Research Paper

Decarbonizing Rural Residences: Spatial Heterogeneity in Multi-level Environmental Governance and Pathways for Agile SDG Localization in China

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Abstract

In meeting global climate challenges, China is working to achieve its goals on carbon neutrality, for which adaptive governance structures are needed to implement Sustainable Development Goals (SDGs) at various levels. Environmental regulation is called for as an important means for decarbonization, but its execution also displays problems within existing top-down governance structures that disregard complex province-level obligations and municipal implementation practices, making it difficult to find strategies for decarbonization in rural residential districts. This research fills the aforementioned critical research gap by adopting the Hierarchical Linear Model to address multi-level governance issues and seeking to clarify the complex mediating relationship between provincial environmental regulation and carbon emissions from local rural residential construction. The municipal environmental regulation intensity was measured via computational text analysis using Python to calculate keyword frequency ratio scores. Hierarchical Linear Modeling examined the research question using null models, models for slopes and intercepts, and full models to explore complex cross-level regulation effects on emissions. It shows that environmental regulation has significant mediating relations with carbon dioxide emissions from rural residential buildings on nine built environment variables, including housing characteristics in terms of kitchen and sanitation facilities. These results imply that the carbon impacts of rural residential development are not only related to physical housing conditions, but also to the interaction between higher-level regulatory arrangements and implementation contexts. The practical significance appears in terms of actionable route maps for governing dynamic cities. Collectively, these elements place the challenge of decarbonization as an issue of institutional design, with the need for greater vertical integration between policy stability and action-oriented flexibility, policy priority and practice in the provincial government, as well as horizontal coordination through community-sensitive design and the adaptive localization of the SDGs through the use of technology-based citizen engagement. This way, the regulation of the environment can be enhanced as a civic-enabling construct.

Keywords

Carbon emissions, Environmental regulations, SDG localization, Spatial governance, Longitudinal

associations

1. Introduction

The aggravation of the global warming problem is inextricably bound to the persistent growth in carbon dioxide emissions. Data analysis has disclosed a systemic turnaround in per capita carbon dioxide emissions for residential buildings in both advanced and undeveloped areas, with inequalities escalating for rural areas (Ge, Li and Yang, 2024). It is important to note that actual carbon dioxide emissions for operating residential buildings contribute 12.9% to China's countrywide emissions, with one-third of this portion attributed to rural areas (You et al., 2023). Rural residence decarbonization has thus become an important link for China to realize its dual carbon targets and directly impacts the speed of the country's fulfillment of its national climate obligations. Rural residence decarbonization is characterized by its own complexity and urgency. Rural residences are mostly self-built, and their energy-saving designs are not standardized, with poor thermal insulation performance in building envelope structures. Rural residences' heating and cooking energy consumption is highly dependent on coal and biomass energy, with low energy use efficiency. At the same time, the promotion of the rural revitalization strategy has led to a sharp increase in the demand for new construction and renovation of rural residences. If there is no effective low-carbon guidance, new buildings will cause long-term emission lock-in effects, further increasing the pressure of carbon emissions.

Although some studies have analyzed the correlation between environmental regulations and carbon emissions, there is still a gap in the study on rural residence in particular. The achievements in this field are still insufficient for practice. Despite research efforts to understand the underlying mechanisms between environmental regulation and carbon emissions, theory remains fraught with inconsistencies. First, the contrast between green paradox and forced reduction hypothesis has no way to integrate into frameworks that recognize heterogeneities in regional areas, especially with regard to systemic gaps in policy implementation for environmental regulations adopted at central levels (Zheng and Kahn, 2017). It has been observed that the degree to which environmental regulations are successively implemented at regional levels varies widely in diverged ways to reveal regional disparities for provincial areas for central environmental legislation implementation disparity reasons disclosed in studies at regional levels (Chen, Xu and Qi, 2022). Second, reliance on static cross-sectional data obscures dynamic interactions between fluctuating regulatory intensity and emission trajectories (Li, Dong and Ji, 2021; Cao, Ren and Yue, 2024). Third, while technological pathways for rural building decarbonization have been extensively studied (Padovani et al., 2021), the interplay between institutional constraints and behavioral responses, remains unexamined.

