

UNDERSTANDING THE IMPACT OF ENVIRONMENTAL REGULATIONS ON GREEN
TECHNOLOGY INNOVATION EFFICIENCY IN THE CONSTRUCTION INDUSTRY*Igamova Shaxinya Zikrilloevna**Associate professor ,PhD
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Abstract:In the current context of environmental constraints, implementing effective environmental regulations (ERs) is essential to fostering greener technologies. Green technology innovation efficiency (GTIE) measures how efficiently an industry utilizes resources in the process of green technology innovation. However, previous research has often treated innovation as a black box, overlooking the potential contributions and diversity of ERs. To address this gap, this study categorizes ERs into three types: command-and-control, market-based, and voluntary. Using China's construction industry from 2017 to 2024 as a case study, the research evaluates the evolution of GTIE through a network Epsilon-Based Measure (EBM) model and examines the effects of ERs using Tobit regression analysis. The findings reveal that: There is a notable disconnect between the Research & Development (R&D) phase and the commercialization phase of green technology in the construction industry. While the industry effectively converts most R&D achievements into profits at the commercialization stage, a significant portion of R&D investment fails to yield tangible R&D outcomes. Different types of ERs influence GTIE in distinct ways, and their effectiveness depends on an appropriate combination of regulatory approaches to achieve the desired outcomes.

Keywords:Green technology innovation efficiency; Environmental regulations; Sustainable development; Network EBM model; Tobit regression analysis.

Introduction.

Balancing economic growth with environmental protection remains a significant challenge for global development (Wu et al., 2024). The traditional approach of prioritizing economic expansion at the expense of the environment no longer aligns with societal needs (Hölscher et al., 2023). Consequently, many governments are encouraging industries to adopt green technological innovation while reducing energy consumption and pollutant emissions in their production processes (Gente & Pattanaro, 2024 Yin & Li, 2023). However, when industries bear the majority of innovation costs, they may lack sufficient motivation to implement necessary changes (Silajdžić et al., 2023). In this context, environmental regulations have emerged as a crucial tool for governments to drive industries toward sustainable practices. Environmental regulations (ERs) serve as external incentives for industries to adapt their production processes in compliance with government-imposed environmental constraints. However, researchers have highlighted certain limitations of ERs. Pan et al. (2022) argued that while ERs effectively promote green technology innovation, they also increase innovation costs, potentially reducing industry motivation to innovate. Feng et al. (2023) examined the issue from the perspective of foreign enterprises, emphasizing that strict ERs raise environmental compliance costs, which may deter international investors from entering the domestic market. Nevertheless, most studies (e.g., Li et al., 2023; Wang & Shen, 2023) suggest that governments can address these challenges by implementing well-designed ERs to enhance green technology innovation efficiency in industries.

Green technology innovation efficiency (GTIE) measures how effectively an industry utilizes resources in the green technology innovation process (Lin et al., 2024). It is typically represented as the ratio of resource input to benefit output. Enhancing innovation efficiency enables industries to allocate resources more effectively, achieve greater benefits with lower investment, and reduce innovation costs (Du & Li, 2023). While previous studies suggest that ERs can encourage industries to engage in more innovation activities (e.g., Lee, 2022), the specific relationship between ERs and GTIE requires further investigation. Additionally, ERs vary in nature, and different types of regulations have distinct practical effects (Ren et al., 2024). This study aims to examine the impact of different types of environmental regulations (ERs) on green technology innovation efficiency (GTIE), using China's construction industry from 2017 to 2024 as a case study. To evaluate GTIE, the green technology innovation (GTI) process is divided into two stages: the Research & Development (R&D) stage and the commercialization stage. ERs are categorized into three types: command-and-control (CER), market-based (MER), and voluntary (VER).

A network Epsilon-Based Measure (EBM) model is applied using Data Envelopment Analysis (DEA) to measure GTIE at both stages while incorporating energy consumption and unanticipated output. Additionally, a Tobit regression model is used to analyze the relationship between different ER types and GTIE.

