REVIEW

of the official reviewer for dissertation work

Yelnar Bakytkhanuly Yerdesh on the theme «Thermodynamic optimization of ground source heat pump (GSHP) systems with four thermal reservoirs» presented for the degree of Doctor of Philosophy (PhD) in the specialty «8D05403 – Mechanics».

№	Criteria	Eligibility (one of the options must be checked)	Justification of the position of the official reviewer
1.	The topic of the thesis (as of the date of its approval) corresponds to the directions of development of science and/or state programs	1.1 Compliance with priority areas of science development or government programs: 1) The thesis was completed within the framework of a project or target program financed from the state budget (indicate the name and number of the project or program) 2) The thesis was completed within the framework of another state program (indicate the name of the program) 3) The dissertation corresponds to the priority direction of the development of science, approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan (indicate the direction)	The dissertation is aligned with national priorities related to energy efficiency, renewable energy integration, decarbonization of heating and cooling systems, and sustainable technological development. The work was carried out within the framework of several state-funded scientific projects, including AP26102323, AP14871988, AP08857319, AP05132668, and APP-SSG-17/0280F, which confirms its direct relevance to state scientific programs.
2.	Importance for science	The work **makes**/does not make a significant contribution to science, and its importance is well disclosed/not disclosed	The dissertation develops a unified finite-time thermodynamics (FTT) optimization framework for GSHP systems, introduces new allocation criteria for heat exchangers, and provides experimentally validated 3E models. These results advance thermodynamic optimization theory and its application to geothermal heat pump systems.
3.	The principle of independence	Self-reliance level: 1) **High;** 2) Medium; 3) Low;	The author independently formulated research objectives, developed models, performed simulations, conducted experimental work, and wrote the

		4) No independence	dissertation. The personal contribution is clearly stated
4.	The principle of inner unity	4.1 Justification of the relevance of the thesis: 1) **Justified;** 2) Partially justified; 3) Not justified.	The introduction thoroughly demonstrates the global and national need for efficient heating technologies, especially in continental climates such as Kazakhstan
		4.2 The content of the thesis reflects the topic of the thesis: 1) **Reflects;** 2) Partially reflects; 3) Does not reflect	Each chapter directly addresses the thermodynamic optimization of GSHP systems using FTT and 3E analysis.
		4.3. The purpose and objectives correspond to the topic of the thesis: 1) **correspond;** 2) partially correspond; 3) do not correspond	The objectives are directly aligned with developing and validating thermodynamic optimization methods for GSHPs.
		4.4 All sections and provisions of the thesis are logically interconnected: 1) **completely interconnected**; 2) the interconnection is partial; 3) there is no interconnection	Chapter 1 develops theory, Chapter 2 provides experimental validation and 3E analysis, conclusions synthesize the results.
		4.5 The new solutions (principles, methods) proposed by the author are reasoned and evaluated in comparison with the known solutions: 1) **there is a critical analysis;** 2) partial analysis; 3) the analysis does not represent one's own opinions, but quotes from other authors	The author compares new optimization criteria with existing FTT and GSHP literature, identifies gaps, and provides improved formulations supported by numerical and experimental results.
5.	Scientific novelty principle	5.1 Are the scientific results and provisions new? 1) completely new; 2) **partially new (25-75% are new);** 3) not new (less than 25% are new)	The dissertation builds upon existing finite-time thermodynamics (FTT) and ground source heat pump (GSHP) modeling literature, expanding these frameworks to a four-reservoir configuration. While some theoretical

			foundations (endoreversible modeling, irreversibility representation, and classical FTT optimization principles) are known, the author introduces new combinations and extensions tailored for GSHP operation. Specifically, the integration of FTT with a four-heat-exchanger scheme, the derivation of allocation rules under imposed heat extraction/production constraints, and their application to continental-climate GSHP systems represent original contributions. Thus, the overall scientific results are partially new, innovatively extending existing models rather than proposing an entirely new theoretical paradigm.
		5.2 Are the dissertation findings new? 1) completely new; 2) **partially new (25-75% are new);** 3) not new (less than 25% are new)	The dissertation presents new findings within the established domain of GSHP thermodynamic analysis. While the fundamental thermodynamic equations and optimization methods originate from classical FTT theory, the author extends them to a four-reservoir GSHP configuration, which is not conventionally addressed in the literature. The outcomes, such as optimal allocation tendencies for heat exchanger effectiveness and capacity rates, performance maps under imposed operating conditions, and quantified irreversibility effects, are new in their application and interpretation, even though the underlying methodological principles are known.

			Therefore, the findings introduce novel extensions of existing models rather than entirely new theoretical constructs.
		5.3 Technical, technological, economic or management decisions are new and reasonable: 1) completely new; 2) **partially new (25-75% are new);** 3) not new (less than 25% are new)	The technical recommendations, such as heat exchanger resource allocation strategies, operating temperature optimization, and guidelines for system design in continental climates, are based on a combination of new model results and established engineering principles. The technological decisions do not introduce entirely new hardware or GSHP configurations, but they provide refined, optimized design rules derived from the author's FTT and 3E analyses. Thus, the decisions are partially new, contributing substantively to improving GSHP system design and operation without introducing radically new technologies.
6.	The validity of the main findings	All main conclusions **are**/are not based on scientifically significant evidence or well-grounded (for qualitative research and areas of training in the arts and humanities)	The conclusions rely on analytical models, numerical optimization, and experimental validation consistent with thermodynamic principles.
7.	The main provisions for the defense	It is necessary to answer the following questions for each provision separately: 7.1 Is the provition proven? 1) **proven;** 2) rather proven; 3) rather not proven; 4) not proven 7.2 Is it trivial? 1) yes; 2) **no** 7.3 Is it new? 1) **yes;**	The provisions correspond to the scientific novelty described in the thesis and are supported by 7 peer-reviewed publications, including Q1–Q3 Scopus journals.

