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Special Issue Reprint

Economic Policies for the Sustainability Transition

Edited by
Roberto Zoboli, Massimiliano Mazzanti and Simone Tagliapietra

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Editorial

Economic Policies for the Sustainability Transition: Approaches, Outcomes and Prospects in the EU and China

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1. Rationale and Framework

The sustainability transition is a macro-scale process that calls for a deep transformation of the economy, society and technological system to achieve a better life in prosperity. The transition is largely triggered and accompanied by a wide range of public policies that intentionally introduce sustainability strategies, e.g., the European Union's Green Deal, legislation and regulations, fiscal and market-based instruments, selection and conditionality criteria to drive companies (production) and people (consumption) towards sustainability. Dynamically, markets are expected to converge towards a paradigm of green economy and green growth in which sustainability can be economically self-sustained while becoming the new dominant culture.

In this dynamic process, the conventional boundaries of environmental and energy policies are weakening and broadening, as is the case with waste policies and industrial strategies jointly leading to the circular economy, or the overwhelming role of climate change policies for energy and technology policies. The process is hopefully one of convergence in which economic and social objectives are increasingly important within environmental and climate policies, while all public policies embody a sustainability dimension, to the point where sustainability is seen as the leading objective of macroeconomic and growth/development policies. However, the process can also be one of conflicts and disappointments, given the many specific and general trade-offs that can emerge in the transition pathway. This risk applies to sectors, countries, competing technologies, and to the new inequalities possibly induced by the sustainability selection process.

This Special Issue collects original research contributions on the changing landscape of sustainability policies and their economic and social impacts.

After a first paper on the 'green growth' and 'de-growth' recipes for global climate change, the other ten papers address transition policies of two major actors of the world system: the European Union (five papers) and China (five papers). These two major actors substantially differ from political, institutional, administrative, economic, social, and cultural perspectives. However, both are major leading actors in key sustainability areas like climate change, where Europe has been the historical leader in building a global governance regime for climate and China has become the critical actor for the success of that governance regime.

The different climate/energy and environmental policy approaches of China and Europe are also reflected in the papers presented here. In the case of China, the development of climate and transition policies has been based on the combination between major plans and specific large-scale initiatives at the level of regions and sectors [1]. In the case of the European Union, until the adoption of the European Green Deal in 2019, the approach has been dominated by an extensive EU-level legislative process that called for the actions by

Member States and the actors of the economic system, with a large variability of outcomes. With the EGD, the EU embodied a myriad of specific sector-level policies into an overall highest-level strategy that pushes for the most ambitious sustainability transition in the world [2].

2. The Contributions

Contribution 1 addresses the recurring debate on 'green growth' vs. 'de-growth' in search for a feasible pathway to achieve the Net Zero of greenhouse gas (GHG) emissions at the global scale. The 'green growth' approach argues that strong policies and induced technological change can enable fast and sufficient decoupling between economic growth and emissions, while 'de-growth' proponents argue that global growth must be scaled down, and a socio-economic co-evolution must be pursued to accommodate for a de-growth regime. The authors provide an assessment of the gap between the historical performance in reducing emission intensity of GDP and the reduction required for the success of the green growth pathway. The results suggest that the decoupling gaps are considerable at the global scale, and there are various uncertainties and risks affecting the technological solutions for decoupling. However, welfare approaches like de-growth can hardly convince a critical mass of countries and people to embark on a de-growth pathway. This conclusion points to a critical and challenging role of governments in triggering a massive wave of investments in innovation along the green growth pathway, but also in pursuing behavioral changes that can allow us to avoid growth in excess of what is needed. However, behavioral change is still the weakest side of transition policies in the majority of countries.

The implications and perspectives of the European Green Deal are addressed by Contributions 2 and 3 with different objectives and methodologies.

In Contribution 2, different modelling tools are 'soft-linked' to disentangle the intrinsic complexity of the EGD and its key open questions. The system thinking (ST) approach is used to highlight the main economic feedback loops associated with the EGD strategy. Then, a dynamic computable general equilibrium (CGE) model is exploited to elaborate an ex ante assessment of policy options. The emerging suggestion is that positive outcomes can arise from carbon pricing policies in which the recycling of the fiscal revenues is used to support the diffusion of clean energy technologies. This policy approach can benefit both the European Union and non-EU countries via technology transfer.

The green transition pushed by the EGD from 2019 had to face relevant external shocks that revealed Europe's vulnerabilities. The idea of EU strategic autonomy (SA) is becoming the new framework of the EGD process. Contribution 3 investigates whether SA supports the EGD, and vice versa, or whether the two processes may be subject to contradictions. The EGD actually embeds SA elements, especially in the most recent phase, but some trade-offs may arise. Environmental, economic, and social concerns are raised by current measures that promote self-sufficiency for energy and materials and the extension of environmental requirements to foreign products accessing the EU market. These concerns can be partly addressed through higher strategic attention to the external dimension of the EGD.

The other two contributions on the EU look at the development of the Circular Economy paradigm, which is part of the EGD through the CE Action Plan of 2020.

Contribution 4 looks at how institutional quality and trust in institutions can affect the performance in waste recycling in EU countries. The paper applies panel econometrics to measure the role of institutional variables vis à vis the role of waste policies (Waste Framework Directive (WFD) and first Circular Economy Action Plan (CEAP) of 2015) for the recycling of municipal solid waste in EU27. The results confirm that the quality of institutions can influence waste recycling results, whereas institutional trust can have adverse effects on recycling rates because of a possible 'delegation effect'. On the policy side, both the WFD and the CEAP 2015 had a role in driving recycling performances. Therefore, local institutional quality and high-level public policies can be complementary in achieving developments of the CE.

Contribution 5 investigates how public policies can support CE-related developments in the construction sector in the Nordics (Denmark, Finland, Norway, and Sweden). From a systematic collection of evidence, the paper shows that the construction sector is extensively addressed by CE policies, and business opportunities are generated when appropriate national and local policies are put into practice. In particular, successful policies may arise from jointly implementing appropriate real estate planning, sustainability technical requirements for constructions, and public procurement.

The first two articles on China revolve around the concept of 'Green Total factor Productivity' and how policies can have an impact on it.

Contribution 6 applies the data envelopment analysis method to a panel of Chinese provinces in the period 2011-2019 to measure their performance in industrial green total factor productivity (GTFP). Then, it uses a generalized method of moments (GMM) model to show how environmental regulation can have positive effects on industrial GTFP. Regulation can improve productivity while reducing industrial pollution. Among policy instruments, market-based environmental regulations do not have a significant impact and can even negatively affect GTFP in economically laggard areas. Instead, innovation induced by environmental regulation can be a lever of success.