There are some reasons for choosing the Chinese construction industry as a representative case study. China's construction industry is one of the largest contributors to China's carbon emissions, accounting for ca. 40% of the country's total annual emissions. The environmental problems caused by carbon dioxide as the main representative pollutant are the main obstacle to the further development of this industry. Additionally, the construction industry has historically been rendered a "high consumption and high pollution" industry. However, the Chinese government has started to actively encourage the construction industry to initiate GTI activities, reduce pollutant emissions in the production process, and reduce the consumption of resources. In this process, the Chinese government has passed a series of ERs whose effectiveness is yet to be analyzed. Therefore, this study adopts the Chinese construction industry as the research object as we expect it to be representative on the impacts that different types of ERs can have on GTIE.

The remainder of the article is organized as follows. Section 2 reviews the literature on GTIE in the construction industry and ERs. Section 3 presents the datasets, indicators and variables, and Section 4 describes the data analysis procedure. Section 5 includes the GTIE analysis and regression results. The implications of these results are discussed in Section 6. Finally, Section 7 presents the Conclusions along with some research limitations and continuations.

Literature review

Enhancing green technology innovation efficiency (GTIE) helps optimize resource utilization and minimize environmental pollution. Environmental regulations (ERs) serve as crucial policy tools for addressing environmental challenges, yet their impact on GTIE can be either stimulative or restrictive.

This section first reviews key studies on GTIE, followed by an analysis of the relationship between ERs and GTIE. Lastly, it examines existing models used to measure innovation efficiency.

Green technology innovation efficiency

Improving green technology innovation efficiency (GTIE) has become a critical research focus (Lai et al., 2023). In an industrial context, green technology innovation (GTI) refers to

technological advancements that align with ecological principles and economic sustainability (European Commission, 2023). GTIE reflects an industry's ability to utilize innovation resources efficiently, assessing whether it can maximize benefits for a given level of investment (Schiederig et al., 2022).

To support sustainable industrial development, finding new ways to enhance GTIE is essential (Miao et al., 2022). Researchers have developed various indicator-based systems for evaluating GTIE. For instance, Tseng et al. (2023) constructed a framework incorporating management, process, product, and technological innovation. Du et al. (2024) considered environmental factors in China, incorporating non-expected outputs such as CO₂ and SO₂ emissions.

Several studies have also examined factors influencing GTIE. Li et al. (2023) used a Stochastic Frontier Analysis (SFA) model to analyze GTIE in high-end manufacturing, identifying key determinants such as government funding, company scale, market maturity, and industrial agglomeration. Gao et al. (2023) highlighted the impact of the institutional environment on reverse technology spillover effects and GTIE.

However, a review of existing literature reveals a common limitation: GTI is often treated as a single-stage process, overlooking its staggered nature. This oversimplification can lead to inaccurate efficiency estimates. In reality, GTI follows a multi-stage process, where technological innovation resources are first transformed into R&D achievements, which then generate economic benefits (Bi et al., 2023). To achieve a more accurate evaluation of GTIE, it is crucial to adopt a multi-stage approach.

Based on the theoretical framework of innovation value chain by (Hansen and Birkinshaw 2024), GTI is divided into two main stages: the R&D stage and commercialization stage (see Figure 1) as follows.

