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R&D Tax Deduction Intensity and Patent-Based Low-Carbon Innovation in Photovoltaic Firms: Structural and Conditional Evidence from China

Zhengyang Luan ¹, Hsing Hung Chen ¹, Ruofei Lan ¹ and Chen Song ^{2,*} 

¹ School of Business, Macau University of Science and Technology, Avenida Wai Long, Taipa, Macao SAR, China; 3240004791@student.must.edu.mo (Z.L.); hhchen@must.edu.mo (H.H.C.); 3250005701@student.must.edu.mo (R.L.)

² Faculty of Business, Macao Polytechnic University, R. de Luís Gonzaga Gomes, Macao SAR, China

* Correspondence: songchen@mpu.edu.mo; Tel.: +853-8599-3295

Abstract

Under the growing pressures of climate change and low-carbon transition, economic policy instruments play an important role in shaping technological innovation in renewable energy industries. This study examines the association between research and development (R&D) tax deduction intensity and patent-based low-carbon innovation among Chinese photovoltaic firms. Using a panel of 71 Chinese A-share listed photovoltaic firms during 2019–2024 and two-way fixed effects models, we find no stable association between R&D tax deduction intensity and firms' overall innovation output. However, after distinguishing innovation types, R&D tax deduction intensity is positively associated with radical innovation output and negatively associated with incremental innovation output, indicating that R&D tax deduction intensity leads to a structural reallocation of innovation resources rather than a simple expansion of innovation quantity. Further results suggest that financing constraints and the external government subsidy intensity shape the marginal effect of R&D tax deduction intensity. Financing constraints exhibit a relatively stable moderating role, while the effect of the government subsidy intensity becomes more evident when firm financing conditions are jointly considered. These findings highlight the need to evaluate energy-transition policies not only by aggregate innovation output, but also by innovation structure, firm heterogeneity, and complementary policy environments.

Keywords: R&D tax deduction; photovoltaic innovation; low-carbon energy transition; economic policy



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1. Introduction

Against the backdrop of an accelerating global energy transition and the growing emphasis on low-carbon development, how to effectively promote technological innovation in new energy firms through well-designed economic policies has become a crucial issue in energy economics and industrial policy research [1,2]. As a core sector of the renewable energy system, technological progress of photovoltaic (PV) industry not only relates to corporate competitiveness but also directly impacts low-carbon energy supply capacity and the quality of energy transition [3]. However, the long-term development of PV firms does not solely rely on capacity expansion but also on continuous innovation activities, such as improvement in battery efficiency, refinement of manufacturing processes, cost reduction, and accumulation of high-quality patents [2]. Within the context of the energy

transition, tax incentives have emerged as an important economic policy tool to stimulate firms' research and development (R&D) investment and promote low-carbon technological progress [4,5]. In China, the R&D tax deduction policy allows eligible firms to deduct a proportion of qualified R&D expenses from their taxable income in addition to the normal deductions. This deduction ratio has been adjusted over time and varied across firm types. Since 2023, eligible R&D expenses can be deducted at 100% of their actual amount, while R&D expenses capitalized as intangible assets can be deducted at 200% of their cost. Consequently, as an important tax incentive tool, the R&D tax deduction policy may influence corporate innovation decisions by reducing R&D costs, improving R&D funding constraints, and increasing the expected return on innovation investment [6,7]. Examining the impact of the R&D tax deduction intensity on the innovation output of PV firms not only enhances our understanding of firms' responses to tax incentives but also provides empirical evidence on the actual effectiveness of economic policy tools in the context of contemporary energy transition.

Existing research has mainly examined the impact of tax incentives on corporate innovation activities from relatively isolated perspectives. For example, since financing constraints limit firms' ability to sustain continuous R&D investment and engage in high-risk innovation activities, tax relief policies are generally considered to reduce R&D costs and increase the expected return on R&D investment, thereby influencing corporate innovation decisions [4,8]. The government support may also improve corporate innovation conditions through government R&D subsidies, resource supply, and policy support [9,10]. However, these factors have rarely been examined within a unified framework to examine how they jointly influence the transformation of tax incentives into corporate innovation output [6]. Meanwhile, current research primarily focuses on general manufacturing firms or overall green innovation, with insufficient attention paid to PV firms, a core industry in the energy transition [1,11]. In terms of innovation measurement, current research typically uses total patents or total innovation indicators. The lack of differentiation between innovation types may obscure the heterogeneous effects of tax incentives on high-quality innovation and incremental innovation [7,12,13].

Based on the above analysis, this study aims to address the research gap by exploring the impact of R&D tax deduction policy in the patent-based innovation of Chinese PV firms from three dimensions: PV industry-specific context, innovation structure, and conditional effects. Specifically, this study focuses on two interrelated research questions. First, is the R&D tax deduction intensity related to the patent-based innovation output of Chinese PV firms, and if so, does this relationship exhibit differences among different types of innovation output? Second, do corporate financing constraints and external government subsidy intensity, individually or jointly, moderate the relationship between R&D tax deduction intensity and patent-based innovation output? To answer these questions, this paper places the R&D tax deduction within the context of energy transition and the development of the PV industry, no longer evaluating the policy-related association solely from the perspective of overall innovation output, but analyzing it from the two levels of innovation structure and conditional differences. Specifically, this paper distinguishes between overall innovation output, radical innovation output, and incremental innovation output. Simultaneously, by combining internal firm financing conditions and the external government subsidy intensity, this paper aims to clarify how tax incentives are associated with the innovation behavior of PV firms under different conditions.

2. Literature Review

2.1. Economic Policy, Energy Transition and Photovoltaic Innovation

Croitoru [14] argues that innovation is the core driving force for industrial upgrading and economic development, providing a theoretical basis for understanding the role of PV technology progress in energy transition. Based on the theory of technological innovation, corporate innovation relies on continuous R&D investment, technological accumulation, and expected returns. Johnstone et al. [15] point out that public policy significantly influences patent innovation in the renewable energy sector, and different policy tools have inconsistent effects on different energy technologies. Wang et al. [2] further argue that green innovation is an important component of environmental and energy policies. Policy tools can influence the development of clean technologies by changing corporate innovation incentives. For the PV industry, technological progress is crucial for improving power generation efficiency, reducing production costs, and enhancing low-carbon energy supply capacity.

PV innovation possesses distinct industry-specific characteristics. At the technical level, it manifests not only in capacity expansion but also in improvements regarding cell conversion efficiency, module durability and reliability, material substitution, manufacturing process optimization, system integration, and cost-reduction technologies [16,17]. Recent research indicates that PV innovation encompasses both hardware-level advancements and production-related technological learning [18]. Meanwhile, evidence derived from patent networks reveals that China's PV industry has developed an evolving structure of technological innovation along the value chain [19]. At the application level, these innovations underpin large-scale solar power generation, distributed PV deployment, integrated PV-plus-storage systems, and the long-term competitiveness of PV firms. Consequently, innovation within PV firms differs from that in general manufacturing firms, as it is closely linked to the upgrading of renewable energy technologies, rapid product iteration, patent accumulation, and the declining costs of low-carbon energy [18,20]. Che, Zhou, and Wang [3] also find that regional PV policy tools can influence PV technology innovation in China. The additional deduction for R&D expenses, as an important form of R&D tax incentive, can reduce the actual cost of corporate R&D activities and provide policy support for low-carbon technology innovation. Therefore, examining how economic policies affect innovation in PV firms is an important entry point for understanding the energy transition path and the effectiveness of low-carbon policies.

2.2. R&D Tax Deduction Intensity and Innovation Structure

Dai and Chapman [4] argue that the core role of R&D tax deduction lies in reducing the cost of R&D activities for firms, thereby increasing their willingness to invest in R&D. Agrawal et al. [8] also point out that R&D tax deduction can promote firms to increase R&D expenditures, suggesting that the additional deduction of R&D expenses may affect firm innovation through a cost compensation mechanism. Similarly, Tang and Liu [6] find that R&D tax incentives not only affect R&D investment but may also affect firm patent output and innovation quality. However, other studies suggest that tax incentives do not necessarily improve innovation quality in a uniform manner. Dai and Wang [13] find that R&D tax credits may not necessarily increase the overall quantity or scientific quality of innovation, but may improve patent novelty and market value. Xiang et al. [7] point out that China's reform of the additional deduction of R&D expenses is more likely to promote incremental innovation, while its impact on breakthrough innovation is unstable.