Contribution 7 uses a model of endogenous technological progress to analyze the impact of environmental regulations on industrial GTFP using a panel dataset of 30 Chinese provinces in the period 2000–2017. The results show that the direct impact of environmental regulations on GTFP has an inverted "U" shape, and the same regulations can influence manufacturers' investments in the quality of workers. Therefore, environmental policies, also mixing different regulatory instruments, can accelerate a positive environmental and economic transition of the Chinese industrial system.

The other three contributions on China address the regional and city-level dimension of the effectiveness of transition policies, particularly their economic implications.

Contribution 8 uses a difference-in-difference (DID) model to study the relationship between regional integration and carbon emission performance and exploits the Yangtze River Economic Belt as a quasi-natural experiment. The results show that regional integration can improve carbon emissions through three transmission mechanisms: better allocation of production factors, economies of scale, and eco-innovation. In particular, regional integration can differently improve carbon emission performance in different types of cities (e.g., high-level carbon emission cities and cities not based on natural resources).

Contribution 9 uses a difference-in-difference approach applied to data of 227 cities in China from 2004 to 2019 to explore the relationship between the policies of 'low-carbon pilot city' (LCC) and the quality of urban development. The main conclusion is that the LCC policy has promoted high-quality economic development, and it has long-term effects at three levels: innovation, quality of life, and quality of public services. The positive effect is emerging mainly in the large cities and in the Eastern and Central regions.

Contribution 10 uses a Data Envelopment Analysis (DEA) model to measure the High-Quality Development (HQD) level of 102 resource-based Chinese cities (RBCs) with data from 2003 to 2019. The effect of environmental information disclosure (EID) on HQD in these cities is empirically measured by adopting a difference-in-difference approach with propensity score matching. The results show that EID has a significant and positive effect on the HQD of RBCs. EID is more effective for HQD in RBCs of Central China, resource-dependent RBCs, growth RBCs, and regenerative RBCs.

While keeping a regional perspective, Contribution 11 investigates the impact of environmental regulations on Taiwanese investment in mainland China, checking whether local governments are competing with one another to attract Taiwanese investment through the adoption of weaker environmental standards. The approach is based on a two-stage game model, applied to a panel data of provinces in mainland China from 2006 to 2016 through a GMM estimation method. The environmental policies adopted by the local governments have a significant inhibitory effect on the investment volume of Taiwanese enterprises, and a negative effect also arises from the interaction between environmental regulations and local tax policy.

3. Conclusion and Prospects

The papers in the Special Issue show that, in spite of the huge differences between the EU27 and China, in both cases, environmental and climate-energy policies, as well as circular economy policies, can be effective in driving a sustainability transition or some of its core processes. Furthermore, effectiveness emerges for a broad range of different policy approaches. This conclusion does not mean that policies are also efficient in the conventional meaning of delivering results at the minimum possible cost in an ex ante predictable way. Instead, they induce responses by industries and the socio-economic systems that can be initially contrasted, uncertain, unpredictably evolving, and differentiated across sectors and countries, as in the case of the EU, and across regions/provinces/cities, as in the case of China. A clear-cut conclusion emerging from the papers is that innovation, be it technological, social, or institutional, is the key lever to make policies effective.

These conclusions support the idea that, in this unique historical phase, the sustainability transition is largely policy-driven, and the transition could not take place without a strong and persistent high-level policy commitment [3]. On the one hand, climate-energy and environmental policies are able to generate new markets, innovations, and industrial dynamics that have structural and non-reversible socio-economic consequences, thus becoming a central component of the macroeconomic long-term development strategies of countries and regions [4]. On the other hand, these same transformative responses to policies can entail costs for those parts of the industrial and social system that cannot keep pace with the policy-driven transformation, and these possible side-effects are still a key open socio-economic issue of transition policies.

These economic and industrial implications are increasing—and increasingly visible—within the current evolution of the transition strategies both in Europe and in China.

In Europe, one of the first steps of the interaction between the EGD and the strategic autonomy approach (see Contribution 3) is the Green Deal Industrial Plan (GDIA) launched in 2023 through the Net Zero Industrial Act and the Critical Raw Materials Act. In response to the increasing risks of the international system, this policy aims at protecting the EGD transition by creating strong industrial interests in pursuing self-sufficiency in the Net Zero industries, together with a possible alleviation of the large EU's import dependency for critical material inputs. The GDIA is not yet a true new green industrial policy, which requires other major changes across EU strategies [5], but it is starting to create a new industrial consensus on the transition. It can be seen in the framework of a possible new boost to the EU Single Market and the EU competitiveness that will animate the transition debate between the present EU Commission and the future EU Commission emerging from the EU 2024 elections.

Undertaking a green industrial policy within a strategic autonomy framework for a new EU competitiveness reveals that the EU fears the rising power and the competing leadership of China in the clean tech industries. Data indicate that China is the manufacturing and trading leader, and the most important deployer, of solar photovoltaic technologies, wind technologies, batteries, and electric mobility technologies (see Bruegel's 'European clean tech tracker', https://www.bruegel.org/dataset/european-clean-tech-tracker, accessed 10 June 2024). This industrial leadership of China provides a sound economic justification for its own domestic transition policies and can be fed by the same global-scale sustainability transition, in particular the global pathways to Net Zero, unless the Net Zero industrial strategies of the EU and the US will be fully successful in keeping domestically the economic value generated by their huge transition investments.

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List of Contributions:

1. Lenaerts, K.; Tagliapietra, S.; Wolff, G.B. The Global Quest for Green Growth: An Economic Policy Perspective. *Sustainability* **2022**, *14*, 5555.
2. Bassi, A.M.; Costantini, V.; Paglialunga, E. Modelling the European Union Sustainability Transition: A Soft-Linking Approach. *Sustainability* **2021**, *13*, 6303.
3. Paleari, S. The Role of Strategic Autonomy in the EU Green Transition. *Sustainability* **2024**, *16*, 2597.
4. Pronti, A.; Zoboli, R. Institutional Quality, Trust in Institutions, and Waste Recycling Performance in the EU27. *Sustainability* **2024**, *16*, 892.
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8. Ai, A.; Xu, N. Does Regional Integration Improve Carbon Emission Performance?—A Quasi-Natural Experiment on Regional Integration in the Yangtze River Economic Belt. *Sustainability* **2023**, *15*, 15154.
9. Tang, Q.G.X.; Wang, X. Can Low-Carbon Pilot City Policies Effectively Promote High-Quality Urban Economic Development?—Quasi-Natural Experiments Based on 227 Cities. *Sustainability* **2022**, *14*, 15173.
10. Xin, C.; Lai, X. Does the Environmental Information Disclosure Promote the High-Quality Development of China's Resource-Based Cities? *Sustainability* **2022**, *14*, 6518.
11. Yang, F.; Gan, Q. Impact of Regional Environmental Regulations on Taiwanese Investment in Mainland China. *Sustainability* **2021**, *13*, 4134.