Such limitations underscore the importance of a more comprehensive and dynamic research approach that can take into account regional variations, over time dynamics, and institutional and behavioral interactions in rural decarbonization. In addition, the localization of the Global Sustainable Development Goals (SDGs) has created new needs for rural area collaboration in the process of decarbonization. The realization of SDG 7, SDG 11, and SDG 13, which are about the development of clean and affordable energy, sustainable cities and communities, and climate actions, respectively, needs rural areas to achieve a balance in the development of energy, housing, and reduction of emissions. However, previous studies failed to connect the localization of SDGs with the essential relationship between multi-level environmental governance in rural areas, resulting in a lack of systematicness in policy recommendations. This research introduces a new methodological approach to untangle the evolving interrelationship between provincial environmental regulation intensity (RI) and carbon emissions from rural residential buildings (CERB) (Zhang, Liu and Zhang, 2022; Zhao et al., 2022).

The key innovations of this study are as follows. It builds a theoretical model of intensity-heterogeneity-response to account for the non-linear features of policy transmission in multi-level governance systems, filling a theoretical gap in the relationship between environmental regulation and carbon emissions from rural residences from a regional heterogeneity perspective. It introduces rural housing quality, local climatic conditions, and geographical features as key variables to be analyzed, achieving an integration of technical and institutional factors. It applies dynamic panel data to account for the lagged impact of policy implementation and the trend effect of carbon emissions. The research has profound implications. From the perspective of theory, this paper can bridge the research gap in the relationship between environmental regulation and carbon emissions of rural residences with regional heterogeneity, thus perfecting the theoretical system of multi-level environmental governance. From the perspective of practice, this paper can provide a set of tools for the low-carbon transformation of rural areas, thus promoting the joint progress of rural revitalization and low-carbon transformation. From the perspective of the world, this paper can provide a reference for developing countries in dealing with the problem of urban-rural climate equity; it can promote the localization of the SDGs in rural areas in an agile manner; and it can provide a practical paradigm of inclusive global climate governance. The rest of the paper is organized as follows. Section 2 discusses the methodology and the data sources, while Section 3 outlines the results and discusses the findings. Finally, Section 4 concludes the paper with the main findings.

2. Methodology

2.1. Model specification

Classic linear regression approaches are limited by linearity, normality, and independence assumptions in areas where homoscedasticity and independence in error terms are violated naturally by nesting data structures.

Regarding this research, for the interrelated nature between provincial RI and CERB at the municipal level to be captured, it becomes important to approach this research using a hierarchical framework that involves two levels. Temporal dynamics are explicitly incorporated by nesting the time variable (T) within the municipal level, allowing for precise assessment of temporal effects on emission trajectories. The outcome variable CERB is modeled using 9 municipal-level predictors: proportion of rural residential buildings with independent bathrooms (IB), independent kitchens (IK), flush toilets (FT), constructed using precast slabs (PS), newly constructed (NC), retrofitted (R), vacancy (V), average household homestead area (HHA), and time (T). Two municipal-level covariates, thermal climate zones (CZ) and landform types (L), are included to control for geographical heterogeneity.

The research has established an unconditional model or null model and computed its intra-class correlation coefficient (ICC1) to validate our method for measuring reliability. After that, various hierarchical linear models or HLM were built successively, including the random coefficient regression model, followed by the regression model with only intercepts as outcomes, and finally, it ended with the full two-level model. The full two-level model encompasses all our variables, its slopes are both fixed and random, capturing observations at city level but classified into units at province levels.