Regarding the measurement of innovation output, existing studies typically use patent applications or grants as proxies for corporate innovation activities; however, relying solely on aggregate patent metrics may obscure structural differences between distinct

types of innovation [6,12,13]. Under China's patent system, invention patents and utility model patents differ significantly in terms of examination rigor and technical requirements. Invention patents generally undergo more stringent substantive examination and better reflect innovation activities characterized by higher technical complexity, greater uncertainty, and longer R&D cycles [21]. In contrast, utility model patents primarily protect product structures, technical solutions, or practical improvements at the application level, typically aligning more closely with short-cycle, applied, and incremental innovations [22]. For PV firms, distinguishing between patent types—and using them to represent overall, radical, and incremental innovation—is a highly applicable approach within this industry context [18,20]. Therefore, the effectiveness of tax incentives should not be judged solely by the total number of innovation output, but should further distinguish between radical innovation and incremental innovation output in order to identify their impact on the innovation structure of PV firms.

2.3. Financing Constraints, Government Subsidy Intensity and Conditional Effects

Resource dependence theory posits that firm innovation is not entirely determined by internal will but is influenced by the availability of key external resources [23]. Regarding financing constraints, Hadlock and Pierce [24] use the SA index to measure firm financing constraints, emphasizing that firm size and age can reflect external financing frictions. Liang [25] points out that R&D activities are characterized by high risk, long cycles, and information asymmetry, making them more susceptible to financing constraints. Similarly, some studies suggest that firms with higher financing constraints rely more heavily on internal funding and policy-based funding. Tax incentives release funds with higher marginal value, potentially enhancing the impact of tax deductions on innovation output [7,9]. Conversely, some studies argue that excessive financing constraints may weaken firms' ability to absorb policy incentives and translate them into actual R&D. Therefore, the moderating direction needs to be tested in specific contexts [26].

Regarding the government subsidy intensity, institutional theory emphasizes that firm behavior is influenced by external institutional arrangements, policy support, and resource environment [27]. Existing research often measures the government subsidy intensity of firms using government subsidies, policy support, or regional innovation resources. It argues that a favorable government subsidy intensity can reduce innovation uncertainty and improve firms' ability to translate tax incentives into R&D activities [11,28]. However, another type of research points out that external support does not necessarily improve innovation efficiency. Over-reliance on subsidies may lead to resource misallocation or policy dependence [10]. Therefore, government subsidy intensity (GSI) should not be regarded simply as an independent facilitator. Its effect should be further examined together with firms' financing conditions to determine whether they jointly shape the marginal effect of tax deduction.

Recent research on R&D tax incentives increasingly emphasizes empirical identification. Some studies leverage changes in eligibility criteria for R&D super-deduction policies to identify the impact of tax incentives on corporate R&D investment and patent output [29]. Others examine the effects of R&D tax incentives on corporate R&D activities and patent output using tax thresholds, quasi-experimental variations, or regression discontinuity designs [30,31]. Recent studies have also focused on the impact of R&D tax credits on innovation quality indicators, such as patent novelty and market value [32]. These studies demonstrate that policy evaluation must account for issues such as firm selection, reverse causality, and other forms of endogeneity. Unlike the aforementioned studies that focus on exogenous policy shocks or eligibility thresholds, this paper examines variations in the intensity of R&D tax super-deductions at the firm-year level and employs a two-way fixed

effects (TWFE) framework to analyze the conditional relationship between this intensity and various types of patent-based innovation outputs.

2.4. Hypothesis Development

Based on the preceding literature and theoretical logic, this section proposes research hypotheses regarding the association between R&D tax deduction intensity and innovation output in PV firms. Unlike studies that focus solely on changes in the quantity of innovation, this study emphasizes the structural impact of tax incentives on different types of innovation, as well as the conditional roles played by financing constraints and GSI [7,12].

2.4.1. Structural Hypotheses: R&D Tax Deduction Intensity and Innovation Structure

Tax incentives for R&D can reduce corporate R&D costs and increase the expected returns of R&D activities [8]. However, different types of innovation differ in terms of technological difficulty, uncertainty, R&D cycle, and resource requirements, so policy incentives may have heterogeneous effects. Higham et al. [12] point out that using only total patent indicators may mask differences in patent quality and innovation type. For PV firms, radical innovation typically involves breakthroughs in core technologies, such as improving cell conversion efficiency and optimizing high-efficiency cell structures. These breakthroughs often rely on in-depth optimization of cell structure, contact layers, and material systems [33]. Simultaneously, developing new materials and advancing system integration technologies are also crucial directions for PV technology evolution, requiring alignment with industrialization processes, reliability, and long-term performance requirements [34]. These projects typically require repeated experimentation, specialized technical knowledge, and long-term technological accumulation, especially during the commercialization of novel PV technologies such as perovskite–silicon tandem, where uncertainties and technological risks are more pronounced [35]. Therefore, compared to routine product or process improvements, radical innovation is generally more complex, involves greater uncertainty, and is more costly. It also relies more heavily on continuous R&D investment and a stronger risk tolerance. Therefore, they are more likely to benefit from the R&D tax deduction.

In contrast, incremental innovation in PV firms is typically more application-oriented and has a shorter cycle, primarily manifested in continuous improvements based on existing products and production processes. Examples include optimization of module encapsulation materials, frame and support structures, improvements in welding and lamination processes, and adjustments to production equipment parameters. These manufacturing process improvements and learning effects are significant drivers of cost reductions in solar PV technology [36]. Simultaneously, improvements in module reliability and optimization of installation schemes are also typical examples of incremental improvements, as they typically enhance product performance through quality control, fault identification, and operational risk reduction [37]. Furthermore, rapid response to customer application scenarios and market feedback is more about optimizing system configuration, operational efficiency, and application adaptability, rather than developing entirely new core technologies [38]. Therefore, incremental innovation relies more on existing technology platforms, production experience, supply chain cooperation, and short-term operational adjustments. Its response to the intensity of R&D tax deductions may differ from that of radical innovation. We propose the first hypothesis as follows:

H1a: The intensity of R&D tax deduction is positively correlated with the radical innovation output of PV firms.

H1b: The association between R&D tax deduction intensity and incremental innovation output differs from its association with radical innovation output.

2.4.2. Conditional Hypotheses: Financing Constraints and GSI

The relationship between the intensity of R&D tax deduction and corporate innovation output may also be influenced by corporate resource conditions. According to resource dependence theory, corporate innovation activities depend not only on internal innovation willingness but also on the availability of key resources and resource allocation capabilities [23]. Because R&D activities are typically characterized by high risk, long cycles, and information asymmetry, external financing often fails to fully meet the continuous R&D needs of firms. Therefore, funding continuity affects whether firms can translate tax incentives into actual innovation output [39]. For PV firms, financing constraints may have two moderating effects. On the one hand, firms with stronger financing constraints face higher external financing costs, and the internal funds released by the R&D tax deduction intensity have a higher marginal value, thus making them more likely to maintain R&D and patent application activities [40]. On the other hand, if financing constraints are too strong, firms may lack sufficient R&D personnel, technology reserves, and organizational absorption capacity, thereby weakening their ability to absorb policy resources and conduct high-risk R&D [41].