		2) no 7.4 Application level: 1) narrow; 2) **medium;** 3) wide 7.5 Is it proven in the article? 1) **yes;** 2) no	
8.	The principle of reliability Reliability of sources and information provided	8.1 Choice of methodology - is justified or the methodology is described in sufficient detail 1) **yes;** 2) no	The FTT and 3E methods are rigorously derived, citing standard thermodynamic principles and validated models.
		8.2 The results of the thesis were obtained using modern methods of scientific research and methods of processing and interpreting data using computer technologies: 1) **yes;** 2) no	The author uses contemporary numerical optimization, non-dimensional parameter analysis, and experimental measurement methods.
		8.3 Theoretical conclusions, models, identified relationships and patterns have been proven and confirmed by experimental research (for areas of training in pedagogical sciences, the results have been proven on the basis of a pedagogical experiment): 1) **yes;** 2) no	Chapter 2 validates COP, ground temperature response, and exergy characteristics using measured GSHP data.
		8.4 Important statements are **confirmed** / partially confirmed / not confirmed by references to current and reliable scientific literature	
		8.5 Used literature sources are **sufficient**/not sufficient for a literature review	The thesis includes a comprehensive literature review covering FTT, GSHP, 3E, and climate-specific heating technologies.
9	Practical value principle	9.1 The thesis has theoretical value: 1) **yes;** 2) no	

		9.2 The thesis is of practical importance and there is a high probability of applying the results obtained in practice: 1) **yes;** 2) no	
		9.3 Are the practice suggestions new? 1) completely new; 2) **partially new (25-75% are new);** 3) not new (less than 25% are new)	The optimization framework enables more efficient GSHP design in Kazakhstan's climate and is applicable to system sizing and refrigerant selection.
10.	The quality of writing and design	Academic writing quality: 1) **high;** 2) average; 3) below average; 4) low.	The thesis is structured clearly, written in academic language, includes 29 figures and 6 tables, and conforms to formatting rules.
11.	Notes on a thesis	The dissertation is generally well written and scientifically strong, but several aspects can be improved for clarity, consistency, and precision. 1. Writing clarity and structure o Some paragraphs in the Introduction and Chapter 1 are too long and syntactically heavy, especially where multiple clauses appear in one sentence. Splitting them would improve readability. o Minor issues with punctuation and citation formatting appear throughout (e.g., double bracket "[5,9]]", double period "replacements.."). These should be corrected for a polished final version. o Ensure consistent hyphenation (e.g., "boiler-based heating", "building-sector systems"). 2. Strengthening methodological explanation o In Chapter 1, some composite parameters (α′, α′s,g, α′s,p) and the physical meaning of non-dimensional variables could be more clearly explained to help the reader interpret the optimization results. o A brief clarification of how the four-reservoir FTT representation differs from conventional HP models would help highlight the novelty without overstating it. 3. Presentation of validation results o Chapter 2 contains strong experimental validation, but the COP ranges and model–experiment deviation (up to ~6%) should be emphasized earlier when the text first states that "the model is	

		validated." ○ The validation section would benefit from a compact summary table comparing measured vs. modeled heating capacity, power input, and COP. 4. Figures and experimental setup ○ Figures showing the GSHP installation and hydraulic diagram are clear; however, some measurement points (T1–T8) should be referenced more explicitly in the text to help interpretation. ○ Adding a short note on the impact of standard modeling assumptions (e.g., isentropic compression) on accuracy would strengthen the methodology explanation. 5. Refrigerant analysis ○ The refrigerant selection results (R152a, R450A, R513A, R1234yf, R1234ze) are valuable, but it would be helpful to: ▪ gather COP and TEWI comparisons in a single summary table, ▪ briefly mention safety considerations (A2L flammability) alongside environmental performance.
12.	Scientific level of the doctoral student's articles on the topic of research (in case of defense of the dissertation in the form of a series of articles, the official reviewers comment on the scientific level of each article of the doctoral student on the topic of research)	The doctoral student has 7 publications, including Q1 and Q3 journals, demonstrating a high scientific level and compliance with PhD requirements.
13.	Decision of the official reviewer (pursuant to paragraph 28 of the present Model Regulations)	The dissertation is carried out at a high scientific and methodological level and demonstrates a clear command of academic writing and professional terminology. The structure of the work is logically coherent, and the main provisions and conclusions are formulated precisely and convincingly. The author demonstrates a deep understanding of thermodynamic optimization, finite-time thermodynamics, and 3E analysis as applied to ground source heat pump systems. The theoretical developments are well substantiated, the obtained results are validated with experimental data, and the conclusions reflect the scientific and practical significance of the research. The dissertation

		fully meets the requirements for scientific novelty, validity of findings, theoretical contribution, practical applicability, and the quality of the doctoral candidate's publications.

Conclusion: I believe that the dissertation of **Yelnar Bakytkhanuly Yerdesh**, on the topic "**Thermodynamic optimization of ground source heat pump systems with four thermal reservoirs**", fully satisfies the requirements for dissertations submitted for the degree of Doctor of Philosophy (PhD). The research demonstrates scientific novelty, methodological soundness, and practical relevance, and the main results are convincingly substantiated and validated.
Therefore, **I conclude that Yelnar Bakytkhanuly Yerdesh deserves to be awarded the degree of Doctor of Philosophy (PhD) in the specialty 8D05403 – Mechanics**.

Official Reviewer:

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Zarina Turtayeva.
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