2.2. Variables

CERB data applied for this research has been systematically compiled by our research group (Huo et al., 2020). Within the context of its governance structure, annual work reports for China's government are important policy documents that integrate socioeconomic achievements, including growth in income,

unemployment rates, and industrial output, while also statingfuture priority goals for subsequent years. Besides summarizing respective administration priorities, the work reports also act as mechanisms for government accountability, where societal oversight obliges local administration on stated obligations (Wang and Lei, 2020; Zhu and Wei, 2024). For this research to implement RI, it uses text data extraction via term frequency, where work reports are extracted for provinces from 2015 to 2021. The design of the measurement method consisted of three steps: manual integration of official documents for 26 provinces, computational text segmentation using natural language processing technology, and calculation of RI using the proportional occurrence frequency of 21 prespecified terms about environmental protection out of total content. The important terms include 'prefabricated building', 'building envelope', 'rural housing renovation', 'green building', 'environmental protection', 'pollution', 'energy consumption', 'emission reduction', 'waste discharge', 'ecology', 'sponge city', 'low-carbon development', and 'emission reduction', alongside specific indicators including 'building heating', 'building energy conservation', 'sulfur dioxide (SO_2)', 'carbon dioxide (CO_2)', 'PM10', 'PM2.5'. This method, giving more emphasis to term frequency than to character frequency, can reduce semantic inaccuracies caused by 'the redundancy trap' in literary expressions to effectively retain the meaning or context behind environmental protection policies in documents (Chen et al., 2018; Kiss and Popovics, 2021).

Analysis on a 2021 RI dataset also identified substantial regional asymmetries in terms of regulatory engagement. Inner Mongolia ranked highest on degree, followed by identified northwestern and Eastern provinces, with weaker attention in central and Southern parts. Lexical prioritization further underscored provincial idiosyncrasies: although terms such as 'ecology', 'green development', and 'pollution' dominated national discourse, subnational emphases diverged markedly. Inner Mongolia's reports disproportionately emphasized 'energy consumption', Sichuan prioritized 'green building', and Jiangsu focused on 'prefabricated building'. Geographically nuanced priorities were evident in the prominence of 'low-carbon' terminology in Fujian, Zhejiang, and Jiangsu, contrasted with 'emission reduction' rhetoric in Guangxi, Fujian, and Anhui. Moreover, regional priorities reflected complex patterns where regional economic needs, ecological realities, and regulatory realities are deeply intertwined to shape regional regulatory rhetoric on environmental matters. This combinatorial approach to environmental regulation using semantically nuanced analysis effectively moves focus away from easily quantifiable factors to provide regional nuances for examining complex patterns in environmental regulation in China.

IB and IK identify energy usage patterns in households for water heating and cooking, directly relating to energy intensity for residential areas (Ankrah Twumasi et al., 2021; Wang et al., 2022). FT and PS identify patterns for innovations in sanitation and construction materials with reduced life cycle emissions (Cheng et al., 2018; Liu, Tan and Li, 2020; Huang, Qiu and Zhou, 2021), and NC and R identify patterns for modernization, either reducing or increasing life cycle emissions for material replacement cycles (Liu et al., 2020; Wu et al., 2024). V and HHA identify efficiency patterns for space allocation, essential for both life cycle and operational emissions in rural areas (Hegarty and Kinnane, 2023; Zheng et al., 2025). Temporal trends (T) account for evolving policy impacts and technological adoption rates.