This paper assumes a positive moderating effect of financing constraints primarily because the sample consists of listed PV firms. These firms typically possess basic R&D, production, and patent application capabilities, and their financing constraints manifest more as insufficient funding continuity than a complete lack of R&D absorption capacity. In this case, funds released by tax deductions are more likely to be used to sustain short-cycle and application-oriented innovation activities, such as improvements in module materials, optimization of production processes, adjustment of equipment parameters, reliability testing, and improvement of installation schemes. Existing research also indicates that the impact of financing constraints on corporate R&D activities varies depending on the firm's financial foundation and innovation capabilities, and does not necessarily completely inhibit all innovation activities [42]. These incremental innovations have relatively low thresholds, short feedback cycles, and respond more directly to new funding. Overall innovation is composed of both radical and incremental innovation. Therefore, financing constraints are expected to strengthen the relationship between the intensity of R&D tax deductions and overall innovation output and incremental innovation output. In contrast, radical innovation typically requires larger-scale, longer-term, and more uncertain R&D investment, and the limited funds released by tax deductions alone may not be sufficient to support its stable output. Therefore, this paper does not expect financing constraints to have the same clear positive moderating effect on radical innovation. We propose the second hypothesis as follows:

H2a: Financing constraints positively moderate the association between R&D tax deduction intensity and overall innovation output in PV firms.

H2b: Financing constraints positively moderate the association between R&D tax deduction intensity and incremental innovation output in PV firms, such that this association becomes stronger when financing constraints are higher.

Meanwhile, the intensity of government subsidies may also affect the relationship between the intensity of R&D tax deduction and corporate innovation output. According to institutional theory, corporate innovation behavior is influenced not only by resource conditions but also by external institutional arrangements, policy signals, and public resource

support [27]. The intensity of government subsidies is a concrete manifestation of external institutional support, reflecting the subsidized public financial support that firms receive relative to their operating scale. Existing research shows that government R&D subsidies can alleviate the financing pressure on corporate innovation and have a positive impact on corporate patent applications and innovation output [43]. For PV firms, government subsidies may support activities such as technology upgrades, demonstration projects, equipment renewal, module reliability testing, production process improvement, and integrated PV and energy storage systems. These subsidies not only provide direct financial support but may also convey policy approval signals, thereby reduce the uncertainty of corporate innovation and enhancing their subsequent resource acquisition capabilities [44]. Furthermore, government subsidies and R&D tax deduction intensity can complement each other, meaning that government subsidies provide project-based or direct financial support, while R&D tax deduction intensity reduces the after-tax costs of corporate R&D activities. Therefore, higher levels of government subsidies may enhance firms' ability to translate R&D-related incentives into patented innovation outputs.

However, the intensity of government subsidies may also have another effect. If firms rely excessively on subsidies, resource misallocation, policy dependence, or inefficient innovation may occur, thereby weakening the synergistic effect of subsidies and tax incentives [45]. This paper still expects GSI to have a positive moderating effect primarily because the sample consists of listed PV firms, which typically possess basic R&D, production, and patent application capabilities. Government subsidies are more likely to supplement existing innovation activities with external resources rather than completely replacing firms' own R&D investment [10,28]. Considering financing constraints, government subsidies can further alleviate financial pressure and help firms maintain R&D continuity during periods of limited funding [46]. Therefore, government subsidies and tax deductions are more likely to jointly support short-cycle, application-oriented, and patentable innovation activities, such as component testing, process optimization, product reliability improvement, and installation scheme adjustments. Therefore, the intensity of government subsidies is expected to strengthen the relationship between the intensity of R&D tax deductions and overall innovation output and incremental innovation output. In contrast, radical innovation has a higher threshold, typically requiring larger-scale, longer-term, and more uncertain R&D investment. A combination of government subsidies and tax deductions alone may not be sufficient to generate stable radical innovation output. Therefore, this paper does not expect the intensity of government subsidies to have the same clear positive moderating effect on radical innovation. We propose the third hypothesis as follows:

H3a: GSI positively moderates the relationship between R&D tax deduction intensity and overall innovation output in PV firms when financing constraints are jointly accounted for.

H3b: GSI positively moderates the relationship between R&D tax deduction intensity and incremental innovation output in PV firms when financing constraints are jointly accounted for.

3. Materials and Methods

3.1. Data Sources and Sample Selection

This study uses Chinese A-share listed PV firms as the research object and constructs a firm-year panel dataset. According to the Shenwan Level 3 Industry Classification System (SW 2021), the sample includes 71 listed PV firms. The sample period is set to 2019–2024. This choice is made because the R&D tax deduction policy has continuously affected the innovation activities of PV firms during this period, which provides the basis

for constructing the R&D tax deduction intensity variable. In other words, this core explanatory variable is consistently available in CSMAR database only from 2019 onwards; therefore, earlier years are not included due to missing relevant data. All financial variables were organized using an annual basis to ensure consistency in the time dimension between different variables. The data used in this study are all obtained from the CSMAR database. All statistical analyses were conducted using Stata 17.0 (StataCorp LLC, College Station, TX, USA).

3.2. Key Variables and Measurement

This section defines the key variables used in our empirical analysis, including R&D tax deduction intensity, patent-based innovation outcomes, moderator variables, and firm-level controls. The definitions and measurements of these variables are summarized in Table 1.

Table 1. Variable definitions.

Type of Variables	Variable	Indicators
Dependent variables	Overall innovation output	$\ln(1 + \text{patent applications} + \text{patent grants})$
	Radical innovation output	$\ln(1 + \text{invention patent applications} + \text{invention patent grants})$
	Incremental innovation output	$\ln(1 + \text{utility model patent applications} + \text{utility model patent grants})$
Independent variable	R&D TaxDeduction	$\text{R\&D TaxDeduction} = \text{R\&D tax deduction amount} / \text{OperationRevenue}$
Mechanism-related variables	Financing constraints	SA (SA index)
	Government subsidy intensity	GSI (government subsidy/main business revenue)
Control variables	Firm size	Size = $\ln(\text{total assets})$
	Profitability	ROA = $\text{net profit} / \text{total assets}$
	Leverage	Lev = $\text{total liabilities} / \text{total assets}$
	Operating cash flow ratio	OCF = $\text{operating cash flow} / \text{total assets}$

3.2.1. R&D Tax Deduction Intensity

The core explanatory variable is R&D tax deduction intensity, denoted as TaxDeduction. Unlike simply using policy dummy variables, this paper measures the R&D tax deduction intensity by the ratio of the actual amount of R&D tax deductions received by firms to their main business revenue, as defined below:

$$\text{TaxDeduction}_{it} = \frac{|\text{TaxDeductionAmount}_{it}|}{\text{OperatingRevenue}_{it}} \quad (1)$$

where i represents the firm. t represents the year. This study directly uses the firm-level R&D tax deduction amount as a proxy for R&D tax incentives over the period 2019–2024, rather than employing R&D expenditure as an indirect proxy commonly used in previous studies [47]. Since the R&D tax deduction amount is recorded as a negative deduction in CSMAR database, we take its absolute value and standardize it by dividing by operating revenue. This treatment reflects the economic scale of a firm's R&D tax deduction benefits, rather than the accounting notation in the database. Therefore, the higher the value of this variable, the greater the R&D tax deduction intensity that the firm receives relative to its operating scale.

3.2.2. Innovation Outcomes

This study uses patent-based indicators as proxy for the low-carbon innovation achievements of PV firms. In the renewable energy industry, PV firms' core technological activities are closely related to solar energy conversion, module efficiency improvement, manufacturing process optimization, cost reduction, and clean energy deployment. Therefore, their patent output can reasonably reflect firm-level innovation activities related to the low-carbon energy transition.

This study measures the innovation output of PV firms from two aspects: the quantity of innovation and the structure of innovation. First, total patent output is used to measure the overall innovation level of firms:

$$\ln TotalPatent_{it} = \ln(1 + PatentApplications_{it} + PatentGrants_{it}) \quad (2)$$

Secondly, to identify whether tax incentives alter a firm's innovation structure, this paper further distinguishes between invention patents and utility model patents. Radical innovation is primarily manifested in technological breakthroughs that improve core energy conversion performance, production efficiency, and long-term competitiveness. Examples include improved battery conversion efficiency, high-efficiency battery structures, advanced module technologies, novel PV materials, and PV system integration technologies. Invention patents typically have higher technological content and longer R&D cycles, making them suitable for measuring relatively radical innovation output.

$$\ln Invention_{it} = \ln(1 + InventionApplications_{it} + InventionGrants_{it}) \quad (3)$$

Utility patents tend to favor applied, improvement-oriented, and short-cycle innovations, making them suitable for measuring incremental innovation output.

$$\ln Utility_{it} = \ln(1 + UtilityModelApplications_{it} + UtilityModelGrants_{it}) \quad (4)$$

By examining three types of patent indicators, this paper avoids the problem of relying solely on overall innovation output, which may obscure the structural differences between different innovation types.