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Article

The Global Quest for Green Growth: An Economic Policy Perspective

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Abstract: Economic growth has historically been the main driver of rising greenhouse gas (GHG) emissions. To achieve steep emission reductions, the world would have to either decouple global GHG emissions from gross domestic product (GDP) at an unprecedented pace or face deep cuts to GDP. The so-called 'green growth' literature is optimistic that suitable policies and technology can enable such fast decoupling, while 'degrowth' proponents dismiss this and argue that the global economy must be scaled down, and that systemic change and redistribution is necessary to accomplish this. We use the so-called Kaya identity to offer a simple quantitative assessment of the gap between the historic performance in reducing the emission intensity of GDP and what is required for green growth, i.e., the basis of ongoing disagreement. We then review the literature on both degrowth and green growth and discuss their most important arguments and proposals. Degrowth authors are right to point out the considerable gap between current climate mitigation efforts and what is needed, as well as the various technological uncertainties and risks such as rebound effects. However, the often radical degrowth proposals also suffer from many uncertainties and risks. Most importantly, it is very unlikely that alternative welfare conceptions can convince a critical mass of countries to go along with a degrowth agenda. Governments should therefore instead focus on mobilizing the necessary investments, pricing carbon emissions, and encouraging innovation and behavioral change.

Keywords: green growth; degrowth; decoupling; Kaya identity; climate change

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1. Introduction

Climate change is one of the most pressing issues of our time. The science is clear: human activities have already caused approximately 1.1 °C of global warming and at current rates will almost certainly cause over 1.5 °C of global warming above pre-industrial levels as early as by mid-century [1] With the Paris Agreement, governments have committed to limiting the temperature increase this century to well below 2 °C above pre-industrial levels and to pursuing efforts to limit it to 1.5 °C [2]. Keeping global warming below this limit will require net global net CO_2 emissions to decline sharply by 2030 and to reach net zero around 2050. Any delay will push forward the net-zero deadline, as cumulative emissions must stay within a given carbon budget. Emissions of other greenhouse gasses (GHG) must face similar cuts [1,3].

Economic growth has historically been the main driver of rising GHG emissions. To achieve steep emission reductions, the world would have to either decouple global GHG emissions from gross domestic product (GDP) at an unprecedented pace or face deep cuts to GDP. In other words, the causality between economic activity and GHG emissions must be eliminated quickly, or economic activity must be scaled back. Because of the weak historical track record of decoupling, scholars disagree about whether humanity can afford continued economic growth [4].

Very broadly speaking, two camps exist in this debate, although both are quite diverse, with both moderate and extreme positions. The so-called 'green growth' literature is optimistic that suitable policies and technology will reduce emissions to sustainable levels, while allowing for continued or even boosted economic growth. This thinking is backed by many governments and international organizations. For instance, the European Commission defines its European Green Deal as "Europe's new growth strategy". Likewise, the long-term climate strategy of the US government promises broad economic benefits [5]. Degrowth (i.e., negative growth) proponents, on the other hand, dismiss this as "fairy tales of eternal economic growth" (see Greta Thunberg's speech at the 2019 UN Climate Action Summit [6]) and argue that the global economy must be scaled down, and that systemic change and redistribution is necessary to accomplish this.

On some level, this academic debate on extreme positions is largely theoretical. Developing countries will want to grow and will implement policies to that effect. The alternative, which is to allow developing countries to grow to a 'sustainable' global GDP per capita and to cut GDP per capita in rich countries to the same level, is also theoretical, as economic growth is of central importance for welfare and issues, such as debt sustainability, pensions, and social security. A shrinking or 'degrowing' economy could potentially also exacerbate the distributional implications of decarbonization (stopping the release of carbon gasses by eliminating fossil fuel combustion and other polluting activities) that will arise regardless (see, for example, [7]).

However, the sharp contrast in the theoretical positions of scholars is a way to conceptualize the magnitude and uncertainty of the climate challenge and should remind policy makers not to take established narratives for granted. The purpose of this paper is therefore to introduce the reader to the debate by briefly reviewing the main green growth and degrowth ideas, and to assess whether these visions can realistically help us reach net zero in due time. To that end, Section 2 first explains the problem of decoupling by discussing the so-called 'Kaya identity' and by offering a simple quantitative assessment of the gap between our historic performance in reducing the emission intensity of GDP and what is required for green growth, i.e., the basis of ongoing disagreement. Section 3 reviews the literature on degrowth, while Section 4 discusses green growth. Section 5 presents some critical comments and concludes that, despite the fact that both visions suffer from uncertainties regarding their feasibility, unlikely support for degrowth makes green growth imperative. Section 6 concludes.

2. The Challenge of Decoupling

Pursuing deep decarbonization will be challenging. Annual global GHG emissions keep rising and show no sign of peaking. In 2019, they were 62 percent higher than in 1990, the year of the first Intergovernmental Panel on Climate Change report, and 4 percent higher than in 2015 when the Paris Agreement was signed [8]. Even unprecedented circumstances such as the massive restrictions introduced to contain COVID-19 led only to a 6 percent drop in emissions in 2020, from which a quick rebound to pre-pandemic levels promptly followed [9].

Historically, economic growth—by which we mean real GDP growth—has long been associated with increasing GHG emissions. Empirically, the causal chain is straightforward: higher levels of economic activity tend to go hand in hand with additional energy use, for example by households wishing to travel more or by industry to meet a higher demand for manufactured goods, and with more consumption of natural resources. Fossil fuels still account for 79 percent of the global energy mix [10], and so energy consumption is closely related to GHG emissions and hence to climate forcing. The expansion of industrial processes, livestock rearing, and other agriculture adds to emissions, while deforestation reduces carbon sinks.

A far-reaching transformation of the global economy is needed to break the causality and reduce emissions. As 73 percent of global GHG emissions (and nearly all CO_2 emissions) comes from energy production [11], the energy sector is an interesting illustration of the broader problem of decoupling. A simple identity, formulated by Kaya and Yokoburi [12] on the basis of Holdren and Ehrlich's work [13], is useful to understand this concept:

$$CO_2\ emissions = population * \frac{GDP}{population} * \frac{energy\ demand}{GDP} * \frac{CO_2\ emissions}{energy\ demand}$$

The 'Kaya identity' breaks down emissions from energy into a logical product of four factors: population, *GDP* per capita, energy intensity of *GDP*, and the carbon intensity of energy. More generally, we can say that GHG emissions are a product of population, *GDP* per capita, and the GHG emission intensity of *GDP*. Such an approach allows to theoretically detangle the drivers of growing emissions and to identify where action can be taken [14,15].