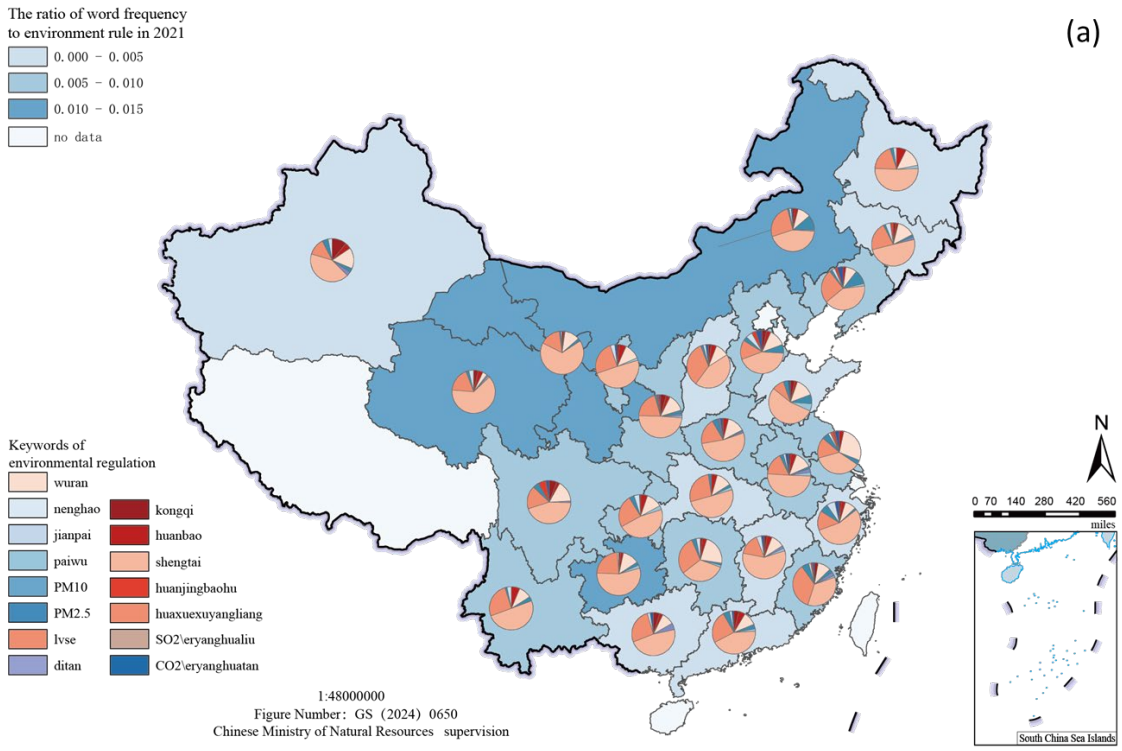
3. Discussion

3.1. Descriptive results

Examination of seven core attributes for critical rural housing points to inefficiencies in rural housing stock in China. V scores averaged 10%, while PS, NC, and R scored lower than 5%, reflecting lethargic

development efforts. However, IK and IB scored moderately on basic facilities. It can also be observed that FT core attributes substantially varied between 90.82% in Huzhou, Zhejiang province, and 3.97% in Tieling, Liaoning province, reflecting regional attitudes on sanitation facilities.

The geographical clustering shown for CERB reveals distinct regional patterns, with high emissions observed in North China, such as Shijiazhuang, Handan, and Xingtai in Hebei Province, followed by South China and Southwest China, reflecting their reliance on coal-based heating. The coastal cities tend to show higher emission intensity patterns than inland areas, reflecting their relatively fast-paced urbanization and resulting reliance on more energy-intensive appliances, with lower inland areas reflecting inhibited economic development and resulting reliance on biomass. This matches energy mix patterns within provinces, where Hebei Province's reliance on coal for power supply aggravates its residential sectors' operating emissions.