3.2.3. Moderator Variables

This paper introduces financing constraints and GSI as moderating variables. Financing constraints are measured using the SA index, which indicates that a higher SA value signifies a stronger degree of financing constraints for the firm. Firms with higher financing constraints rely more heavily on internal funding and policy-based funding. Therefore, the R&D tax deduction policy may have a stronger marginal impact on their innovation activities. GSI is measured using the ratio of government subsidies to main business revenue:

$$GSI_{\{c,it\}} = \frac{GovernmentSubsidies_{it}}{OperatingRevenue_{it}} \quad (5)$$

The GSI variable reflects the external policy support and innovation resource environment in which a firm operates. A favorable GSI may improve a firm's ability to translate tax incentives into R&D investment and innovation output.

3.2.4. Control Variables

To reduce the bias caused by omitted variables, this paper controls for firm size (Size), profitability (ROA), debt-to-asset ratio (Lev), and operating cash flow (OCF). These variables reflect the resource base, financial condition, and financing capabilities of PV

firms, and may also affect their ability to continuously conduct R&D activities and generate innovative outputs [39]. First is firm size. Firm size influences a PV firm's resource acquisition capabilities, financing capabilities, and R&D investment capabilities. Larger PV firms typically have a more stable operating foundation, stronger capital acquisition capabilities, and more comprehensive R&D systems, thus making them more likely to continuously engage in technological innovation and patent application activities. Existing research indicates a close correlation between firm size and innovation activities. Larger firms generally have an advantage in R&D resources and innovation organization capabilities [48]. Therefore, this paper uses the natural logarithm of total assets to measure firm size. Second is profitability (ROA). Profitability reflects the operating performance and internal capital accumulation capacity of PV firms. Firms with stronger profitability typically have more abundant internal capital sources, enabling them to provide more stable financial support for R&D investment, technology testing, and patent applications. Because innovation activities are characterized by long investment cycles, high risks, and high external financing costs, a firm's internal capital capacity affects the sustainability of innovation investment [39]. Therefore, this paper uses the ratio of net profit to total assets to measure corporate profitability.

Third is the debt-to-asset ratio (Lev). The debt-to-asset ratio reflects the capital structure and debt pressure of PV firms. Higher debt may increase the firm's debt repayment pressure, compress the space for R&D and innovation funds, and reduce its ability to undertake high-risk innovation projects. At the same time, moderate debt may also provide external funding sources for R&D investment. Therefore, controlling the debt-to-asset ratio helps to eliminate the impact of differences in capital structure on the firm's innovation output. This paper uses the ratio of total liabilities to total assets to measure the firm's debt-to-asset ratio. Fourth is operating cash flow (OCF). Operating cash flow reflects a PV firm's ability to generate cash flow from its main business and its internal funding situation. Research and development (R&D) activities are typically characterized by continuous funding needs and high uncertainty. Therefore, firms with strong operating cash flow are more likely to continue R&D and patent applications. Related research indicates that a firm's cash flow and internal funding supply affects its R&D investment and innovation growth [49]. Therefore, this paper uses the ratio of net cash flow from operating activities to total assets to measure a firm's operating cash flow.

3.3. Empirical Models

This paper employs a progressive experience identification strategy. First, a two-way fixed effects (TWFE) model is used to examine the baseline association between R&D tax deduction intensity and the innovation output of PV firms. Then, financing constraints and GSI are further introduced to test whether there are conditional differences in the tax incentive effect. Given the observational nature of the data, the TWFE estimates in this study should be interpreted as conditional associations. The baseline model is set as follows:

$$Innovation_{it} = \beta_0 + \beta_1 TaxDeduction_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

where $Innovation_{it}$ represents the innovation output of firm i in year t , which includes the overall innovation output, radical innovation output, and incremental innovation output. $TaxDeduction_{it}$ denotes the intensity of R&D tax deduction. $Controls_{it}$ represents the firm-level control variables, which include Size, ROA, Lev and OCF. μ_i represents firm fixed effects, used to control for firm-specific heterogeneity that does not change over time. λ_t represents the year-fixed effect, used to control for annual shocks caused by changes in the macroeconomic environment, industry cycles, and common policies. To further examine

whether financing constraints and GSI alter the marginal impact of R&D tax deduction intensity on innovation output, this paper constructs a single-moderator model:

$$Innovation_{it} = \beta_0 + \beta_1 TaxDeduction_{it} + \beta_2 Moderator_{it} + \beta_3 TaxDeduction_{it} \times Moderator_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (7)$$

In Equation (7), $Moderator_{it}$ represents the financing constraint index (SA) and the GSI, respectively. The interaction coefficient β_3 is used to determine whether the corresponding variables enhance or weaken the impact of the R&D tax deduction intensity on corporate innovation output. This paper further constructs a dual-moderation model, simultaneously incorporating SA, GSI, and their interaction terms with R&D tax deduction intensity.

$$Innovation_{it} = \beta_0 + \beta_1 R\&D\ TaxDeduction_{c,it} + \beta_2 SA_{c,it} + \beta_3 GSI_{\{c,it\}} + \beta_4 R\&D\ TaxDeduction_{c,it} \times SA_{c,it} + \beta_5 R\&D\ TaxDeduction_{c,it} \times GSI_{\{c,it\}} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (8)$$

In Equation (8), c indicates that the corresponding variables have been mean-centered to reduce the mechanical correlation between the interaction terms and the main effects. In this equation, β_1 represents the conditional association between R&D tax deduction intensity and innovation output when SA and GSI are at their mean levels. β_4 and β_5 represent the moderating effects of financing constraints and GSI, respectively. All regressions employ robust standard errors based on firm-level clustering to mitigate estimation biases that may arise from correlations within the same firm. The robustness testing section further verifies the reliability of the main conclusions through methods such as changing the definition of the innovation variable, replacing core explanatory variables, winsorizing continuous variables, and model diagnostic tests.

4. Empirical Results and Analysis

This section conducts an empirical analysis based on the TWFE model. First, it examines the baseline association between R&D tax deduction intensity and different innovation outputs of PV firms. Then, it introduces SA and GSI to test whether financing constraints and government subsidy intensity condition this association. Finally, robustness and supplementary tests are conducted to assess the reliability of the main results, providing an empirical basis for subsequent discussion.

4.1. Descriptive Statistics and Sample Construction

Table 2 reports the descriptive statistics of the key variables used in the baseline regressions, including the patent-based innovation variables, R&D tax deduction intensity, moderating variables, and firm-level controls.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Overall innovation	132	4.658	1.341	1.946	7.891
Radical innovation	115	3.834	1.415	0.693	7.376
Incremental innovation	96	4.112	1.500	0.000	7.270
R&D tax deduction intensity	211	0.0383	0.0367	0.0002	0.2838
Financing constraint index (SA)	330	3.823	0.256	3.310	4.757
Government subsidy intensity (GSI)	346	0.0131	0.0210	0.0000	0.1898
Firm size (ln assets)	346	22.719	1.396	17.775	26.001
Return on assets (ROA)	346	0.0289	0.0855	−0.3964	0.3658
Leverage	346	0.529	0.194	0.0647	1.2949
OCF	346	0.0316	0.0918	−0.4500	0.3017

Table 3 reports the sample availability and construction procedure for the regression samples. The observations reported in Table 2 refer to variable-level non-missing firm-year observations before complete-case regression estimation. Although the initial sample includes 71 PV firms during 2019–2024, not all variables are available for every firm-year observation. Therefore, the number of observations differs across variables. The final regression samples are based on firm-year observations in which all variables included in a given model are simultaneously non-missing.

