This activity marked as complete as of this status update)

Dissemination
This funding has resulted in 8 publications (conference and journal papers) in total. Two M.Sc. students, Prem Agarwal (M.Sc. University of Minnesota Duluth) and Amirhossein Darbandi
(M.Sc. University of Calgary), have graduated with the support of this funding. Another student, Jordan Gruenes, is completing his studies this year. Since the last update, the following outputs have been prepared.
1. Darbandi A., Davani S., Gruenes J., Hoxie A., and Mwesigye A. Numerical investigation of the long-term thermal performance of a solar assisted foundation heat exchanger - ground source heat pump system for cold climates. Submitted to Energy Build (Impact factor: 6.7)
2. Davani S., Darbandi A., Gruenes J., Hoxie A., and Mwesigye A. Long-term thermal performance of a solar-assisted slinky foundation heat exchanger coupled with a heat pump for a cold climate. Submitted to Applied Thermal Engineering (Impact factor: 6.465).
We would also like to mention that the paper presented at this years ASTFE's conference receive the Best Research Paper Award, awarded to the 5 best research papers among the over 300 papers presented at the 9 th Thermal and Fluids Engineering Conference, American Society of Thermal and Fluids Engineers (ASTFE), Oregon State University, OR.

Status Update Reporting

Status Update June 1, 2024

Date Submitted: February 28, 2025

Date Approved: February 28, 2025

Overall Update
The project comprised three activities: (i) determining building energy loads and ground temperature profiles for different locations in different regions; (ii) developing, evaluating, and optimizing thermally enhanced heat exchanger configurations for thermo-active foundations; and (iv) evaluating the long-term system performance and techno-economic assessment of the developed heat exchanger configurations.
In activity1, building energy loads and soil thermal properties for representative locations across the state were determined for use in the subsequent analysis. For activity 2, preliminary studies indicated that the higher heating loads than cooling loads in Minnesota make the use of non-enhanced foundation heat exchangers not feasible. Further, preliminary investigations with latent thermal energy storage did not yield substation improvements in performance. Therefore, coupling foundation heat exchangers with solar thermal energy was considered as the feasible alternative for such a cold climate. Studies of solar-enhanced foundation heat exchangers for three representative locations – Winona, Duluth, and International Falls have been completed. For activity 3, the long-term performance studies have been conducted for a 5-year period to determine the evolution of heat pump's entering water temperatures and ground temperature. These were conducted in parallel with studies in activity 3. The techno-economic performance analyses of the different configurations are now complete.

Activity 1
This activity was previously marked complete.
(This activity marked as complete as of this status update)

Activity 2
As per our last update in November 2023, preliminary investigations of the use of latent thermal energy storage did not show significant potential in cold climates. Thus, the studies related to this activity focused on enhancing foundation heat exchangers and pile systems with solar thermal energy. The studies focused on solar enhancement of these systems are now complete for three locations in Minnesota. These locations are deemed to have a diversity of building energy loads: International Falls, Duluth, and Winona.
Both horizontal foundation heat exchanger configurations coupled with the secondary recovery solar loop and the vertical system with two independent U-loop heat exchangers (one for the heat pump and one for the solar thermal recharging loop) have shown promising improvements in terms of heat pump efficiency (coefficient of performance), prevention of heat pump shutdown caused by low entering fluid temperature, shortening the soil freezing period, and solving the thermal imbalance problem. Completed studies on both serpentine and slinky configurations confirm that extending the heat exchanger length to the backyard or wrapping it around the basement is necessary to meet the heating loads.
(This activity marked as complete as of this status update)

Activity 3
Long-term performance studies have been conducted on the developed foundation heat exchanger concepts. For the serpentine foundation heat exchangers, studies covering a 5-year period for Duluth, International Falls, and Winona were conducted. The long-term studies are computationally expensive, taking weeks to complete, as such, only a study period of 5 years was considered sufficient for such studies. From these studies, the percentage of the time when soil freezing is expected, the energy consumption, and the emissions reduction potential of the optimal configuration that extends the piping to the backyard have been determined. Similar studies have been conducted for the SlinkyTM,

horizontal foundation heat exchangers with and without solar enhancement as well as helical pile foundation heat exchangers with and without solar enhancement.
(This activity marked as complete as of this status update)

Dissemination
This funding has resulted in 8 publications (conference and journal papers) in total. Two M.Sc. students, Prem Agarwal (M.Sc. University of Minnesota Duluth) and Amirhossein Darbandi (M.Sc. University of Calgary), have graduated with the support of this funding. Another student, Jordan Gruenes, is completing his studies this year. Since the last update, the following outputs have been prepared.