Limiting population growth is one way to limit growth in CO_2 or general GHG emissions, but the debate on this topic goes far beyond the scope of our paper. We instead consider population growth as a given. Cutting emissions from energy would therefore need to happen by lowering some or all of the other factors. Since lowering the second factor (GDP per capita) is regarded as compromising economic and social welfare in 'mainstream' policy discussions, the core question is whether the third and fourth factor (energy intensity and carbon intensity) can decline at a sufficient speed to allow the first and the second factor to remain on their current paths.

A decline in energy demand/real GDP can be driven by improvements in energy efficiency from using better technologies for production, transport, and isolation; by behavioral change towards less energy-intensive consumption (e.g., increased use of public transport, a larger sharing economy, and more re-use of durable goods); and by a changing economic structure towards a more 'immaterial' service-oriented economy. A decline in CO_2/energy demand is mostly driven by the shift from fossil fuels to renewable energy sources.

If the decline in these two factors outpaces economic growth, absolute decoupling of GDP and emissions will take place (i.e., a situation in which emissions go down while real GDP continues to grow). This is already happening, albeit modestly, in Europe and the United States. (Note that developed economies such as the EU and the US import a lot of goods that are produced elsewhere, and thus GHG emissions attributable to consumption are somewhat higher than territorial emissions. Fortunately, these broader emissions are also declining for the EU [8].) Globally, however, there is no sign of absolute decoupling, but only of relative decoupling (CO_2 emissions grow less than proportionately to real GDP). Explained in terms of the Kaya identity, while energy-related CO_2 emissions per unit of GDP are falling (the third and fourth factors combined), the fall is slower than the increase in real GDP (the first and second factors) so that overall emissions continue to rise. Figure 1 shows that in the last 100 years, annual CO_2 emissions from energy production have risen tenfold, even though emissions per unit of GDP have been slashed by almost two thirds (1.6 percent per year on average since 1995, see Table 1). This is simply because the global economy has grown at a much faster pace (3.8 percent per year on average since 1995).

To understand how much the world still falls short of the required speed of decoupling, we use historical and projected data from the OECD on population and GPD per capita, as well as historical IEA data on energy and emissions, to compare recent average rates of change in each factor of the Kaya identity to what it would take to reach net-zero emissions by 2050 (Table 1). We assume that the reduction in energy use to produce GDP will continue its current downward trend rather than decline faster. We make this assumption because, unlike energy use in general, one can eliminate the use of fossil fuels with technology. Furthermore, while energy efficiency has an important role to play in reducing emissions, most of the 'untapped' potential to accelerate decoupling is with the speed at which energy production decarbonizes. The methodology is presented in Figure 2.

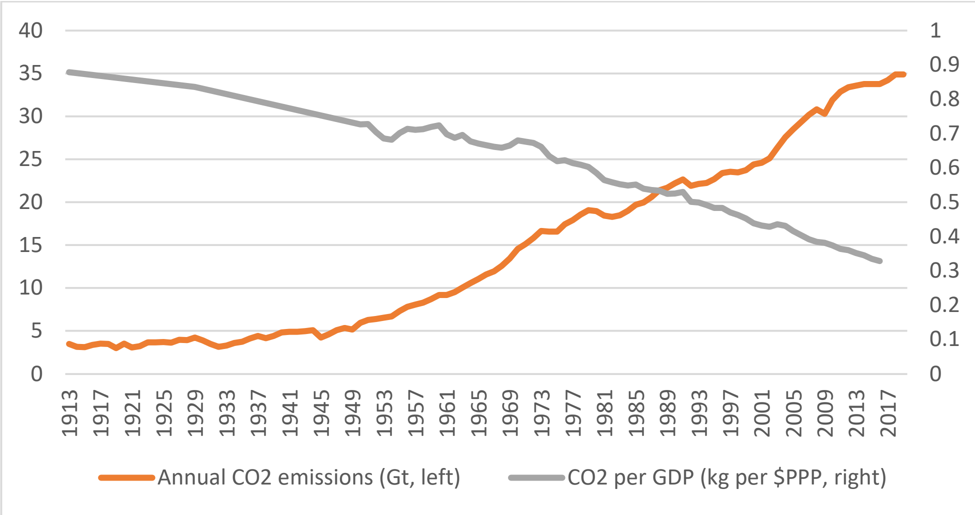

Figure 1. Global annual CO_2 emissions from burning fossil fuels for energy production (in gigatons) and CO_2 emissions per unit of GDP (in kg per USD/PPP). Source of data: Our World in Data [16].

Table 1. Factors of the Kaya identity, CO_2 and CO_2/GDP, and average yearly rates of change (%) in 1995–2018 (historical data) and in net-zero emission scenario 2019–2050. Source of data: based on data from IEA [17] for CO_2 emissions, CO_2/real GDP, and CO_2/energy demand; OECD for GDP per capita [18]; for population [19]; and for energy demand/real GDP [20].

	World		**EU27**	
	Historical 1995–2018	**Scenario 2019–2050**	**Historical 1995–2018**	**Scenario 2019–2050**
CO_2	2.0	−6.9	−0.7	−6.9
population	1.2	0.8	0.2	0.0
real GDPpc	2.6	2.3	1.2	1.4
energy/GDP	−1.7	−1.7	−1.8	−1.8
CO_2/energy	0.0	−8.2	−0.7	−6.5
CO_2/GDP	−1.6	−9.7	−2.5	−8.2
	US		**China**	
	Historical 1995–2018	**Scenario 2019–2050**	**Historical 1995–2018**	**Scenario 2019–2050**
CO_2	−0.1	−6.9	5.3	−6.9
population	0.9	0.5	0.6	−0.1
real GDPpc	1.5	1.3	8.4	3.0
energy/GDP	−2.1	−2.1	−3.7	−3.7
CO_2/energy	−0.5	−6.7	0.3	−6.1
CO_2/GDP	−2.5	−8.6	−3.4	−9.6

The global decoupling rate between emissions and GDP (bottom row) needs to accelerate by a factor of six to reach net zero by 2050. If the reduction in energy use continues on its current path, the decarbonization of the energy system has to proceed at around 8.2% per year—a huge acceleration compared to previous decades. The same exercise as above shows that for the EU and the US, the decoupling challenge is somewhat less daunting, as only a threefold acceleration is needed. This is partly because their economies are expected to grow more slowly than the global average. However, it is also because the EU and the US both have higher decoupling rates of −2.5%, as they are already visibly reducing the carbon intensity of their energy production. Meanwhile, China has seen even faster decoupling of CO_2 and real GDP, as well as very strong catch-up growth in GDP per capita still drove up emissions for now. China's historic decoupling rate seems largely driven by efficiency gains that arose as its economy rapidly modernized during the last decade. As this may not continue as before, China will also have to double down on decarbonizing its energy production in order to bridge the gap with its required decoupling rate.