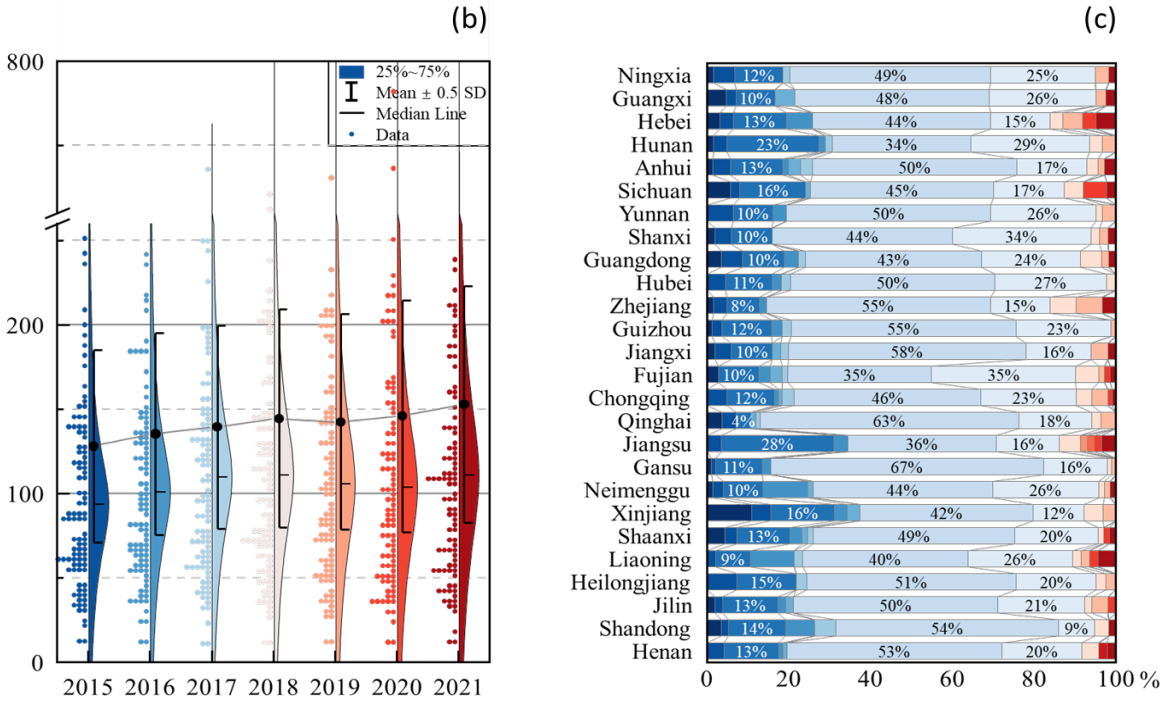


Figure 1. The word frequency distribution of RI in provinces. Source: Author's own analysis.

3.2. Longitudinal associations

Overtly high CERB has posed great challenges to the environment, so it is essential to investigate whether RI affects CERB. To achieve this, HLM is adopted to estimate CERB on panel data that contains 105 cities from 26 provinces in China for seven years in succession from 2015 to 2021. HLM has the ability to decompose variance between hierarchical levels into distinct sources and can control cross-level heterogeneity effectively, making HLM ideal for research on CERB with its multi-level causes and avoiding problems introduced by estimation procedures.

During the analysis, four HLM models followed sequentially: The ICC1 in the unconditional model or Model 1 was 0.772, which exceeded the threshold level of 0.059. On top of the null model, Model 2 added nine new variables: IB, IK, FT, PS, NC, R, V, T, and HHA, together with CZ and L. This simplification verifies that housing variables and change over time together explain 12.3% variation in within-province CERB, but unobserved variation at the province level remains.

Model 3 generalized the null model by including municipal controls variables again, and incorporating province variables altogether: RI as the primary control variable for regulation, FA and P. This yields a deviance decrease to 8250.33, which indicates that provincial variables explain 11.9% variation between provinces, with RI as an important driving force in shaping differences in baseline emissions. The complex model including all municipal and provincial variables with cross-level terms can now be seen as the culmination of our analysis.

The full model, incorporating all municipal and provincial variables with cross-level interactions, represents the analytical culmination. Fixed effects reveal a significant temporal escalation in CERB ($\gamma 110 = 3.51$, $p < 0.001$), equating to an annualized emission growth of 3.8%, a trend unmitigated by existing regulatory

frameworks. This upward trajectory aligns with rural urbanization rates yet contrasts sharply with declining urban residential emissions, highlighting systemic decarbonization asymmetries. The full model's parameter estimates reveal nuanced interactions between housing characteristics and carbon emissions. Increased proportions of independent kitchens (IK: $\gamma 50 = 1.44$, $p < 0.05$), flush toilets (FT: $\gamma 70 = 4.22$, $p < 0.001$), and newly constructed buildings (NC: $\gamma 90 = 17.18$, $p < 0.001$) significantly elevate CERB, likely due to energy-intensive water heating systems and embodied carbon from modern construction materials. Conversely, higher rates of independent bathrooms (IB: $\gamma 60 = -4.29$, $p < 0.001$), prefabricated slabs (PS: $\gamma 80 = -1.59$, $p < 0.001$), and retrofitted buildings (R: $\gamma 100 = -12.73$, $p < 0.001$) reduce emissions, underscoring the decarbonization potential of modular construction and energy-efficient renovations.