Table 3. Sample availability and regression sample construction.

Step	Sample Availability/Construction Procedure	Firms	Firm-Year Observations
1	Initial Chinese A-share listed photovoltaic firms identified by SW 2021 Level 3 classification, 2019–2024	71	426
2	Non-missing financial controls	71	346
3	Non-missing financing constraint index (SA)	71	330
4	Non-missing R&D tax deduction intensity (TaxDeduction)	71	211
5	Non-missing overall innovation variable	71	132
6	Non-missing radical innovation variable	71	115
7	Non-missing incremental innovation variable	71	96
8	Final complete-case sample for overall innovation regression	31	85
9	Final complete-case sample for radical innovation regression	28	75
10	Final complete-case sample for incremental innovation regression	23	68

4.2. Structural Evidence from Baseline TWFE Results

4.2.1. Average Effects on Overall Innovation

The baseline TWFE results in Table 4 show that R&D tax deduction intensity is not significantly associated with overall innovation output at conventional levels. This suggests that the overall innovation measure may be relatively broad, as it aggregates different patent types and may obscure structural differences across innovation outcomes. Therefore, it is necessary to further examine the estimation results for different patent types.

Table 4. Baseline TWFE results.

Variable	Overall Innovation	Radical Innovation	Incremental Innovation
R&D TaxDeduction	1.691 (2.639)	4.173 * (2.728)	−6.132 ** (2.483)
Size	−0.005 (0.307)	0.098 (0.335)	0.810 ** (0.299)
ROA	1.677 (1.094)	2.341 * (1.259)	−0.741 (1.023)
Lev	−1.666 ** (0.757)	−0.857 (0.891)	0.957 (0.712)
OCF	−1.072 (0.670)	−1.150 * (0.570)	−1.237 (1.359)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	85	75	68
Number of firms	31	28	23
Within R-squared	0.525	0.476	0.495

Note: Robust standard errors clustered at the firm level are reported in parentheses. *, **, and denote significance at the 10%, 5% levels, respectively.

4.2.2. Structural Differences Across Innovation Types

Table 4 reports the baseline TWFE regression results for overall innovation, radical innovation, and incremental innovation. After further distinguishing innovation types, the estimation results of R&D tax deduction for radical innovation output and incremental

innovation output show different directions. Specifically, the coefficient of Deduction for invention patents is significantly positive, indicating a positive relationship between it and radical innovation output. In contrast, the coefficient of R&D TaxDeduction for incremental innovation output is -6.132 which is significantly negative at the 5% level. The result indicates that its effect on incremental innovation output is opposite. These results show that the estimation results of TaxDeduction are inconsistent across different patent types. Subsequent analysis needs to incorporate conditional variables to examine whether this difference is affected by financing constraints and GSI.

The signs and significance of the coefficients for control variables vary across different innovation outcomes, a pattern consistent with the heterogeneous nature of patent-based innovation. “Overall innovation” encompasses diverse types of patent outputs; radical innovation is typically associated with long-cycle, high-risk technological breakthroughs, whereas incremental innovation aligns more closely with short-cycle process and product improvements. Consequently, a single firm characteristic may influence different types of innovation outputs through distinct mechanisms.

Specifically, the coefficient for firm size is positive in the incremental innovation model, suggesting that larger PV firms—benefiting from greater production scale and more mature operational systems—are better positioned to generate process- and application-oriented incremental innovations [50]. The positive coefficient for return on assets (ROA) in the radical innovation model indicates that highly profitable firms likely possess superior internal financial capacity to sustain long-term, high-risk R&D activities [51]. The negative coefficient for the debt-to-asset ratio in the overall innovation model implies that debt pressure may constrain the financial flexibility available for innovation investment [52]. The coefficient for operating cash flow requires cautious interpretation, as it may primarily reflect a firm’s current operational focus rather than directly representing R&D investment. Overall, these findings demonstrate that firm-level financial characteristics can influence different types of patent-based innovation through varied channels.

4.3. Conditional Effects in TWFE: Outcome-Specific Moderation by SA and GSI

4.3.1. Conditional Effects on Overall Innovation

For overall innovation output, this paper examines whether SA and GSI condition the association between R&D tax deduction intensity and overall innovation. The single-moderator results show that $\text{R\&D TaxDeduction} \times \text{SA}$ is significantly positive, with a coefficient of 38.314, while $\text{R\&D TaxDeduction} \times \text{GSI}$ is not significant. This indicates that when each moderating variable is considered individually, financing constraints have a more pronounced moderating effect on the relationship between R&D tax deduction intensity and overall innovation output. The individual moderating effect of GSI is relatively limited.

Furthermore, after simultaneously including SA, GSI, and their interaction term with R&D TaxDeduction, the double-adjustment model shows that both $\text{R\&D TaxDeduction} \times \text{SA}$ and $\text{R\&D TaxDeduction} \times \text{GSI}$ are significantly positive, with coefficients of 41.450 and 141.500, respectively. The joint test result for the two interaction terms is $F = 6.31$, $p = 0.0052$, indicating that in the overall innovation output, financing constraints and GSI together have significant moderation effects. Specifically, the positive interaction term indicates that the marginal impact of R&D tax deduction intensity on overall innovation output increases with the improvement in SA or GSI levels. In other words, the effect of R&D tax deduction intensity on overall innovation is not constant but varies with the degree of corporate financing constraints and the external GSI.

It is noteworthy that GSI is not significant in the single-moderation model but becomes significant in the double-moderation model, indicating that the effect of GSI be clearly

only when firm financing constraints are considered simultaneously. Therefore, for overall innovation output, the double-moderator model reflects the conditional differences in the marginal effect of R&D tax deduction intensity better than the single-moderator model. To illustrate the moderating pattern more intuitively, Figure 1 visualizes the association between R&D tax deduction intensity and innovation outcomes across different levels of financing constraints. The upward-sloping pattern suggests a stronger association under higher financing constraints, especially for overall innovation.

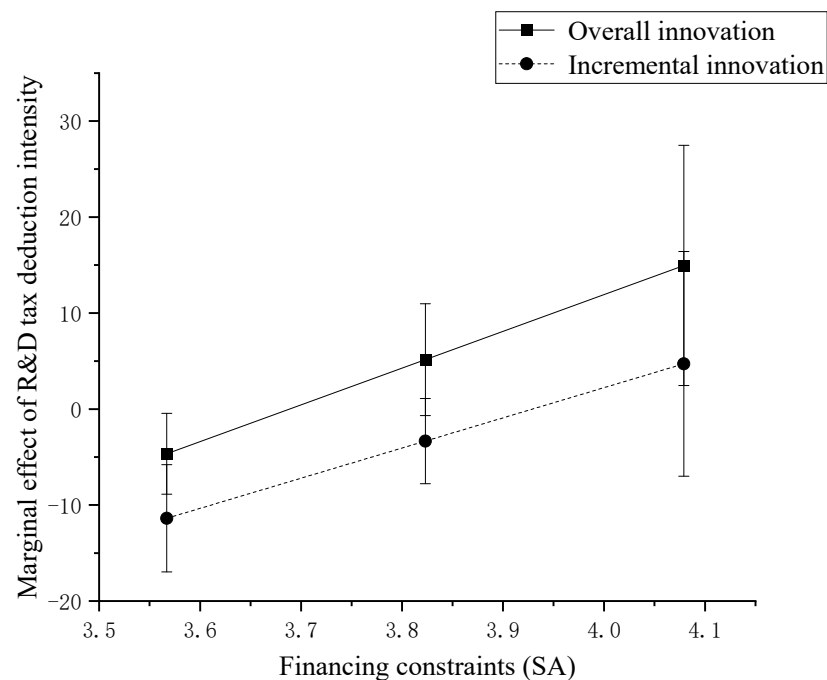


Figure 1. Marginal effects of R&D tax deduction intensity across financing constraints.

