YELNAR YERDESH

Thermodynamic optimization of ground source heat pump systems with four thermal reservoirs

ABSTRACT

of the dissertation for the degree
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“8D05403 – Mechanics”

Relevance of the research. Space heating is one of the most energy- and carbon-intensive end uses in cold, continental climates like Kazakhstan’s. Reliance on coal and gas boilers drives CO_2 emissions and urban air pollution, while large winter temperature lifts make efficiency hard to sustain. Ground source heat pumps (GSHPs) offer a strong decarbonization pathway because subsurface temperatures are stable and seasonal performance can remain high. Yet deployment is constrained by high drilling costs, seasonal thermal imbalance around boreholes, and tightly coupled design choices – refrigerant, heat exchanger sizing, and operating temperatures – that are context-specific.

Scientifically, the topic is relevant because a persistent gap remains between component-level studies and a system-level thermodynamic theory that captures finite-rate heat transfer and irreversibilities. Much of the literature relies on idealized or steady-state models and simplified reservoir abstractions, which blur how exchanger and capacity resources should be allocated across the coupled source-sink interfaces. Without a framework that captures these interdependencies, designers cannot reliably anticipate COP losses at large temperature lifts, quantify trade-offs between heat exchanger effectiveness and capacity rates, or formulate robust rules to limit long-term ground cooling under winter-dominant loads.

Practically, the topic matters because policymakers and engineers need bankable, climate-specific guidance to scale GSHPs while meeting environmental commitments. Choices on low-GWP refrigerants, borehole sizing, and operating temperatures shape not only efficiency and reliability but also environmental impact (e.g., total equivalent warming impact, TEWI) and cost. In continental climates – where heating seasons are long and peaks are high – validated thermodynamic-environmental criteria are essential to de-risk investments, prioritize limited capital (e.g., heat exchanger area), and ensure that GSHPs deliver durable emissions reductions and modernized heating services aligned with national decarbonization strategies.

The aim of this research is to develop theoretical and methodological foundations for the thermodynamic optimization of ground source heat pump (GSHP) systems, based on the integration of finite-time thermodynamics (FTT) models, 3E (energy, exergy, environmental) analysis, and experimental validation under continental climatic conditions.

Objectives of the research:

- Build an FTT optimization framework for GSHPs with four heat exchangers.

- Formulate multi-variable optimization for imposed operating conditions.
- Perform parametric analyses of heat exchanger effectiveness, capacity rates, irreversibility.
- Develop and validate a 3E framework using Almaty GSHP data.
- Provide design and operational guidelines for continental climates.

Object of the research: ground source heat pump systems for heating applications in continental climatic conditions.

Subject of the research: thermodynamic optimization of GSHP performance, with emphasis on irreversibility, allocation of heat exchanger resources, refrigerant selection, and efficiency-environmental trade-offs.

Research methods integrate finite-time thermodynamic modeling with energy-exergy analysis and environmental assessment to optimize GSHP performance. The workflow includes numerical simulation, experimental testing, and benchmarking against measured data and published studies.

Scientific novelty of the research is as follows:

1. A unified finite-time thermodynamics (FTT) framework for GSHPs that treats system-level cycle-reservoir coupling across the four heat exchangers.
2. New optimization criteria for operation under imposed conditions – specifically imposed heat extraction and heat production rates.
3. Modeling of heat pump irreversibility, which allows deriving optimal allocation rules for heat exchanger effectiveness and capacity rates.
4. A comprehensive, validated 3E (energy-exergy-environmental) analysis of GSHP performance, supported by experimental operating data under continental climate conditions.
5. Generalizable design rules for heat exchanger resources allocation, refrigerant selection, and operating temperatures applicable to continental climates.

Theoretical and practical significance of the research.