While RI exhibits no statistically significant direct effect on CERB, its cross-level moderating role proves pivotal. Under stringent RI regimes, functional housing upgrades demonstrate amplified emission mitigation effects. RI positively moderates the relationships between CERB and vacancy rates (V: $\gamma 41 = 800.95$, $p < 0.1$), independent kitchens (IK: $\gamma 51 = 1838.49$, $p < 0.001$), and flush toilets (FT: $\gamma 71 = 886.54$, $p < 0.05$), suggesting that regulatory pressure enhances the emission intensity of underutilized or amenity-rich housing. Conversely, RI negatively moderates impacts of independent bathrooms (IB: $\gamma 61 = -1589.51$, $p < 0.001$) and prefabricated construction (PS: $\gamma 81 = -1264.77$, $p < 0.001$), indicating that robust regulations amplify their decarbonization benefits.

The full model's deviance reduction to 7,758.62 ($\Delta = -573.50$ vs. null model) confirms its superior explanatory capacity, resolving 76.4% of total variance. This set of outputs strongly supports its hypothesis that provincial RI asymmetry plays a significant role in uneven municipal emission factors but only to a certain degree depending on regional policy regulation capacity. It goes against traditional decarbonization strategies where top-down approaches must give way to regional adaptive policies that are sensitive to infrastructural preparedness for change.

4. Conclusion

This research reveals the complex dynamic interrelationship between RI and CERB within diverse China, and provides critical clarity into second-order decarbonization governance issues in rural areas. This research, which employed HLM analysis on its longitudinal data collected over seven years, covering 26 provinces, aims to transcend the limitations of a cross-sectional analysis, in which not only is the lagged effect between implementation and emission quantitatively measured but also in which the potential role of governance structure is recognized as a contextual moderator in these analyses. Longitudinal analysis reveals that provincial RI is not a direct force but a contextual factor in which its effectiveness is conditional upon infrastructural support and implementation in various levels.The collaborative effort changes the emphasis on decarbonization in rural regions from technology to the sociopolitics that have to be managed by polycentric governance. For emerging nations, on a global level, its applications offer a paradigm for climate equity between urban and rural regions, emphasizing the importance of developing a regulatory framework for each in a dialectic approach rather than relying on standardized frameworks.

However, a crucial limitation is the timeliness of the data, in that the study is only up to 2021, thereby missing the post-2022 trends, including the strengthening of China's "dual carbon" strategy and the fast-tracked rural energy transition schemes.The future study should extend the dataset to include the period 2022-2025, to align with the current policy evolution and emission patterns. Based on the updated dataset, further analysis can be conducted to incorporate the new policy instruments and rural energy

infrastructure development, to make the study more current and responsive to the evolving reality. This will improve the decarbonization strategies and offer more current and focused support for China's carbon neutrality agenda and global climate governance.

5. References

Ankrah Twumasi, M., Jiang, Y., Addai, B., Asante, D., Liu, D. and Ding, Z. (2021) 'Determinants of household choice of cooking energy and the effect of clean cooking energy consumption on household members' health status: The case of rural Ghana', *Sustainable Production and Consumption*, 28, pp.484–495.

Cao, Y., Ren, W. and Yue, L. (2024) 'Environmental regulation and carbon emissions: New mechanisms in game theory', *Cities*, 149, p.104945.

Chen, G., Xu, J. and Qi, Y. (2022) 'Environmental (de)centralization and local environmental governance: Evidence from a natural experiment in China', *China Economic Review*, 72, p.101755.

Chen, Z., Kahn, M.E., Liu, Y. and Wang, Z. (2018) 'The consequences of spatially differentiated water pollution regulation in China', *Journal of Environmental Economics and Management*, 88, pp.468–485.