Figure 2 presents the association between R&D tax deduction intensity and innovation outcomes across different levels of GSI. The upward-sloping patterns suggest that this association becomes stronger as GSI increases.

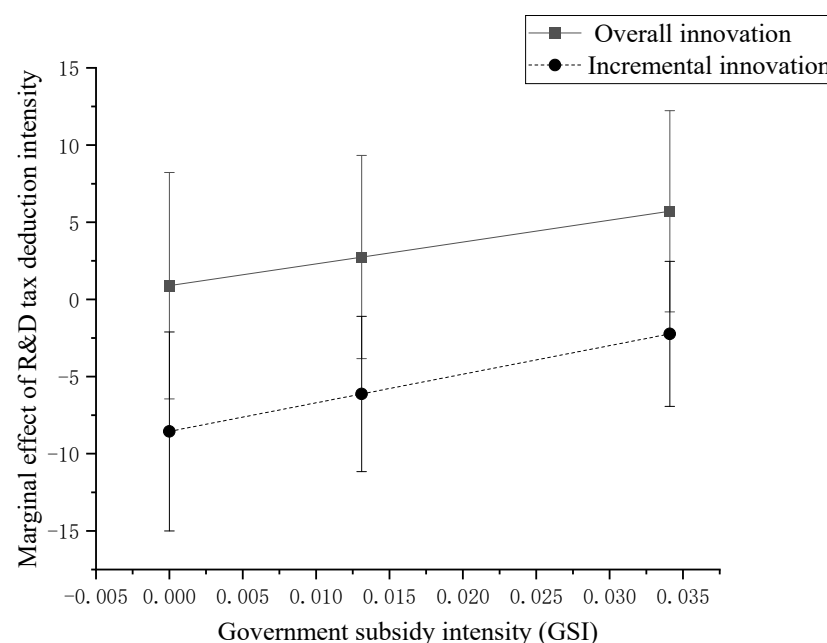


Figure 2. Marginal effects of R&D tax deduction intensity across government subsidy intensity.

4.3.2. Conditional Effects on Incremental Innovation Output

For incremental innovation output, this paper further examines whether SA and GSI alter the impact of R&D tax deduction on incremental innovation output. The single adjustment results in Table 5 show that R&D TaxDeduction $\times$ SA is significantly positive, indicating that financing constraints change the relationship between R&D tax deduction intensity and incremental innovation output. In contrast, when GSI is introduced alone, R&D TaxDeduction $\times$ GSI does not reach a significant level, indicating that the single moderating effect of GSI is not significant.

Table 5. Moderation analysis (TWFE): SA as the only moderator.

Variable	Overall Innovation	Radical Innovation	Incremental Innovation
R&D TaxDeduction	5.150 * (2.973)	5.937 * (3.335)	−3.332 (2.266)
SA_c (centered)	−3.712 (3.671)	−8.813 *** (1.733)	−7.513 *** (1.126)
R&D TaxDeduction $\times$ SA (TD_SA)	38.314 ** (14.525)	26.196 (19.679)	31.432 * (15.978)
Size	−0.333 (0.340)	−0.095 (0.512)	0.551 * (0.309)
ROA	2.469 * (1.359)	2.042 (1.529)	−0.646 (1.266)
Lev	−1.695 ** (0.783)	−0.826 (0.929)	1.005 * (0.549)
OCF	−1.227 * (0.610)	−1.579 *** (0.515)	−1.536 (1.375)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	85	75	68
Within R-squared	0.568	0.617	0.605
Clustered SE	Firm	Firm	Firm

Note: Robust standard errors are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Furthermore, after simultaneously incorporating SA, GSI, and their interaction term with R&D tax deduction intensity, the dual-modulation model shows that R&D TaxDeduction_c remains significantly negative, with a coefficient of −6.124 in Table 6. This indicates that when SA and GSI are at their average levels, R&D tax deduction intensity remains negatively associated with incremental innovation output. Meanwhile, R&D TaxDeduction $\times$ SA and R&D TaxDeduction $\times$ GSI are both significantly positive, with coefficients of 37.357 and 185.213, respectively. The joint test result in Table 6 for the two interaction terms is $F = 6.19$, $p = 0.0074$, indicating that in the incremental innovation output model, both financing constraints and GSI have significant conditional effects.

Specifically, the main effect of R&D TaxDeduction_c is negative, while both interaction terms are positive, suggesting that as the level of SA or GSI increases, the negative marginal effect of R&D TaxDeduction on incremental innovation output weakens. In other words, in firms with high financing constraints or a strong GSI, the negative impact of R&D TaxDeduction on incremental innovation output is partially buffered. Similar to overall innovation output, GSI is insignificant in the single-adjustment model but significant in the double-adjustment model, indicating that the conditional effect of GSI needs to be considered in conjunction with corporate financing constraints to be more clearly reflected. This result is consistent with resource dependence theory and the perspective of financing constraints. According to resource dependence theory, corporate innovation is not entirely

dependent on internal resources but is also influenced by external policies, fiscal support, and the environment for the supply of innovation resources. Therefore, the government subsidy intensity represented by GSI can be understood as an important channel for firms to obtain external innovation resources. At the same time, the financing constraint perspective emphasizes that firms' ability to transform external support into actual innovation output also depends on their internal funding pressure and financing capacity. When corporate financing constraints are strong, the external resources provided by government subsidies may have a higher marginal value; while when corporate financing pressure is weak, the independent effect of subsidy intensity may not be obvious. Therefore, GSI is insignificant in the single-adjustment model but becomes significant after controlling for SA and its interaction term with R&D tax deduction intensity, indicating that the effect of GSI does not occur independently but is activated and amplified under the constraints of corporate financing conditions. Existing research has also shown that both government subsidies and financing constraints are associated with firm innovation performance, especially in the context of green innovation [9,10]. Therefore, the significance of TaxDeduction $\times$ GSI should be understood as the result of the combined effect of external policy support and internal firm financing conditions.

Table 6. Joint moderation TWFE results with GSI and SA as moderators.

Variable	Overall Innovation	Incremental Innovation
R&D TaxDeduction_c	2.744 (3.221)	−6.124 ** (2.427)
GSI_c (centered)	−8.704 (5.649)	−12.598 * (6.967)
SA_c (centered)	−2.989 (3.564)	−7.326 *** (1.155)
R&D TaxDeduction $\times$ GSI (TD_GSI)	141.500 * (73.429)	185.213 ** (86.006)
R&D TaxDeduction $\times$ SA (TD_SA)	41.450 *** (12.896)	37.357 *** (12.276)
Size	−0.517 (0.364)	0.269 (0.381)
ROA	2.485 * (1.293)	−0.628 (1.068)
Lev	−1.425 * (0.837)	1.205 ** (0.542)
OCF	−1.481 ** (0.672)	−1.459 (1.542)
Year FE	Yes	Yes
Firm FE	Yes	Yes
Observations	85	68
Within R-squared	0.594	0.635
Joint F-test (TD_GSI = TD_SA = 0)	6.31	6.19
Joint test <i>p</i> -value	0.0052	0.0074
Clustered SE	Firm	Firm

Note: Robust standard errors are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The interaction coefficients should be interpreted according to the scales of the moderators. Since GSI is measured as a small ratio variable, a full one-unit increase is not economically meaningful. A 0.01 increase in GSI corresponds to an increase of about 1.415 and 1.852 in the marginal effect of R&D tax deduction intensity for overall and incremental innovation, respectively. Similarly, a one-standard-deviation increase in SA changes the marginal effect by about 10.61 and 9.56, respectively. Therefore, the large interaction coefficients mainly reflect the measurement scales of GSI and SA rather than abnormal model estimates.

4.4. Robustness and Supplementary Checks

To further assess the reliability of the main results, this paper conducted supplementary tests from five aspects: heterogeneity across innovation outcomes, alternative dependent-variable construction, alternative core explanatory variable, winsorization of continuous variables, and model diagnostic tests.