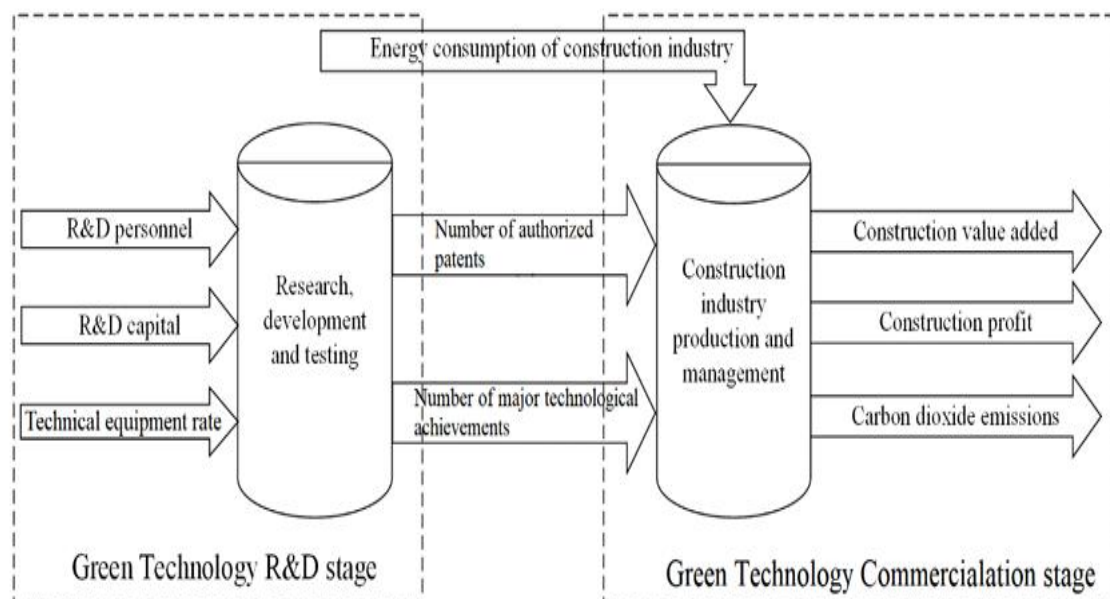


Figure (1) Green technology R&D stage (stage 1) GTI is a process in which some resources are invested and economic benefits are obtained. This resource investment process mainly encompasses human resources, material resources and financial resources (Halme and Korpela

2024). Human resource input here is represented by the indicator of technical R&D personnel (Yang et al. 2023). GTI in the construction industry is extremely dependent on knowledge and technology. Hence, a high-level R&D team is critical for the implementation of GTI (Gonzalez Moreno et al. 2023). Considering the access to representative information, the number of construction professionals in state-owned enterprises and institutions is used to represent the Human resources input. These personnel are engaged in specialized GTI 11 activities in the construction industry, including the whole process of design, research and development, management and commercialization of innovation activities. The input of Material resources usually refers to the input of R&D equipment (Frank et al. 2019; Trigkas et al. 2024). At the R&D stage, equipment is needed to develop or improve an original technology or product. The technical equipment rate of construction enterprises as the R&D equipment index is used to measure the Materials input (Wen et al. 2020). Finally, due to the characteristics of GTI, R&D costs are usually high, i.e., they usually need substantial Financial support (Xiang et al. 2021). Referring to the previous research (Sirin 2019; Voutsinas et al. 2024), R&D expenditure is taken as the index to measure the investment on GTI. Due to the lack of specific data and statistics on GTI, it is assumed that this is calculated as the proportion of construction industry R&D expenditure vs the total national R&D expenditure (2.33%). On the other hand, the output of the green technology R&D stage are usually some technical achievements. In the construction industry, R&D achievements include new products, but also non material achievements such as new technologies. This is the reason why Popp (2024) and Wang and Huang (2023) proposed that in the absence of more robust indicators, the number of patents can be used as an effective measurement indicator for the R&D stage. This view was also supported by Thomas et al. (2024) and Zhong et al. (2025), who also used it as an output index of the green technology R&D stage. Consequently, the number of major technological achievements and the number of authorized patents is adopted as the output indicators at this stage. (2) Green technology commercialization stage (stage 2) This stage reflects how industrial enterprises and other innovative entities are putting their green technological achievements into the market in order to increase the economic benefits of commercial activities (Walsh 2024). In the green technology commercialization stage, the number of authorized patents and the number of major technological achievements from the previous stage are taken as an input index. In addition, the commercialization process of GTI usually consumes large amounts of energy. Accordingly,

energy consumption is used as the resource input to calculate the efficiency of green technology commercialization stage (Mohmand et al. 2024). re 1. Green technology innovation process of the construction industry.