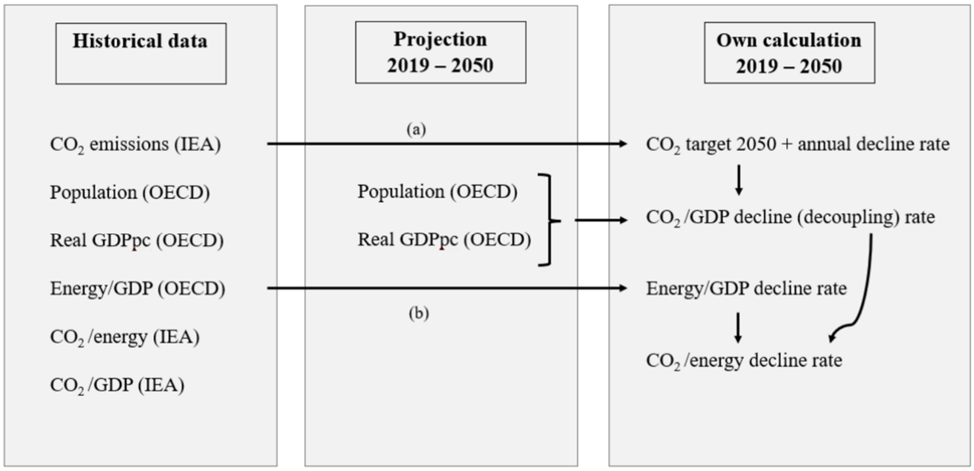

Figure 2. Methodology for the calculation of Table 1. [a] For this simple exercise, we assume that all regions must reduce CO_2 emissions from burning fossil fuels by 90% between 2019 and 2050 (remaining emissions are offset by negative emissions from agriculture, forestry, and other land use), consistent with the IPCC [3] pathways that lead to 1.5 °C warming with low temperature overshooting. We disregard international fairness and efficiency arguments.[b] We assume that energy demand/real GDP will continue to decline at the same yearly rate as its average in the period 1995–2018, i.e., up until when data were available for all regions.

Thus, progress on decoupling GDP growth from CO_2 emissions has been achieved; however, the continued expansion of the global economy has proven to stop annual emissions from increasing, let alone to allow them to decrease at the high pace required by the Paris Agreement. Whether decoupling can accelerate to this extent is the central question in the green growth vs. degrowth debate.

3. Degrowth

Guided by past experience, the basic premise of degrowth theorists is that the world will not be able to sufficiently reduce GHG emissions while global GDP grows. Current economic models, which are inherently focused on accumulation and growth, are therefore inevitably headed towards environmental and climate disaster.

Such pessimistic views about the long-term sustainability of economic growth are not new. They have been around in some form at least since the Essay on the Principle of Population by Thomas Malthus [21]. He postulated that famines and economic collapse were inevitable unless birth rates decreased, based on the belief that population growth is exponential and growth of food production merely linear. This argument was echoed throughout the twentieth century in environmentally inspired works by, for example, Osborn [22] and Vogt [23], and most notably in *The Population Bomb* by Paul Ehrlich [24]. Meadows et al. [25] predicted in *The Limits to Growth* that global population and economic activity would peak in the early twenty-first century and advocated an economic and demographic "equilibrium state" to avoid an uncontrolled collapse when humanity's need for resources finally exceeds the earth's capacity.

As iterated by *The Limits to Growth*, modern degrowth theories subscribe to the idea that humanity must achieve a lower economic 'steady state' to avoid environmental catastrophe. The term 'degrowth' was probably first used in the writings of French philosopher André Gorz in 1972 [26], and in the work of economist Georgescu-Roegen [27,28], who wrote that economic activity in the long run is limited to a level supported by solar flows due to the laws of thermodynamics. The term was popularized in the 1990s and 2000s by Serge Latouche [29] who criticized economic development as a goal. In the early 2000s, 'degrowth' was used as a slogan by social and environmental activists in France, Italy, and Spain. Finally, it emerged as an international research area in 2008 at the first Degrowth Conference in Paris [30,31], with many publications being produced particularly in the first half of the 2010s, in the context of the global financial crisis and the sovereign debt crisis in Europe. Authors including Giorgos Kallis (e.g., [32]), Jason Hickel (e.g., [33]), Tim Jackson (e.g., [34]), and Kate Raworth (e.g., [35]) are at the current forefront. Several variations of degrowth are advocated under different names, including 'wellbeing economics', 'steady-state economics', 'post-growth economics', and 'doughnut economics'.

Despite the common basic premise, 'degrowth' does not always mean the same in practice. Authors are also not always clear on exactly what should 'degrow' (shrink). There are at least five different interpretations: degrowth of GDP, consumption, worktime, the economy's physical size, or 'radical' degrowth, referring to a wholesale transformation of the economic system [36]. It is perhaps better to say that degrowth covers all these interpretations. Material and energy consumption and the economy's physical size need to degrow, out of a concern for resource depletion and, more recently, climate change. Worktime degrowth is one tool to do so, GDP degrowth is an inevitable consequence (not an aim per se), and radical degrowth is a necessary condition to make a post-growth economy socially sustainable [32].

By realizing the negative social consequences commonly associated with recessions, degrowth scholars indeed set out to define a path to actively 'guide' GDP downward, rather than to passively let the world slip into a depression and to cause widespread suffering. Demaria et al. [30] (p. 209) therefore defined degrowth as a call for "a democratically led redistributive downscaling of production and consumption in industrialised countries as a means to achieve environmental sustainability, social justice and well-being". As the definition suggests, the degrowth literature is not limited to the economy–environment nexus, but is also concerned with (international) redistribution and equity, political participation, social fairness, and 'beyond GDP' conceptions of welfare.

To achieve a managed transition, proponents advance a myriad of policies as part of a systemic change. We will only touch on them superficially. Perhaps the most important and common proposal is to limit the supply of production factors, most notably labor. Reductions in working hours are seen as a way to reduce consumption while increasing social welfare through more free time and achieving high levels of employment. The latter must also be supported by shifting employment towards labor-intensive sectors and steering innovation to increase resource productivity rather than labor productivity, using green taxes and 'cap-and-share' schemes [31,32]. Another element is to reduce aggregate investment by firms to net zero, which does not exclude that some (clean) sectors grow at the expense of other (dirty) sectors [31].