Status Update Reporting

Status Update December 1, 2023

Date Submitted: December 6, 2023

Date Approved: December 20, 2023

Overall Update

All three milestones of Activity 2 are achieved for vertical FHX with/without LTES. However, owing to the notable improvements observed with horizontal FHX systems integrated with solar thermal energy, solar thermal coupling was prioritized over LTES for the vertical system. Milestone 2 tasks are finished for horizontal serpentine and slinky configurations, and a specific vertical configuration, with finalization expected shortly for vertical double U-loop solar-assisted configuration. Concurrently, some Activity 3 milestones are accomplished including long-term performance studies of different configurations. Current progress includes:

 Evaluating vertical system with integrated LTES across different locations and loads, assessing the utility of integrated LTES.

 Extension of solar-assisted GSHP concept for thermo-active foundation for two horizontal and two vertical FHX configurations

 Conducted long-term studies (at least 4 years) for field-scale systems for all configurations except double U-loop across at least three representative locations in Minnesota.

 Validation of double U-loop model in two ways: (1) based on experimental inlet temperatures (2) using the model of GSHP coupled with solar collector.

 Utilization of field-scale models to determine the proper system size in terms of heat exchanger length and the solar collector area for horizontal systems, and the required number of piles in the vertical system.

Activity 1

This activity was previously marked complete.

(This activity marked as complete as of this status update)

Activity 2

Our simulations on non-enhanced foundation heat exchangers (FHX) demonstrate the urgent need for enhancement for operability in Minnesota. The vertical system studies indicated that integrating latent thermal energy storage (LTES) is helpful but not significant. Contrarily, horizontal system configurations coupled with the secondary recovery solar loop have shown promising improvements in terms of COP enhancement, prevention of heat pump shutdown caused by low entering fluid temperature, shortening the soil freezing period, and solving the thermal imbalance problem. Studies on both serpentine and slinky configurations reveal the necessity of extending the heat exchanger length to the backyard or wrapping it around the basement to meet the heating loads.

This prompted us to shift our focus to solar-aided enhancement concepts for vertical FHX system. Two novel vertical arrangements are considered: (1) two independent U-shaped heat exchangers in a pile, one connected to the heat pump and one to a solar collector (2) solar loop fluid mixing with the outlet of a vertical FHX during heating and with the inlet during cooling mode. The configuration (1) model is validated and simulations for Minnesota locations are ongoing, whereas simulations for configuration (2) are complete for cases with/without enhancement and for different locations inMinnesota.

Activity 3
Activity 3 is about to start.

Dissemination
We have one manuscript ready for submission to Energy and Buildings (IF 6.7), focused on a solar-assisted FHX ground source heat pump system with serpentine piping configuration, and another manuscript is currently in preparation using the slinky configuration. in addition to the already reported papers, the following are in preparation:

1. Gruenes J., Davani S., Darbandi A., Agarwala P., Hoxie A., Mwesigye A. Thermal Performance Analysis of Solar Assisted Double U-Loop Heat Exchanger in Helical Steel Pile as Thermo-Active Foundations for Cold Climates, Accepted abstract, full-text Read for submission to 9th Thermal and Fluids Engineering Conference (Hybrid), American Society of Thermal and Fluids Engineers (ASTFE), April 21-24, 2024, Corvallis, OR, US.
2. Darbandi A., Davani S., Gruenes J., Hoxie A., Mwesigye A. Performance of a Solar Assisted Foundation Exchanger- Ground Source Heat Pump System for Cold Climates, Ready for Submission to Energy and Buildings
3. Davani S., Darbandi A., Agarwala P., Gruenes J., Hoxie A., Mwesigye A. Design and performance analysis of solar assisted slinky TM type foundation heat exchangers for space heating and cooling in a cold climate. Presented in 1 st Northland Complex Fluids Workshop, Oct 27 th , Duluth, MN, US.