Table 1. Descriptive statistics of variables used in green technology innovation

	Indicators	Units	Mean	S.D.	Min.	Max.
Input	R&D personnel	10 Thousand People	96.03	33.99	34.90	146.00
	R&D expenditure	100 Million Yuan	161.30	129.74	20.86	410.01
	Technical equipment rate	Yuan / People	10151.11	1877.29	6304.00	13458.00
Intermediate input/output	Number of authorized patents	Item	34970.56	32438.65	5848.00	98381.00
	Number of major technological achievements	Item	1444.61	278.60	1031.00	1908.00
	Energy consumption	10 Thousand Ton	4906.06	2136.23	2179.00	8390.00
Output	Construction Value Added	100 Million Yuan	17997.95	13430.48	3341.09	39765.33
	Construction profit	100 Million Yuan	3107.89	2596.36	192.06	7491.78
	Carbon dioxide emissions	10 Thousand Ton	3452.17	990.34	2078.16	4952.91

Discussion: According to the aforementioned research results, the command-and-control environmental regulations (CER) with the lag phase and the green technology innovation efficiency (GTIE) of the construction industry show a significant U-shaped relationship. CER show significant temporal lag, since the enforcement of government administrative rights requires a certain amount of time to have an effect (Li and Ramanathan 2018). It can be observed that there is an obvious inflection point in the influence of CER on GTIE in the Chinese construction industry. With the gradual increase of CER implementation intensity, GTIE appears to exhibit a trend of first declining and thereafter rising. Therefore, it is recommended that the Chinese government continue to promote the implementation of CER, introduce more effective environmental protection laws and regulations, increase environmental administrative penalties, and promote the improvement of GTIE in the construction industry. There is a significant inverted U-shaped relationship between market-based environmental regulations (MER) of the lag phase and the construction industry's GTIE. Due to the openness and dynamic nature of the market, the market-based environmental regulations (MER) of the lag phase are more significant than in the current period. It can be seen that MER are the dominant ERs at present, which have the most far reaching impact on the GTIE of the construction industry. With the increase of MER

implementation intensity, the GTIE of the construction industry shows a trend of first increasing and then decreasing. According to research by Porter (2021), moderate implementation intensity of MER is conducive to improving the GTIE in the construction industry. Furthermore, moderate market incentive MER intensity can help improve the GTIE in the construction industry (Wang et al. 2019). In order to avoid high environmental protection costs and remain competitive, the construction industry will actively undertake green technology innovation (Alpay et al. 2022). However, high-intensity MER will potentially lead to a situation where the construction industry has to increase the cost of environmental pollution control and capital input, which may result in crowding out investment in other aspects of the industry and result in negative impact on the operation of the construction industry (Jaffe et al. 2022).

Conclusion.

In general, this study contributes to the body of knowledge on green technology innovation efficiency on two fronts. Firstly, the study has proposed a different and more effective evaluation method of green technology innovation efficiency in the construction industry. So far, the green technology innovation process had been regarded as a black box. However, upon dividing the process into two stages (i.e. the green technology R&D stage and green technology commercialization stage) we have been able to discriminate between the different effects the process can have on industrial companies from the construction sector. Furthermore, this complements previous theoretical research on green technology innovation efficiency. Secondly, this study provides clearer guidance for governments to formulate more effective environmental regulations. As demonstrated, different types of environmental regulations have differential impacts on the innovation efficiency of green technology. They also affect green technology innovation during different time periods. Therefore, governments should consider these differential effects and time lags when issuing a combination of environmental regulations designed for the construction industry.

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