

分类号:  
学号: 20232110045

密级:  
单位代码: 10759

# 石河子大学

## 硕士学位论文



### 南疆近零能耗农村住宅多目标优化适用性研究

学位申请人	李春澳
指导教师	王玉山 教授 姜沙 高级工程师
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专业名称	土木水利
研究领域	土木工程
所在学院	水利建筑工程学院

中国·新疆·石河子  
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**Research on the Applicability of Multi-Objective Optimization for  
Nearly Zero-Energy Rural Housing in Southern Xinjiang**

A Dissertation Submitted to  
**Shihezi University**

In Partial Fulfillment of the Requirements  
for the Degree of  
**Master of Civil and Hydraulic Engineering**

**By**

**Li Chun-ao**

**(Civil Engineering)**

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May, 2026



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## 摘要

随着我国“双碳”战略目标与乡村振兴战略的统筹推进，农村住宅建筑节能改造与近零能耗目标实现成为研究热点。南疆地区同时涵盖有严寒与寒冷气候分区，其农村住宅普遍存在围护结构热工性能薄弱、采暖能耗高、室内热舒适性差等突出短板，已成为制约农村建筑领域节能降碳落地、乡村人居品质提升的关键痛点。针对南疆农村住宅能耗特征与近零能耗改造的现实需求，本研究以南疆典型农宅为研究对象，引入喀什、库尔勒、阿合奇和塔县四个覆盖不同建筑热工分区的气象数据，开展不同建筑热工分区下的近零能耗改造研究。系统开展了农村住宅现状调研、能耗模拟与敏感性分析、节能改造方案研究，并基于 Grasshopper 平台的 wallacei 插件对南疆农村住宅的建筑能耗综合值、全生命周期成本、冬季最冷日热舒适不满意率进行多目标优化，旨在构建适配南疆地域特征的农村住宅近零能耗改造技术的框架与优化方法。

1.本研究通过抽样实地调研与冬夏两季现场实测，系统梳理南疆农村住宅的建筑本体特征、能耗规律与室内热环境现状，明确南疆农村住宅以单层砖木结构为主，围护结构保温措施缺失，采暖能耗占比高；以上是节能改造的关键因素。基于调研数据构建适配南疆地域特征的农宅基准能耗模型，经现场实测数据完成模型校验，冬夏两季模拟的归一化平均偏差（NMBE）均小于 3%，变异系数根均方误差（CVRMSE）均小于 10%，满足建筑热工模拟精度要求，为后续研究提供了可靠的模型支撑与数据基础。

2.基于 Rhino-Grasshopper 参数化模拟平台，本研究搭建了南疆农村住宅建筑性能模拟流程，并开展建筑能耗全局敏感性分析，识别影响南疆农村住宅能耗的关键控制因子与改造优先级。以显著性水平 $\alpha=0.05$ 对秩相关分析（PRCC）显著性进行判定，并结合 Sobol 全局敏感性指数对排序稳健性进行校核，最终明确了南疆农村住宅节能改造的参数优先级排序为：制热温度>外墙保温厚度>阳光间进深>外窗类型>屋顶保温厚度>北窗墙比，为后续改造方案的制定提供了参考依据与优先级指引。

3.基于敏感性分析结果，从被动节能、主动节能与可再生能源利用三个维度，量化分析了不同改造措施对四个不同建筑热工分区农村住宅能耗的影响规律，提出了分区域差异化的近零能耗改造方案与参数阈值。（1）被动节能层面，PU 板为四地优选保温材料，寒冷地区推荐墙体保温厚度 150mm、屋面 100mm，严寒地区推荐墙体与屋面保温厚度 200mm；外窗优选塑钢窗框加三层 Low-E 充氩气玻璃，窗墙比遵循南向推荐 0.5~0.6，北向不超过 0.2，阳光间实用最优进深为 1.5m。（2）主动节能层面，空气源热泵为四地优选能源系统，可实现 38%~51%的建筑能耗降低，18°C为室内制热温度兼顾能耗与热舒适的平衡值。（3）可再生能源利用层面，四地光伏板最优水平夹角为 35°~40°，横纵向间距 0.8~1.0m，优化后的光伏阵列年发电量可抵消 28%~33%的建筑总能耗。（4）分阶段实施效果验证表明，被动节能措施可使不同建筑热工分区农村住宅建筑能耗降低 43.67%~52.37%，叠加主动节能措施后节能率提升至 56.41%~60.88%，整合可再生能源利用后，总节能率均超过 81%。

4.以农村住宅建筑能耗综合值、全生命周期成本、冬季最冷日热舒适不满意率为优化目标，采用 NSGA-II 遗传算法开展多目标协同优化，在四个不同建筑热工分区下均获得了收敛性良好的 Pareto 非支配解集，基于标准化理想点距离最小准则，确定了兼顾节能、经济与舒适的综合最优改

造方案，综合改造方案可使塔县的建筑能耗综合值降至  $27.01\text{kWh}/(\text{m}^2\cdot\text{a})$ ，阿合奇县的冬季最冷日热舒适不满意率降至  $61.64\%$ ，库尔勒的全生命周期成本控制在  $59774.53$  元，且各地指标均满足《近零能耗建筑技术标准》GB/T 51350-2019 要求。

本文研究成果明确了南疆不同热工分区农村住宅近零能耗改造的技术路径与参数阈值，形成了一套适配南疆地域特征的农村住宅节能改造与多目标优化方法，可为南疆以及同气候地区农村住宅近零能耗改造的工程实践提供理论支撑、技术参考与数据依据。

