REVIEW
of the official reviewer for dissertation work
Yelnar Yerdesh Bakytkhanuly on the theme "Thermodynamic optimization of ground source heat pump systems with four thermal reservoirs" presented for the degree of Doctor of Philosophy (PhD) in the educational program "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 thesis was completed within the framework of projects of grant funding from the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (AP26102323, AP14871988, AP08857319, APP-SSG-17/0280F, AP05132668), which are financed from the state budget and aimed at improving the efficiency of heat pump technologies.
2.	Importance for science	The work **makes**/does not make a significant contribution to science, and its importance is well **disclosed**/not disclosed	The thesis develops a finite-time thermodynamics (FTT) framework for ground source heat pump (GSHP) systems and 3E (energy-exergy-environmental) analysis validated by experimental data. This bridges a clear gap between idealized cycle studies and system-level GSHP optimization under realistic climatic and operating constraints. The author formulates new optimization criteria and allocation rules for heat exchanger resources and links them to environmental performance, which substantially

			extends existing knowledge on the thermodynamic optimization of heating systems.
3.	The principle of independence	Self-reliance level: 1) **High;** 2) Medium; 3) Low; 4) No independence	According to the thesis and the author's statement of personal contribution, the doctoral student independently defined the research objectives, developed the mathematical models within the FTT framework, implemented the 3E methodology, carried out numerical simulations and optimization, and participated directly in the preparation of the experimental stand, data collection, and model validation. The main results are presented in publications in which the doctoral student is the first or corresponding author, confirming a high level of scientific independence.
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 clearly substantiates the relevance of the work by linking the decarbonization of space heating in cold continental climates to the need for efficient, environmentally sound GSHP systems. The limitations of existing studies are identified and logically lead to the research aim and objectives.
		4.2 The content of the thesis reflects the topic of the thesis: 1) **Reflects**; 2) Partially reflects; 3) Does not reflect	The content of the thesis fully corresponds to the topic.
		4.3. The purpose and objectives correspond to the topic of the	The declared aim is fully consistent

		thesis: 1) **correspond**; 2) partially correspond; 3) do not correspond	with the thesis title. The listed objectives logically follow from this aim and are addressed in the thesis.
		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	The literature reviews, methodological developments, numerical studies, and experimental validation are organized coherently. The FTT models and optimization results in Chapter 1 provide the theoretical basis for the performance and environmental assessments in Chapter 2. The conclusions summarize and integrate the findings from both chapters into a coherent set of scientific principles and practical recommendations.
		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 dissertation contains a detailed critical review of existing FTT applications to heat pumps and of GSHP/3E studies. The proposed four-reservoir FTT framework, irreversibility indicators, allocation criteria, and 3E evaluation are compared with conventional steady-state models, classical endoreversible formulations, and published GSHP case studies. The advantages and limitations of the proposed approach are discussed, and the results are positioned within the international literature.
5.	Scientific novelty principle	5.1 Are the scientific results and provisions new? 1) **completely new**;	The thesis introduces a unified FTT framework for GSHPs with four heat

		2) partially new (25-75% are new); 3) not new (less than 25% are new)	exchangers, derives new optimization criteria under imposed heat-extraction and heat-production rates, and formulates allocation rules for heat-exchanger effectiveness and capacity rates in the presence of irreversibility.
		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 principal findings have not been previously reported in this integrated form. At the same time, they build on established thermodynamic principles and known HP technologies, which is why they can be classified as partially new.
		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 dissertation proposes practically oriented design and operating guidelines for GSHP systems in continental climates. These recommendations extend existing design practices and are well supported by the theoretical and experimental results.
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 models are derived from first-principles mass, energy, and exergy balances consistent with the first and second laws of thermodynamics. Finite-time effects and irreversibilities are explicitly modeled. The numerical results are checked for consistency, and sensitivity/parametric studies are performed. Experimental measurements from the GSHP installation in Almaty are used to validate the thermodynamic models.