Cheng, S., Li, Z., Uddin, S.M.N., Mang, H.-P., Zhou, X., Zhang, J., Zheng, L. and Zhang, L. (2018) 'Toilet revolution in China', *Journal of Environmental Management*, 216, pp.347–356.

Ge, X., Li, Y. and Yang, H. (2024) 'The green paradox of time dimension: From pilot to national carbon emission trading system in China', *Environmental Impact Assessment Review*, 109, p.107642.

Hegarty, R.O. and Kinnane, O. (2023) 'A whole life carbon analysis of the Irish residential sector - past, present and future', *Energy and Climate Change*, 4, p.100101.

Huang, L., Qiu, M. and Zhou, M. (2021) 'Correlation between general health knowledge and sanitation improvements: evidence from rural China', *npj Clean Water*, 4(1), p.21.

Huo, T., Li, X., Cai, W., Zuo, J., Jia, F. and Wei, H. (2020) 'Exploring the impact of urbanization on urban building carbon emissions in China: Evidence from a provincial panel data model', *Sustainable Cities and Society*, 56, p.102068.

Kiss, T. and Popovics, S. (2021) 'Evaluation on the effectiveness of energy policies – Evidence from the carbon reductions in 25 countries', *Renewable and Sustainable Energy Reviews*, 149, p.111348.

Li, W., Dong, F. and Ji, Z. (2021) 'Research on coordination level and influencing factors spatial heterogeneity of China's urban CO2 emissions', *Sustainable Cities and Society*, 75, p.103323.

Liu, G., Li, X., Tan, Y. and Zhang, G. (2020) 'Building green retrofit in China: Policies, barriers and recommendations', *Energy Policy*, 139, p.111356.

Liu, G., Tan, Y. and Li, X. (2020) 'China's policies of building green retrofit: A state-of-the-art overview', *Building and Environment*, 169, p.106554.

Padovani, F., Sommerfeldt, N., Longobardi, F. and Pearce, J.M. (2021) 'Decarbonizing rural residential buildings in cold climates: A techno-economic analysis of heating electrification', *Energy and Buildings*, 250, p.111284.

Wang, X. and Lei, P. (2020) 'Does strict environmental regulation lead to incentive contradiction? — Evidence from China', *Journal of Environmental Management*, 269, p.110632.

Wang, Z., Wang, Y., Huang, F., Shuai, C., Li, J., Ding, L. and Cheng, X. (2022) 'The environmental impact of household domestic energy consumption in rural areas: Empirical evidence from China's photovoltaic poverty alleviation regions', *Sustainable Production and Consumption*, 30, pp.1019–1031.

Wu, S., Sun, H., Song, J., Liu, S., Shi, S., Tso, C. and Lin, B. (2024) 'Comprehensive analysis on building performance enhancement based on selective split-band modulated adaptive thermochromic windows', *Applied Energy*, 372, p.123754.

You, K., Ren, H., Cai, W., Huang, R. and Li, Y. (2023) 'Modeling carbon emission trend in China's building sector to year 2060', *Resources, Conservation and Recycling*, 188, p.106679.

Zhang, H., Liu, Z. and Zhang, Y.-J. (2022) 'Assessing the economic and environmental effects of environmental regulation in China: The dynamic and spatial perspectives', *Journal of Cleaner Production*, 334, p.130256.

Zhao, X., Ma, X., Chen, B., Shang, Y. and Song, M. (2022) 'Challenges toward carbon neutrality in China: Strategies and countermeasures', *Resources, Conservation and Recycling*, 176, p.105959.

Zheng, H., Zhang, R., Yin, X. and Wu, J. (2025) 'Unused housing in urban China and its carbon emission impact', *Nature Communications*, 16(1), p.1985.

Zheng, S. and Kahn, M.E. (2017) 'A New Era of Pollution Progress in Urban China?', *Journal of Economic Perspectives*, 31(1), pp.71–92.

Zhu, B. and Wei, C. (2024) 'Strategic interactions for carbon emissions in Chinese cities are influenced by mayors', *Nature Cities*, 1(5), pp.370–377.