**关键词：**南疆农村住宅；近零能耗；敏感性分析；节能改造方案；多目标优化

## Abstract

With the advancement of China's "Dual Carbon" goals and the Rural Revitalization Strategy, energy-efficient renovation of rural housing and the realization of nearly zero-energy targets have become important research topics. Rural houses in southern Xinjiang, which spans both severe cold and cold climate zones, generally suffer from poor thermal performance of the envelope, high heating energy consumption, and unsatisfactory indoor thermal comfort. To address these problems, this study selected typical rural dwellings in Kashgar, Korla, Akqi, and Tashkurgan as research objects, and carried out field investigation, energy simulation, sensitivity analysis, renovation scheme evaluation, and multi-objective optimization. Based on the Wallacei plug-in on the Grasshopper platform, the comprehensive building energy consumption index, life-cycle cost, and thermal comfort dissatisfied rate on the coldest winter day were taken as optimization objectives, with the aim of establishing a technical framework and optimization method for nearly zero-energy renovation of rural housing in southern Xinjiang.

1. Through sample-based field surveys and on-site measurements in both summer and winter, the study systematically identified the architectural characteristics, energy-use patterns, and indoor thermal environment of rural dwellings in southern Xinjiang. The results show that most rural houses are single-story brick-timber buildings with insufficient thermal insulation in the envelope, and that heating accounts for a dominant share of total energy consumption, making it the key focus of energy-saving renovation. Based on the survey data, a baseline energy model suitable for the climatic and architectural characteristics of southern Xinjiang was established and then calibrated using measured data. The normalized mean bias error (NMBE) for both summer and winter simulations was less than 3%, while the coefficient of variation of the root mean square error (CVRMSE) was less than 10%, indicating that the model met the accuracy requirements for building thermal simulation and provided a reliable basis for subsequent analysis.

2. Using the Rhino - Grasshopper parametric simulation platform, a building performance simulation workflow for rural houses in southern Xinjiang was further developed, and a global sensitivity analysis of building energy use was conducted to identify key control variables and retrofit priorities. The significance of the partial rank correlation coefficient (PRCC) was evaluated at a significance level of  $\alpha = 0.05$ , and the robustness of parameter ranking was verified using Sobol global sensitivity indices. The final priority order of influential parameters for energy-saving retrofit was determined as follows: heating set-point temperature > external wall insulation thickness > sunspace depth > window type > roof insulation thickness > north window-to-wall ratio. This ranking provides a clear basis for subsequent strategy formulation and retrofit prioritization.

3. Based on the sensitivity analysis results, the effects of different retrofit measures on the energy performance of rural houses in four building climate zones were quantitatively evaluated from three aspects:

passive measures, active systems, and renewable energy utilization. Regionalized nearly zero-energy retrofit strategies and parameter thresholds were then proposed. (1)For passive retrofit, PU board was found to be the preferred insulation material in all four regions. For houses in cold zones, the recommended insulation thicknesses were 150 mm for external walls and 100 mm for roofs, while in severe cold zones, 200 mm was recommended for both walls and roofs. The preferred window configuration was a plastic-steel frame with triple Low-E argon-filled glazing. The recommended south window-to-wall ratio was 0.5 - 0.6, the north window-to-wall ratio should not exceed 0.2, and the practical optimal depth of the sunspace was 1.5 m. (2)For active systems, the air-source heat pump was identified as the preferred heating system for all four locations, reducing building energy consumption by 38% - 51%, while an indoor heating set-point of 18° C achieved a reasonable balance between energy use and thermal comfort. (3)In terms of renewable energy utilization, the optimal tilt angle of photovoltaic panels was 35° - 40° , with transverse and longitudinal spacing of 0.8 - 1.0 m. Under these conditions, the optimized photovoltaic array could offset 28% - 33% of the annual total building energy consumption. (4)Verification of the phased retrofit effects showed that passive measures alone reduced building energy use by 43.67% - 52.37% across different climate zones; after the addition of active measures, the energy-saving rate increased to 56.41% - 60.88%; and after integrating renewable energy systems, the overall energy-saving rate exceeded 81% in all cases.

4. Taking the comprehensive building energy consumption index, life-cycle cost, and thermal comfort dissatisfied rate on the coldest winter day as optimization objectives, this study adopted the NSGA-II genetic algorithm for multi-objective collaborative optimization. Well-converged Pareto non-dominated solution sets were obtained for all four climate zones. Based on the minimum distance to the standardized ideal point, the integrated optimal retrofit scheme balancing energy performance, economy, and comfort was identified. The results show that the comprehensive building energy consumption index in Tashkurgan could be reduced to 27.01 kWh/(m<sup>2</sup>·a), the predicted percentage dissatisfied (PPD) on the coldest winter day in Akqi could be reduced to 61.64%, and the life-cycle cost in Korla could be controlled at RMB 59,774.53. Meanwhile, the performance indicators in all four locations satisfied the requirements of the Technical Standard for Nearly Zero Energy Buildings (GB/T 51350—2019).

The findings of this study clarify the technical pathways and key parameter thresholds for nearly zero-energy retrofit of rural housing in different climate zones of southern Xinjiang, and establish a set of energy-saving retrofit and multi-objective optimization methods tailored to the regional context. The study can provide theoretical support, technical guidance, and data reference for engineering practice of nearly zero-energy retrofit of rural houses in southern Xinjiang and other regions with similar climatic conditions.

**Key words:** rural housing in southern Xinjiang; nearly zero-energy buildings; sensitivity analysis; energy-saving retrofit strategy; multi-objective optimization.

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