Status Update Reporting

Status Update June 1, 2023

Date Submitted: June 2, 2023

Date Approved: June 12, 2023

Overall Update
All activity 1 milestones were successfully completed as per the previous reporting. For this reporting period, milestone 1 of activity 2 is now complete and we are on track to complete the next two milestones for enhancing the system performance using LTES. In addition, although not included in the milestones, we have evaluated the integration of solar thermal energy into the FHX systems for ground source heat pumps.
Summary of current progress:
 Developed and validated numerical models for three types of FHXs: vertical U-loop, horizontal slinky, and horizontal serpentine heat exchangers, using available experimental data.
 Selected six locations (Duluth, International Falls, St. Cloud, St. Paul, Winona, and Mankato) representing diverse climatic conditions for long-term studies, based on soil properties and building energy loads.
 Developed a solar-assisted recovery system for serpentine horizontal heat exchanger which shows a significant improvement in system performance. This will be extended to the slinky heat exchanger.
 Conducted preliminary model of a helical steel pile using LTES, which showed an 8-10% reduction in the number of hours the entering water temperature drops below the heat pump's minimum operating temperature
 Initiated long-term simulations (five-year) for all systems in the selected locations, both with and without enhancement

Activity 1
This activity was previously marked complete.
(This activity marked as complete as of this status update)

Activity 2
Long-term thermal performance studies have been conducted on various foundation heat exchanger (FHX) configurations since the last update. Efforts to enhance their thermal performance are underway and being evaluated. For activity 2, we have developed, verified, validated, and investigated the performance of enhanced vertical and horizontal FHX models. Simulations were tailored for Minnesota's climatic conditions factoring in water-antifreeze mixture ratios, suitable heat pump models, minimum allowed heat pump entering water temperature, and soil freezing. Our results show that non-enhanced horizontal FHX systems can meet a small fraction of the building's energy load due to small foundation footprint and the significantly higher heating loads of Minnesota. For the vertical FHX, about 8 – 10 piles would be required to meet the building energy loads.
To address this, enhancement techniques are being explored. For horizontal FHX systems, a secondary recovery ground loop connected to a solar collector is being incorporated to circulate warm fluid in the ground which increases soil temperature and heat pump performance. In the case of vertical FHX, the evaluation of macro encapsulated phase change

material (PCM) as latent thermal energy storage (LTES) adjacent to the pile is underway. Both short and long-term numerical modeling for these

Activity 3

Activity 3 has not begun yet.

Dissemination

We recently participated in conferences hosted by American Society of Thermal and Fluids Engineers (ASTFE) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and presented our preliminary work.. The presented papers, some of which are available online are listed below.

i. Davani S., Darbandi A., Agarwala P., Gruenes J., Hoxie A., Mwesigye A. Design and performance analysis of Slinky TM type foundation heat exchangers for space heating and cooling in a cold climate. In Conference Proceedings of the 8th Thermal and Fluids engineering Conference (Hybrid), American Society of Thermal and Fluids Engineers (ASTFE), March , 26-29, 2023, Maryland, College Park, MD, USA. DOI: 10.1615/TFEC2023.ens.046078

ii. Darbandi A., Davani S., Gruenes J., Agarwala P., Hoxie A., Mwesigye A. Long-term thermal performance investigation of horizontal foundation heat exchangers for space heating and cooling in extremely cold climates. In Conference Proceedings of the 8th Thermal and Fluids engineering Conference (Hybrid), American Society of Thermal and Fluids Engineers (ASTFE), March , 26-29, 2023, Maryland, College Park, MD, USA. DOI: 10.1615/TFEC2023.rfs.045922

iii. Agarwala P., Davani S., Gruenes J., Darbandi A., Hoxie A., Mwesigye A. Numerical analysis of vertical thermo-active foundations for cold climates,

Status Update Reporting

Status Update December 1, 2022

Date Submitted: February 9, 2023

Date Approved: February 16, 2023

Overall Update
The milestones for activity one is now complete, and we are on track to complete milestone 2
A summary of the current progress is listed below:
• A survey of the residential foundation in Minnesota prompted us to select the basement foundation for our study. basement
• A vertical U-tube heat exchanger embedded in a helical steel pile model has been developed and validated
• A shallow horizontal linear heat exchanger under the foundation model has been developed and validated
• A shallow Slinky heat exchanger under the foundation model has been developed
• The energy loads and the basement temperature from the building energy model were used in the CFD models
• The collected weather data, site-specific soil thermal properties, and ground temperature profile (Xing-Spitler model) were incorporated into our models
• The CFD model and the building energy loads were coupled through the heat pump coefficient of performance (COP) equation and the first law of thermodynamics
• Impact of flow rate, pile location with respect to the foundation, pipe diameter, horizontal system's buried depth, and the compactness of the slinky heat exchanger were studied
• The vertical, horizontal linear, and the slinky foundation heat exchangers can meet 0.4, 0.8, and 1.9 tons of energy.