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;** 2) no 7.4 Application level: 1) narrow; 2) medium; 3) **wide** 7.5 Is it proven in the article? 1) **yes;** 2) no	Each provision is substantiated by detailed mathematical derivations, numerical optimization, parametric analyses, and, for the 3E framework, experimental validation. The provisions concern non-obvious optimization criteria, allocation rules, and integrated evaluation frameworks that go beyond the straightforward application of standard formulas. The specific formulations of the FTT framework for four-reservoir GSHP systems, the allocation criteria derived with irreversibility explicitly taken into account, and the combined FTT–3E methodology for continental climates are new. The provisions have practical relevance for the design and optimization of GSHPs and related heat pump systems in cold regions, and can be adapted to other configurations where similar finite-time and environmental constraints apply. The main provisions are documented in a series of publications in international peer-reviewed journals and conference proceedings indexed in Scopus and Web of Science, including

			Q1-Q3 journals, which confirms the scientific recognition and validation of the results.
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 dissertation thoroughly describes the FTT models, non-dimensionalization, optimization procedures, and the 3E analysis. The assumptions are clearly outlined, and the selected methods are suitable for the research objectives.
		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 results are achieved through modern numerical modeling, optimization, and data processing tools used in GSHP thermodynamic and environmental analysis.
		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	Experimental data from the GSHP installation in Almaty supports the theoretical findings.
		8.4 Important statements are **confirmed** / partially confirmed / not confirmed by references to current and reliable scientific literature	The work is backed by a comprehensive and current bibliography of both international and national sources, including recent journal articles and standards.
		8.5 Used literature sources are **sufficient**/not sufficient for a literature review	The literature review covers the main areas of FTT, GSHP, and 3E research and is sufficient for positioning the thesis within the current state of the art.
9	Practical value principle	9.1 The thesis has theoretical value: 1) **yes;**	The research advances thermodynamic optimization theory by extending

		2) no	finite-time thermodynamics to GSHP systems with four thermal reservoirs.
		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	The models and guidelines developed can be applied to design and optimize GSHP installations in Kazakhstan and other regions with cold continental climates, enhancing energy efficiency, lowering operating costs and emissions, and supporting national decarbonization initiatives.
		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 proposed rules for allocating heat exchanger resources, selecting refrigerants, and choosing operating temperature ranges provide significant new guidance compared to standard GSHP design practices, while still being compatible with existing engineering tools and standards.
10.	The quality of writing and design	Academic writing quality: 1) **high;** 2) average; 3) below average; 4) low.	The dissertation is clearly structured, follows the required format and standards, and uses appropriate scientific terminology. The English academic style is generally strong; minor stylistic or typographical issues do not hinder understanding. Figures and tables are informative and seamlessly incorporated into the text.
11.	Notes on a thesis	The reviewer suggests the following minor recommendations, which do not impact the overall positive assessment of the work: 1. In future publications, it would be helpful to provide a clearer quantitative uncertainty analysis of experimental measurements and model parameters. 2. The concluding chapter could be improved by including a concise checklist or flowchart for practitioners that summarizes the key design and operational steps derived from the optimization	

		results. 3. A brief discussion of economic indicators (e.g., simple payback or levelized cost of heat) alongside the thermodynamic and environmental metrics would help broaden the appeal of the results to decision-makers.
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 published several articles in reputable international peer-reviewed journals (including Q1-Q3 journals indexed in Scopus and Web of Science) and in indexed conference proceedings. These publications adequately reflect the main scientific results of the dissertation and demonstrate a high scientific level and international visibility of the research.
13.	Decision of the official reviewer (pursuant to paragraph 28 of the present Model Regulations)	On the basis of the analysis presented above, I conclude that the dissertation of Mr. Yelnar Yerdesh Bakytkhanuly on the topic "Thermodynamic optimization of ground source heat pump systems with four thermal reservoirs" fully meets the requirements for dissertations for the degree of Doctor of Philosophy (PhD) in the educational program "8D05403 – Mechanics".

Decision of the official reviewer: **to award the degree of Doctor of Philosophy (PhD) in the educational program "8D05403 – Mechanics".**

Official Reviewer:
PhD, Senior Researcher at PI "National Laboratory Astana",
Nazarbayev University

Omirbekov Sagyn Kumiskhanuly