This work advances thermodynamic optimization by developing an FTT framework for GSHPs that explicitly treats irreversibilities and finite heat transfer rates, yielding new criteria for imposed operating conditions and allocation rules for heat exchanger effectiveness and capacity rates. Integrated with a validated 3E analysis using Almaty field data, it provides a unified, system-level methodology. Practically, the results offer actionable guidance on sizing and allocation of heat exchanger resources, low-GWP refrigerant selection, and operating temperatures for continental climates – improving COP, lowering emissions, and reducing costs. Strategically, they inform policy and investment by de-risking GSHP deployment in cold regions.

Scientific provisions submitted for defense:

1. A finite-time thermodynamic optimization methodology for GSHPs that explicitly treats system-level coupling across four heat exchange interfaces.
2. Thermodynamic models under imposed heat transfer conditions, covering imposed heat extraction and heat production rates.

3. Optimal allocation criteria for heat exchanger effectiveness and capacity rates in the presence of irreversibility.
4. A validated 3E (energy-exergy-environmental) framework for thermal efficiency and environmental performance, supported by experimental data obtained at the GSHP installation in Almaty.

Reliability and validity of the scientific provisions, conclusions, and results of the thesis.

The reliability of this thesis rests on rigorous first-principles modeling and established thermodynamic doctrine: all GSHP models are derived from mass, energy, and exergy balance equations consistent with the first and second laws, while finite-time thermodynamics explicitly represents finite heat-transfer rates, irreversibilities, and entropy production. This ensures internal consistency and theoretical rigor of the optimization criteria and the allocation rules for heat exchanger effectiveness and capacity rates. Environmental quantification follows internationally recognized 3E practice, including lifecycle climate metrics such as TEWI, providing a transparent link between thermodynamic performance and environmental impact.

Validity is demonstrated through multi-layered external checks. Model predictions are experimentally validated against measurements from a GSHP installation in Almaty (e.g., COP, ground temperature response), and show agreement with methodologies and trends reported in international GSHP and cascade HP studies. The results have undergone scholarly approbation via peer-reviewed publications and conference presentations, reinforcing credibility (e.g., Yerdesh et al., 2020; 2022). Together, the convergence of first-principles modeling, empirical validation under continental climate operation, and consistency with the literature establishes both the robustness of the scientific provisions and the practical applicability of the conclusions for GSHP design and optimization in cold regions.

Connection of the thesis with other research projects.

This thesis was carried out within the following scientific research projects:

1. AP26102323 “Optimization of efficiency and configuration of high-temperature heat pumps for integrating renewable energy sources and utilizing waste heat”, grant funding of the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 2025-2027.
2. AP14871988 “Development of a solar-thermal desalination plant based on a heat pump”, grant funding of the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 2022-2024.
3. AP08857319 “Study of heat transfer enhancement mechanisms of vertical type borehole heat exchanger to ensure high heat pump performance”, grant funding of the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 2020-2022.
4. APP-SSG-17/0280F “Cascade solar assisted heat pump for space heating and domestic hot water in continental climate regions”, supported by the Science Committee of the Ministry of Education and Science of the Republic of

Kazakhstan and World Bank under the “Fostering Productive Innovation”, 2018-2020.

5. AP05132668 “Development of an auto-cascade solar heat pump for high-potential residential heating in continental climates”, grant funding of the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 2018-2020.

Publications. The author has published 7 scientific papers on the topic of the dissertation, including **4 articles in international scientific journals indexed in Scopus and Web of Science:**

1. Yerdesh Ye., et al. Numerical simulation on solar collector and cascade heat pump combi water heating systems in Kazakhstan climates, Renewable Energy, Volume 145, 2020, pp. 1222-1234, https://doi.org/10.1016/j.renene.2019.06.102 (Q1, IF 8.001, Percentile 88, SJR 1.825) (**First author**).
2. Yerdesh Ye., et al. Experimental and theoretical investigations of a ground source heat pump system for water and space heating applications in Kazakhstan, MDPI Energies, Volumne 15, №22, 2022, pp. 1-25, https://doi.org/10.3390/en15228336 (Q3, IF 3.2, Percentile 83, SJR 0.632) (**First author**).
3. Karlina Ye., Yerdesh Ye., et al. Numerical simulation study of thermal performance in hot water storage tanks with external and internal heat exchangers, MDPI Energies, Volume 17, №22, 2024, pp.1-18, https://doi.org/10.3390/en17225623 (Q3, IF 3.2, Percentile 85, SJR 0.713) (**Corresponding author**).
4. Baimbetov D., Yerdesh Ye., et al. Thermal analysis of a compression heat pump-assisted solar still for Caspian regions of Kazakhstan, Journal of Thermal Analysis and Calorimetry, Volume 149, №19, 2024, pp. 11269-11291, https://doi.org/10.1007/s10973-024-13446-4 (Q2, IF 3.1, Percentile 85, SJR 0.551) (**Co-author**).