Other ideas found in the literature are the re-localization of economies to shorten the distance between consumers and producers, and encouragement of the sharing economy [37], as well as new forms of (regional) money and limitations to property rights [38,39]. Some advocate for zero interest rates to avoid the growth imperative created by having to pay back interest [40], caps on savings to reduce wealth inequality, and doing away with the logic of accumulation by firms and owners of capital. The aim is to arrive at a steady state in which the whole economy is consumed, which can end growth [41].

Importantly, many of the proposed policies are considered by authors themselves to be incompatible with capitalism and unlikely to be implemented by liberal representative democracies. Kallis et al. [31] therefore argued that, in the absence of democratic degrowth policies, a period of involuntary economic stagnation caused by climate change might usher in an authoritarian version of capitalism, unless more democratic alternatives are put forward.

Finally, it should be noted that degrowth proponents, such as green growth, devote relatively little attention to limiting population growth, which would theoretically offer another—though contentious—way to reconcile GDP per capita growth and emission reductions. Where it is discussed, most authors view it as undesirable, especially when non-voluntary, and point out that the large and growing populations of the Global South put relatively little stress on the environment [42].

4. Green Growth

Whereas degrowth backers believe that the slow decoupling of GDP and emissions thus far is indicative of the future, the green growth narrative is more optimistic. It is often noted that there have not yet been significant climate efforts globally, but this need not continue. For instance, there has been a drastic decline in prices of renewable energy technologies during the last decade. Figure 3 shows that, since 2010, the cost of energy from solar panels and wind turbines have declined by 85 and 68 percent, respectively, thus becoming lower than fossil fuel alternatives even without subsidies. This should change the economic incentives of governments and firms, as well as encourage the much higher investments needed in low-carbon energy generation.

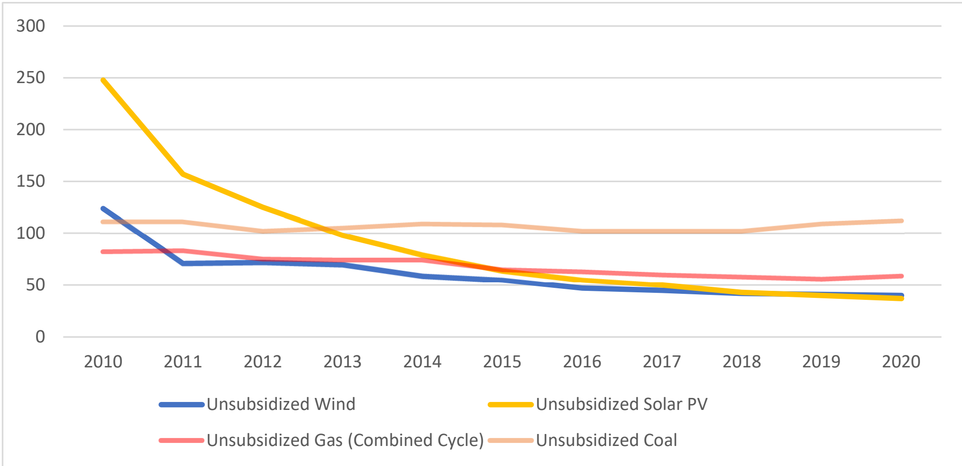

Figure 3. Levelized cost of energy (LCOE) from selected fossil fuels and renewable energy sources, in USD/MWh. Source of data: Lazard [43]. Note: these trends are in line with other sources [44,45].

Furthermore, green growth proponents argue that suitable policies and price mechanisms can spur technological development in unexpected ways, similar to in the past. It is therefore incorrect to say that decoupling cannot accelerate. Already in the earlier literature rejecting degrowth pessimism, the central role of technology was highlighted. Stiglitz [46] and Kamien and Schwartz [47] did not yet address GHG emissions, but rather whether continued consumption growth is possible in a world with exhaustible resources. They found that technology-driven efficiency gains allow the limits set by nature to be pushed forward so that continued expansion is possible. Later papers, including those by Weitzman [48], Acemoglu et al. [49], and Aghion et al. [50], discussed endogenous and directed technical change with more optimistic outlooks.

The 1987 Brundtland *Our Common Future* report is seen as a milestone for green growth with its definition ("Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [51] (p. 41)) of 'sustainable development' (Jacobs 2012), since it laid out the basis of global ecological policy thinking over the next few years, such as at the Earth Summit and the Rio Declaration in 1992, which explicitly called for economic growth to address environmental problems. The term 'green growth' only gained popularity in the wake of the global financial crisis of 2008 as an idea for short-term stimulus that incorporated environmental objectives (e.g., [52]), and was adopted as a policy objective by international organizations in subsequent years [53]. Today, it underpins the United Nations' Sustainable Development Goals (goal 8), and most governments and international organizations have adopted the green growth narrative as part of long-term development policies (e.g., [54–57]) and post-covid recovery plans (e.g., [58]).

Like degrowth, the term 'green growth' is not precisely defined. The OECD [55] (p.4), for example, describes it as "fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies", while the World Bank [56] and UNEP [57] each have different green objectives in their definition, such as simply 'minimizing environmental impacts' or, more ambitiously, 'reducing ecological scarcities' [59]. Regarding the 'growth' part, Jacobs [53] wrote that green GDP growth is understood as either: (1) higher growth than in a scenario without strong environmental or climate policies, both in the short and long run (dubbed the 'strong' version of green growth); or (2) lower though still positive growth in the short run and higher growth in the long run, as high future costs of climate damages are avoided by incurring manageable costs (the 'standard' version, as found in the Stern review [60]). Sometimes adding to the confusion is a lack of clarity about the baseline against which growth is compared. Is it a trajectory based on historical average growth rates or a no-action scenario that includes serious damage from climate change in the long run? This is not trivial, as in comparison to an economy wrecked by runaway climate change, an economic scenario that avoids climate disaster yet has sluggish economic growth could still be called 'green growth'.

Whatever the exact interpretation of green growth, publications following this school of thought promise, on the one hand, environmental benefits in the form of substantial avoided climate damages and short-term co-benefits, such as improved air quality [61], and, on the other hand, economic benefits resulting from increased investment and innovation. This 'double dividend' forms the heart of the green growth argument. Note that maintaining positive GDP growth while decarbonizing does not mean that the costs of the transition (such as high environmental taxes) will not negatively impact certain segments of society. It means that the environmental benefits and new economic opportunities (more than) compensate for the decline of 'dirty' sectors. Overall, however, the empirical evidence for a double dividend looks mixed. In fact, some of the reports by official institutions state that an economic dividend can be achieved only if very specific assumptions are made, while in many scenarios, strong climate action could, at least in the short term, lower GDP growth [62]. Furthermore, whereas green growth plans from advanced economies, such as the EU, are confident that the green transition will bring new business opportunities and jobs to replace old ones, global green growth plans can hide regional differences, since low-tech or fossil-fuel-exporting economies might be less well-positioned to benefit economically from a global energy transition [63].