Activity 1
This activity was previously marked complete. This activity is complete.
(This activity marked as complete as of this status update)

Activity 2
The first milestone for activity 2 will be completed on June 30, 2023. Up to this point, we have developed three different designs of heat exchangers for being integrated into the building foundation, a vertical U-loop embedded in the helical steel pile, a linear, and a Slinky horizontal heat exchanger buried under the building foundation. We have evaluated the overall performance of these heat exchangers when they are coupled with the building energy loads and evaluated them in terms of coefficient of performance (COP). Additionally, we have started working on a solar-assisted design to enhance the performance of the linear horizontal heat exchanger and address the issue of freezing of the soil adjacent to pipes caused by the low operating temperature of the ground source heat pump. Our primary simulations show promising results.

Activity 3
This activity has not been started yet.

Dissemination
We have submitted these conference papers to prestigious conferences in the HVAC and thermo-fluid sectors:
1. "Long-Term Thermal Performance Analysis of a Horizontal Foundation Heat Exchanger for Space Heating and Cooling in Extremely Cold Climates", submitted to ASTFE's 8th Thermal and Fluids Engineering, Accepted
2. "Design and Performance Analysis of Slinky Type Foundation Heat Exchangers for Space Heating and Cooling in a Cold Climate", submitted to ASTFE's 8th Thermal and Fluids Engineering, Under review
3. "Thermal Performance Analysis of Helical Steel Thermo-Active Foundations for Cold Climates" submitted to ASHREA's HVAC Cold Climate Conference 2023

4. “CFD Study of Vertical U-Loop Thermo-Active Foundations for Cold Climates”, presented at 75th Annual meeting of the APS Division of Fluid Dynamics

Status Update Reporting

Status Update June 1, 2022

Date Submitted: July 13, 2022

Date Approved: July 13, 2022

Overall Update
· Detailed determination of the building energy loads was performed for 24 selected locations in Minnesota through Building Energy Modeling verified with another study.

· 3D steady-state CFD simulations of a U-tube heat exchanger for cooling mode based on the experimental study of Miyara et al. was conducted using ANSYS Fluent software and validated against the experimental data. The validated model is used to evaluate the system performance for the cold climate of Minnesota.

· 3D transient CFD simulation of a shallow horizontal heat exchanger was performed in ANSYS Fluent software and validated with an experimental study.

· The validations done for the CFD studies will be the basis for the tasks in Activity 2.

· Annual and spatial typical ground temperature specific to the selected locations in the state was obtained through a two-harmonic model provided by Xing-Spitler. The ground profile can be used as the far-field boundary condition for the ground heat exchanger studies

· Site-specific soil thermal properties including the thermal conductivity, density, and specific heat are being calculated through a mixing model that takes the dry soil composition (silt, sand, clay) and moisture content into account. The composition information was obtained through drilling data and USDA's web soil survey.

Activity 1
The Typical Meteorological Year datasets of 55 Minnesota locations were collected and organized to be used as inputs for building energy models (BEM) and transient CFD simulations. The typical ground temperature of each location was obtained through a two-harmonic model (Xing/Spitler 2017) specific to selected locations. The BEMs are established based on building characteristics of a study conducted by a project team at the University of Minnesota (Huelman et al. 2016) for three single-family, detached residential buildings sizes (2028, 2976, and 3996 square feet) with a basement foundation, all compliant with 2012 IECC and 2015 MN energy codes. We first started with the BEM in the TRNBuild/TRNSYS environment, however BEopt was used later due to its similarity to the simulation software of the reference (REm/RateTM). BEopt is an hourly BEM software using EnergyPlus as the engine and does the steps that would be done in TRNSYS. Results are consistent in both the energy consumption and design loads. The validated models were extrapolated to 24 populated locations in Minnesota, providing the design cooling/heating loads, annual energy consumptions, hourly loads, and hourly temperature of the air zones. The output of the BEMs will be used in CFD simulation
(This activity marked as complete as of this status update)

Activity 2
N/A

Activity 3
N/A

Dissemination

N/A