First, regarding heterogeneity observation, this paper distinguished innovation output into overall innovation output, radical innovation output, and incremental innovation output. It further examined the impact of SA and GSI on the marginal effect of R&D tax deduction intensity. The results show that the estimation results of R&D tax deduction intensity are not entirely consistent across different innovation types. Its marginal impact also varies with different financing constraints and government subsidy intensities, indicating that the results of this paper have a certain degree of structural and conditional heterogeneity.

Second, this paper conducted a robustness test by substituting the dependent variable, expanding the innovation variable from “number of patent applications + number of patent grants” to “number of patent applications + number of patent grants + number of patent transfers.” The results are reported in Supplementary Table S8. After re-regression, the coefficient of R&D tax deduction intensity remains insignificant for overall innovation and significantly negative for incremental innovation, while the coefficient for radical innovation remains positive. This suggests that the structural pattern of the main results is generally robust for overall and incremental innovation, although the evidence for radical innovation is weaker under the alternative patent construction.

Third, this paper further substitutes the core explanatory variable. This paper uses R&D expenditure intensity, i.e., “R&D expenditure/main business revenue,” as a substitute indicator related to corporate R&D investment for supplementary testing. The results are reported in Supplementary Table S6 which shows that the main estimation direction is largely consistent with the previous conclusions, indicating that the results related to R&D Tax Deduction are not entirely driven by a single tax deduction indicator.

Fourth, this paper performed winsorization (at the 1st and 99th percentiles) on the main continuous variables to reduce the impact of extreme values on the estimation results. The results are reported in Supplementary Table S7. After re-regression, the main conclusions did not change substantially: the coefficient remained insignificant for overall innovation, positive for radical innovation, and significantly negative for incremental innovation. The core variables and interaction terms maintained a consistent direction overall. This indicates that the results are not driven by extreme observations.

Finally, this paper further conducted model specification and diagnostic tests, the results of which are shown in Supplementary Tables S1–S5. Supplementary Tables S1–S3 report the VIF tests for the joint moderation models of overall innovation, radical innovation, and incremental innovation, respectively. The average VIF values are 3.51, 3.83, and 6.46, respectively, which are generally within an acceptable range. The Hausman test supports the use of a two-way fixed effects model. Supplementary Table S4 reports the Modified Wald test, which shows that all three innovation models exhibit significant panel heteroscedasticity. Supplementary Table S5 reports the Wooldridge test which shows that only radical innovation exhibits first-order autocorrelation. Therefore, this paper uses firm-level clustering robust standard errors in all TWFE regressions to mitigate the impact of heteroscedasticity and intra-firm error correlation on statistical inference. In addition, the pairwise correlation matrix of the main explanatory variable, moderating variables, and control variables is reported in Supplementary Table S9. Together with the VIF test results, the correlation matrix provides supplementary evidence that multicollinearity is

not a severe concern in the regression models. Overall, the above diagnostic results support the robustness of the main conclusions of this paper.

4.5. Summary of Empirical Findings

In summary, the empirical results in Section 4 demonstrate that the association between R&D tax deduction intensity and innovation output of PV firms is not simply a quantitative expansion. In the baseline TWFE model, the association between R&D tax deduction intensity and overall innovation output does not reach a conventionally significant level. After further distinguishing among innovation types, TaxDeduction shows a positive relationship with radical innovation output but a significant negative impact on incremental innovation output, indicating differences in estimation results across different innovation types.

The conditional analyses further show that SA and GSI shape this association in different ways. The moderating role of SA is more stable across both single-moderator and double-moderator models. The effect of GSI is only clearly reflected when SA is considered simultaneously. In the overall innovation output model, both interaction terms are significantly positive. In the incremental innovation output model, R&D TaxDeduction_c remains significantly negative, while both interaction terms are significantly positive, indicating that SA and GSI affect its negative marginal effect. The robustness and supplementary tests generally support the main findings mentioned above. Overall, the empirical results suggest that the association between R&D tax deduction intensity and innovation output varies across innovation types and conditional contexts.

5. Discussion

5.1. Structural Interpretation: From Patent-Based Innovation Quantity to Patent-Based Innovation Structure

The above results indicate that the association between R&D tax deduction intensity and Chinese PV firm innovation cannot be understood solely by changes in the total amount of innovation. The insignificant overall innovation output result does not necessarily mean that tax incentives are ineffective; rather, it indicates that the positive changes in radical innovation output and the negative changes in incremental innovation output offset each other at the overall level. It should be noted that invention patents and utility model patents are used here as approximate patent-based proxies for radical and incremental innovation, respectively, rather than direct measures of the intrinsic radicalness or incrementality of each patent. Specifically, R&D TaxDeduction reduces the actual cost for firms to engage in long-term R&D activities, leading to greater incentives for firms to invest in higher-tech, longer-cycle radical innovation output. Meanwhile, incremental innovation output typically leans towards short-cycle, low-barrier, and incremental innovations. When firms concentrate their R&D resources on higher-quality R&D activities, their reliance on incremental innovation output may decrease. Therefore, the positive relationship between R&D tax deduction intensity and radical innovation output, as well as its negative impact on incremental innovation output, together reflect that Chinese PV firms are experiencing a possible shift in the structure of patent-based innovation output under tax incentives, rather than simply expanding the quantity of innovation. This structural interpretation is consistent with previous studies showing that R&D tax incentives can reduce firms' R&D costs and support innovation investment [4,6,8]. It also extends Dai and Wang [13] and Xiang et al. [7] by showing that tax incentives may be associated with different innovation types in different ways rather than uniformly improving all innovation outcomes.

5.2. Conditional Interpretation: The Roles of SA and GSI

The effect of R&D tax deduction is not equal across for all Chinese PV firms and all types of innovation; rather, it is influenced by internal financing constraints and the external GSI. For both incremental and overall innovation output, higher financing constraints result in higher value of internal funds released by tax incentives, making their marginal effect more readily apparent. GSI reflects the external support conditions available to firms, including government subsidies, industrial support, and the availability of innovation resources. When GSI is favorable, firms are more likely to convert tax incentives into actual innovation investment.

Further analysis reveals that the mechanisms and effects of SA and GSI are not entirely identical. SA reflects internal financing constraints, and its moderating effect stems more directly from the alleviation of internal funding pressures by tax incentives. This is evident in the single-moderator model. In contrast, GSI reflects external policy support and firm-level government support, and its effects do not necessarily translate into innovation output independently. The effect of GSI is more likely to be realized in conjunction with internal financing conditions. Therefore, the significant transformation of GSI in the dual-moderating model does not imply the ineffectiveness of the government subsidy intensity alone, but rather indicates that the effect of the external government subsidy intensity is conditional.

The preceding results show that the conditional effects of SA and GSI are mainly reflected in the dimensions of overall innovation output and incremental innovation output, while they are unstable in the radical innovation output model. This is because overall innovation output and incremental innovation output better reflect adjustments in the firm's current innovation output, thus more readily exhibiting conditional effects. It is important to note that overall innovation output comprises different types of innovation, including radical innovation output and incremental innovation output. Therefore, the conditional effects in overall innovation output may partly stem from the sensitive response of incremental innovation output to financing constraints and GSI. In contrast, radical innovation output typically has a longer R&D cycle and higher uncertainty, making it less likely to adjust rapidly in the short term to changes in financing conditions and the external environment.

5.3. Contributions and Positioning of the Study

This study makes three specific contributions. Empirically, it provides sector-specific evidence on the association between R&D tax deduction intensity and patent-based innovation outcomes in Chinese PV firms, complementing prior studies that mainly examine tax incentives in general corporate or manufacturing contexts [6]. Theoretically, it highlights the importance of innovation structure when evaluating tax incentives. By distinguishing among overall, radical, and incremental innovation outputs, this study shows that the estimated relationship between tax deductions intensity and innovation output differs across patent types rather than appearing only at the aggregate level [7,12,13]. Methodologically and analytically, it examines firm financing constraints and the external GSI within the same empirical framework, complementing studies that often discuss policy-related association from a single conditional perspective [9,10]. This design allows their separate and joint moderating roles to be compared.