Green growth policy plans generally rest on four pillars: (1) subsidies for innovation and investments in renewable energy and energy efficiency that boost GDP; (2) carbon pricing to further stimulate investments in efficiency and renewables, and to avoid rebound effects, combined with recycling tax revenues to cut corporate or labor taxes and boost employment, or increase redistribution; (3) assumptions about innovation to accelerate the decoupling process, notably about the use of negative emission technologies; and (4) compensation schemes for the poorest households, displaced workers or disadvantaged regions to make the transition politically feasible (see for example Table 2). The green growth narrative therefore usually still involves substantial government intervention, even if the most bullish proponents of green growth argue that it will come about as a result of free markets, and that green growth does not require anything other than carbon pricing.

Table 2. Different green growth scenarios, showing targeted emission reductions, estimated GDP impact, key policies, and adversely affected groups (in case of no compensation).

	Barrett et al. [63]	**European Commission [62] [a]**	**IEA [64]**
Emission reductions	Reduce gross global CO_2 emissions by 80% by 2050	Reduce net EU GHG emissions by 55% by 2030	Reduce global net CO_2 emissions to zero by 2050
GDP impact	Standard version: baseline GDP + 0.7% first 15 years, −1% in 2050, + 13% in 2100	Standard version: baseline GDP −0.27%/+ 0.50% by 2030	Strong version: baseline GDP + 4% in 2030

Table 2. *Cont.*

	Barrett et al. [63]	European Commission [62] [a]	IEA [64]
Key policies	• green investment push • carbon pricing • compensatory transfers • supportive macro policies	• green investment push • carbon pricing • tax recycling	• green investment push • carbon pricing
Adversely affected groups	• Low-income households, due to electricity prices and job status • Fossil-fuel-exporting countries	• Fossil fuel industry • Low-income households	• Fossil-fuel-exporting countries • Fossil fuel industry

[a] Includes JRC-GEM-E3, E3ME, and E-QUEST model estimates.

5. Discussion

As we have seen above, the disagreement between green growth and degrowth scholars is essentially about whether GDP and GHG emissions can be decoupled at a sufficiently fast pace to avoid dangerous climate change. Degrowers argue that absolute decoupling has never been achieved on a global scale and that even countries that do achieve it progress too slowly. As such, they arrive at the conclusion that global GDP must inevitably decline to save the planet.

They are right to highlight the considerable gap that still exists between the current climate mitigation efforts and available tools on the one hand and what is needed on the other hand. They point to the fact that most of the low-emission scenarios envisioned by the IPCC, which assume continued economic growth, rely on technologies to varying degrees, such as carbon capture and storage (CCS) applied to fossil power plants, or bioenergy with carbon capture and storage (BECCS), which are used to extract GHG from the atmosphere and thus compensate for earlier emissions. These technologies do not yet exist at scale and should not be relied on since their economic viability is unproven, and they could even create new environmental problems, such as excessive land and water use [65].

Similarly, the net-zero pathway drawn up by the IEA [64] also relies, to a great extent, on future innovation: 15 percent of the emissions reductions by 2030 and 46 percent of the reductions between 2030 and 2050 are to be achieved with technologies that are currently in a demonstration or prototype phase, such as CCS, green hydrogen, and advanced batteries. The breakthroughs achieved in the current decade will therefore be crucial. Unfortunately, none of the technologies needed beyond 2030 are currently on track to being deployed in time [66], as the road from concept to commercialization is typically long and winding.

Antal and van den Bergh [67] gathered a few more arguments directed against the prospect of decoupling through green policies. The most common argument is the existence of a rebound effect from investment in energy efficiency and clean energy. This means that, as societies invest to reduce emissions, increased income or savings resulting from those investments will at least partially offset the intended beneficial effects through increased consumption of non-renewable energy in another way. This can happen both at a micro level and at a macro level. The former happens if, for example, cars become more energy-efficient, convincing consumers to buy large SUVs, since driving them becomes cheaper [68]. In terms of the Kaya identity, a reduction in the energy intensity of GDP is cancelled out and nothing changes. At the macro level, there could be a rebound effect if large clean energy investments raise GDP per capita growth, which in turn necessitates even faster decoupling. Here, several terms of the Kaya identity are impacted differently, suggesting that they are not independent [69].

In addition, there is a risk that more stringent policies could see lower compliance because of what the authors call an “environmental Laffer curve”, with economic actors preferring to cheat rather than to respect regulations, as the expected cost of being caught and sanctioned is lower than the cost of complying.

A final objection is the possibility of burden shifting. While not an issue for climate change, other environmental risks could be exacerbated indirectly by emission reduction efforts, for example soil pollution from mining for minerals used in batteries.

The arguments above show that there is indeed considerable uncertainty about the feasibility of rapid decoupling and therefore of green growth, not least because of technological questions. However, scholars that predicted an imminent collapse in the past all proved too pessimistic (at least so far) precisely because they failed to predict the significant advances in agricultural yields, technological innovation and substitution, and declines in population growth rates. Advances in resource efficiency have often been driven by market forces, such as for oil in the 1970s, when scarcity drove up prices, creating incentives for cost-saving innovation. However, technological progress is highly unpredictable, and since the atmosphere as a deposit for CO_2 is a rival but non-excludable good, purely market-driven innovation and substitution will not solve the problem of climate change [70]. The other arguments mentioned also do not seem unsurmountable given the right policy responses.

This is why, in any case, strong policies are indeed necessary. However, as stated in the introduction, we do not believe degrowth is a valid option. Firstly, it is hard to imagine that a critical mass of the global population will voluntarily agree to it. The level of income per capita to which rich and poor countries would have to converge is difficult to estimate because it depends on the future dynamics of the factors of the Kaya identity (as well as how much further the global population will grow) and the interactions between them. As average incomes decline in rich countries, there is uncertainty as to whether the energy intensity of GDP will decline too due to a more modest consumption behaviour, or whether the opposite might happen in the absence of incentives for efficiency. Would people revert back to cheaper, more dirty technologies [36]? It is clear that at least *ceteris paribus* the average global income should be even lower than it is today. This will not offer much solace to poor countries that are still allowed to grow, and it is very unlikely that wealthy liberal democracies will find much support.

GDP per capita is of course flawed as a measure of welfare, at least at elevated levels. One can also raise legitimate questions about its normative basis. However, alternative conceptions proposed by degrowth seem equally flawed for the same reason. Furthermore, declines in GDP will have very real effects on debt sustainability and the affordability of health care systems in the current institutional context. In a connected, presumably non-degrowth world, the external effects of degrowth in a single country therefore remain unclear.