2 publications in international conference proceedings indexed in Scopus:

5. Toleukhanov A., Belyayev Ye., Yerdesh Ye., et al. Simulation-based mathematical modeling of borehole heat exchanger thermal performance for ground source heat pumps, Journal of Mathematical Sciences, Conference Paper, Vol. 291, №2, 2025, pp. 323-335, https://doi.org/10.1007/s10958-025-07811-3 (Percentile 10, SJR 0.153)
6. Belyayev Ye., Toleukhanov A., Yerdesh Ye., et al. Energy and exergy performance study of ground source heat pump in continental climate conditions, AIP Conference Proceedings, Volume 3126, №1, 2024, pp. 1-8, https://doi.org/10.1063/5.0200363 (Percentile 10, SJR 0.153)

1 article in international scientific journal:

7. Yerdesh Ye., et al. Air-to-water cascade heat pump thermal performance modelling for continental climate regions, Entropie Thermodynamique,

Volume 3, №1, 2022, pp. 1-16, https://doi.org/10.21494/ISTE.OP.2022.0836 (**First author**).

Personal contribution of the author.

The author defined the research objectives, conducted the literature review, and developed mathematical models of GSHP systems within a finite-time thermodynamics (FTT) framework. The author implemented the 3E (energy-exergy-environmental) methodology, performed numerical simulations and optimization, and analyzed results to derive new optimization criteria and design guidelines for heat exchanger allocation, refrigerant selection, and operating conditions.

The author also contributed to the experimental program: preparing the test stand, collecting thermal and electrical data, and validating the models under Kazakhstan's continental climate (Almaty installation). The dissertation's main text, analyses, and interpretation were written by the author; co-authors provided scientific supervision and methodological support. Results from joint works are co-owned by all contributors, and external materials are cited in the relevant sections.

Thesis structure and scope. The thesis includes a title page, table of contents, introduction, two chapters, a conclusion, and a list of references. It is 81 pages long and contains 29 figures and 6 tables.

Main content of the thesis.

The introduction presents the relevance of the research, formulates the aim and objectives, emphasizes the scientific novelty, and highlights the theoretical and practical significance of the results. It also notes the approbation of the main findings at international conferences and their publication in peer-reviewed journals, and outlines the structure and contents of the thesis.

The main part comprises two chapters and ten sections.

Chapter 1 develops a finite-time thermodynamics (FTT) framework for optimizing ground source heat pump (GSHP) systems. It reviews GSHPs and FTT methods, formulates mathematical models of endoreversible and irreversible heat pump cycles, and considers two imposed operating cases. The results yield new relationships for optimal allocation of heat exchanger effectiveness and capacity rates, and clarify how cycle irreversibility and temperature lift affect performance, providing a theoretical basis for GSHP design rules.

Chapter 2 presents a 3E (energy-exergy-environmental) analysis of GSHPs, validated using experimental data from a pilot installation in Almaty, Kazakhstan. It describes the experimental setup, develops and validates conventional GSHP models against measured data, and analyzes performance under different operating conditions, including refrigerant selection, exergy efficiency, and TEWI. The findings demonstrate the practical applicability of the methodology for GSHP design in continental climates.

The conclusion synthesizes the principal results, formulates scientific and practical outcomes, and offers recommendations for the design and operation of GSHP systems. The thesis also includes a list of references.