6. Implications and Future Research

6.1. Theoretical Implications

This paper provides theoretical implications for understanding the relationship between R&D tax deduction intensity and firm innovation from three aspects: innovation

structure, policy conditions, and the energy transition context. First, it advances the innovation effect of tax incentives from “whether it increases the number of patents” to “whether it changes the innovation structure.” Existing research typically uses total innovation as the core indicator for measuring innovation output. However, this paper’s results show that the association between R&D tax deduction intensity and overall innovation output is not stable. Specifically, R&D tax deduction intensity exhibits different directional relationships with both radical and incremental innovation output. Therefore, the theoretical explanation of tax incentive policies should not be limited to the expansion of the quantity of innovation, but should further consider different types of patent-based innovation outputs.

Second, this paper further illustrates that the association between policy incentives and innovation is conditional. Financing constraints and GSI do not simply and directly affect innovation output, but rather alter the marginal effect of R&D tax deduction intensity on innovation output. This indicates that the same R&D tax deduction policy may produce different effects under different firm resource conditions and external government subsidy intensity. Furthermore, this paper demonstrates that internal financing conditions and the external government subsidy intensity do not operate entirely independently. The moderating effect of the external government subsidy intensity can be more fully realized, interpreted, and utilized only when firms’ financing constraints are taken into account. This finding addresses the insufficient attention paid to firm heterogeneity and differences in the external environment in traditional policy incentive theories.

Finally, this paper discusses the R&D tax deduction policy within the context of Chinese PV firms and energy transition, thereby enriching the discussion of low-carbon innovation research in the PV industry context. The innovation activities of PV firms are not only general firm technological innovation but also related to the supply of low-carbon energy technologies and the quality of energy transition. Therefore, this paper provides new patent-based empirical evidence for understanding how economic policy tools influence the innovation structure of Chinese PV firms.

6.2. Policy Implications for Energy Transition

The above findings offer some evidence-based insights for economic policy design in the context of China’s PV industry and energy transition. First, the empirical results directly suggest that the effectiveness of R&D tax deduction policies should not be evaluated solely based on the total amount of innovation. For Chinese PV firms, innovation output is not only related to their own technological competitiveness but also to the supply of low-carbon energy technologies and the quality of energy transition. Since R&D tax deduction intensity is associated with radical and incremental innovation output in different directions, policy evaluation should focus more on structural changes in innovation output, including patent types, technological content, and innovation quality, rather than simply pursuing an increase in the quantity of innovation. In other words, the policy objective should not merely stimulate firms to “apply for more innovation patents” during the low-carbon transition, but rather to further guide firms to invest R&D resources in innovation activities that better support technological upgrading and industrial transformation.

Second, policymakers should pay attention to the role of firms’ financing constraints in the association between R&D tax deduction intensity and innovation output. The results of this paper show that financing constraints alter the marginal association between R&D tax deduction and innovation output, indicating that the same tax incentive may produce different relationships under different financing conditions. Therefore, in the design of energy transition policies, R&D tax deduction should not be regarded as an isolated tax-reduction tool, but should be evaluated in conjunction with firms’ financing capabilities and the availability of funds. For PV firms with strong financing constraints, the policy focus is

not necessarily on simply increasing tax incentives, but on improving the effectiveness of tax incentives in translating into corporate R&D investment and innovation output. More broadly, although not directly tested in this paper, complementary instruments such as green credit, R&D loan support, or financing facilities for low-carbon technology projects may help alleviate corporate R&D funding pressure and improve the conversion efficiency of policy incentives.

Finally, policy design should also consider the complementary role of GSI. The empirical results suggest that GSI is related to the marginal association between R&D tax deduction intensity and innovation output in the dual-moderator model. Therefore, tax incentive policies should not be evaluated in isolation, but should be considered together with firms' financing conditions and subsidy-support context. For PV firms, a more effective policy design should focus on the matching relationship between tax incentives, corporate financing conditions, and the external government subsidy intensity. More broadly, R&D tax deduction intensity may be considered as part of a broader low-carbon innovation policy portfolio, working together with fiscal subsidies, green finance, supply chain collaboration, and public R&D platforms to support low-carbon technology upgrading and energy transition in Chinese PV firms.

6.3. Limitations and Future Research

First, this paper's sample is limited to A-share listed photovoltaic firms in China from 2019 to 2024. Due to the limited number of A-share listed photovoltaic firms and the relatively systematic availability of R&D expense deduction data in CSMAR primarily from 2019 onwards, the final sample size is relatively small and exhibits an unbalanced panel structure. Furthermore, the effective observations of different models vary. Therefore, future research could extend the study period and expand the sample to other new energy industries such as wind power and energy storage, where data conditions permit, to test the applicability of the conclusions in a larger sample and broader energy transition context.

Second, although this paper uses the TWFE model to control for firm and year fixed effects, it is still difficult to completely eliminate endogeneity issues such as reverse causality and omitted variables. Therefore, future research could combine clearer policy shocks, DID, dynamic DID, or event study methods to further strengthen causal identification.

Finally, the variable measurement in this paper is still relatively simplified. Invention patents and utility model patents are only approximate proxies for overall innovation and incremental innovation. GSI can only reflect subsidy support at the firm level. Therefore, future research could further incorporate patent quality, patent value, R&D project data, and regional innovation environment indicators to more accurately characterize corporate innovation activities and external support conditions.

7. Conclusions

Based on Chinese A-share listed PV firms during 2019–2024, the results indicate that the association between R&D tax deduction intensity and innovation output is not simply an expansion in innovation quantity. Regarding the first research question, the results show that R&D tax deduction intensity is not stably associated with overall innovation output, but its association differs across innovation types: it is positively associated with radical innovation and negatively associated with incremental innovation. For Chinese PV firms, this suggests that the role of R&D tax deduction intensity cannot be judged solely by the quantity of overall innovation output, but should further focus on structural changes in innovation output. Thus, H1a is generally supported, while H1b is supported in the sense that the association between R&D tax deduction intensity and incremental innovation differs from that for radical innovation.

Furthermore, this paper finds that the innovation effect of R&D tax deduction intensity is conditional. Financing constraints and GSI alter the marginal impact of R&D tax deduction intensity on innovation output, indicating that R&D tax deduction policy does not function in the same way for all firms and in all environments. At the same time, financing constraints and GSI play different roles. Financing constraints are a more stable conditional variable, while the role of GSI depends more on its consideration in conjunction with the firm's financing conditions. Therefore, the evaluation of the R&D tax deduction policy should not only focus on the policy itself, but should also be understood in conjunction with the firm's financing conditions, availability of funds, and external government subsidy intensity. Specifically, H2a and H2b received overall support, indicating that financing constraints have a relatively stable moderating effect. H3a and H3b received conditional support, meaning that the role of the government subsidies intensity becomes more pronounced when corporate financing constraints are considered together.

Overall, this paper provides empirical evidence for understanding how economic policy tools are associated with the low-carbon innovation structure of Chinese PV firms. The study shows that in the context of energy transition, policy evaluation should not be limited to changes in the total amount of innovation, but should also pay attention to differences in innovation type, innovation quality, and the conditions under which policies take effect. For PV firms, the role of R&D tax deduction policy is more likely to be reflected in the adjustment of innovation structure and the upgrading of low-carbon technologies. The conclusions of this paper also indicate that future energy transition policy design needs to place greater emphasis on the coordination between tax incentives, corporate financing conditions, and the external government subsidy intensity.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/en19143251/s1>. Table S1. VIF test for joint moderation model: overall innovation; Table S2. VIF test for joint moderation model: radical innovation; Table S3. VIF test for joint moderation model: incremental innovation; Table S4. Panel heteroskedasticity test result; Table S5. Wooldridge test for serial correlation in panel data; Table S6. Robustness check: R&D expenditure intensity; Table S7. Robustness check: winsorized main continuous variables; Table S8. Robustness check: alternative patent measure; Table S9. Correlation matrix of variables.

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