In sum, degrowth narratives carry their own unpredictability and environmental risks, perhaps even more than green growth. Unless degrowth is forced upon society, there might not be many other alternatives besides serious attempts at achieving green growth. For that reason, we end our discussion with a few conditions that are, in our view, key to unlocking green growth.

Firstly, massive investments will have to be mobilized in order to decarbonize energy production and improve energy efficiency globally, in the order of USD 5 trillion per year for the next 30 years, up from a current yearly average of USD 2 trillion per year in 2019 prices. This represents an investment jump of two percentage points of global GDP during this decade [64]. Other estimates by the IRENA [45] and Bloomberg NEF [71] are very similar. Carbon pricing can and should be used to create incentives for private investment in renewables, efficiency, and R&D, as public resources are not sufficient to finance the transition. Revenues from carbon pricing should then serve to help vulnerable households transition away from fossil fuels. In order to mitigate the risk of rebound effects, it is important that carbon prices have a broad coverage. Carbon border taxes could be used to avoid 'carbon leakage' through trade and to finance clean energy investments in developing countries. Moreover, enabling financial 'green' regulations and credible long-term policy commitments can facilitate private investments by reducing the uncertainty that can keep firms from investing [72]. In that regard, detailed net-zero pledges which are cast into law are useful. Unfortunately, by the time of COP26, only the EU (incl. some individual member states), Canada, Japan, and the UK had comprehensive and binding plans to reach net-zero emissions among G20 members (Table 3). Other major economies such as the US, China, and India would do well to follow suit.

Table 3. G20 members net-zero emission goals. Source: UNEP [73].

Country	Net-Zero Year	All GHG	Commitment
Argentina	2050	?	announcement
Brazil	2050	?	announcement
Canada	2050	yes	law
China	2060	yes	announcement
EU	2050	yes	law
India	2070	?	announcement
Japan	2050	yes	law
Rep. of Korea	2050	?	policy document
UK	2050	yes	law
USA	2050	yes	policy document

Uncertainty regarding the timeliness and feasibility of certain technological breakthroughs should not hold back efforts to support their development. It should rather make clear that the prospect of green technological solutions cannot serve as an argument against actual immediate emission abatement. Governments and the private sector both need to substantially increase their research and innovation funding. Public–private partnerships schemes, adequate risk-taking by public institutions, and green industrial policy can further deliver breakthrough innovation [74]. The example of solar panels shows that public policies and global cooperation can, in time, give the necessary push to make new technologies available at competitive prices, fundamentally altering the economic case for decarbonization.

In the meantime, encouraging behavioral change may well be necessary to support a reduction in GHG emissions, especially in the most hard-to-abate areas, also outside of the energy sector. For instance, agriculture and livestock rearing emits a lot of methane and takes up land. Because of its biological nature, there is not much scope for technological progress to reduce emissions here [75].

6. Conclusions

In the above, we looked into both green growth and degrowth ideas, discussing some of their most important arguments. A key argument of degrowers is that absolute decoupling between GDP and GHG emissions has never been observed globally, debunking hopes of green growth. Average decoupling rates of 1.6% per year have indeed been insufficient to lower global emissions. However, in several developed countries, absolute decoupling is ubiquitous, thanks to slower GDP growth and higher decoupling rates of around 2.5%. However, this too falls far short of what is needed to reach net-zero emissions by 2050.

We would argue that faster decoupling then today is possible, given the vast potential to expand renewable energy at competitive prices, which have declined by up to 85% during the previous decade. While there is substantial uncertainty as to whether this, together with technological progress, will sufficiently reduce GHG emissions to limit global warming to 1.5 °C, this uncertainty works both ways, as one cannot exclude the idea that technological progress will bring solutions based on the past. Moreover, the degrowth narrative is also confronted by several other uncertainties, some of which question even their ecological merits.

What does appear clear to us is the very low likelihood that degrowth proposals will be implemented on a global scale. From a pragmatic point of view, it is therefore imperative that governments and society at large can start to create the necessary conditions for green growth without delay, by assertively pushing clean energy and efficiency investments, introducing broad carbon pricing with revenue distribution to vulnerable households, casting green commitments into an enabling regulatory framework, doubling down on green innovation, and encouraging behavioral change where necessary. It remains to be seen to which extent GDP growth can be boosted by global climate action, but any scenario where climate targets are reached without drastic economic contraction in advanced economies or stagnation in emerging economies is preferable, since the latter would go against the eighth UN Sustainable Development Goal. The economic opportunities of the transition seem to be concentrated in advanced economies, although emerging countries around the equator also stand to benefit from avoided damages and from the possibility of producing and exporting cheap and renewable energy. Advanced economies will have to support emerging partners to make the global transition fair and inclusive.

We do not mean to suggest that no more scholarly work should be carried out on alternative development paths and measures of welfare; instead, we advocate more specific attention to how such visions can avoid pitfalls, such as a lack of technological innovation and misalignment of economic incentives, or how individual jurisdictions could implement degrowth in a non-degrowth world, for example. On the other hand, more research could also focus on the presence of interdependencies between factors of the Kaya identity that threaten to undermine green growth efforts (such as the rebound effect), and how such effects could be minimized by adequate policy design.

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Modelling the European Union Sustainability Transition: A Soft-Linking Approach

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Abstract: The European Green Deal (EGD) is the most ambitious decarbonisation strategy currently envisaged, with a complex mix of different instruments aiming at improving the sustainability of the development patterns of the European Union in the next 30 years. The intrinsic complexity brings key open questions on the cost and effectiveness of the strategy. In this paper we propose a novel methodological approach to soft-linking two modelling tools, a systems thinking (ST) and a computable general equilibrium (CGE) model, in order to provide a broader ex-ante policy evaluation process. We use ST to highlight the main economic feedback loops the EGD strategy might trigger. We then quantify these loops with a scenario analysis developed in a dynamic CGE framework. Our main finding is that such a soft-linking approach allows discovery of multiple channels and spillover effects across policy instruments that might help improve the policy mix design. Specifically, positive spillovers arise from the adoption of a revenue recycling mechanism that ensures strong support for the development and diffusion of clean energy technologies. Such spillover effects benefit not only the European Union (EU) market but also non-EU countries via trade-based technology transfer, with a net positive effect in terms of global emissions reduction.

Keywords: clean energy technologies; European Green Deal; dynamic computable general equilibrium model; policy complexity; revenue recycling; technological spillovers; systems thinking; sustainable energy transition

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1. Introduction

The European Green Deal (EGD), a strategy aligned with the United Nation's 2030 Agenda and the sustainable development goals, was designed by the European Union (EU) to benefit all economic actors, via cleaner air, water and soil, healthier food, and better health for current and future generations. This will be achieved through the adoption of reusable or recyclable packaging, reducing waste, reduced used of pesticides and fertilizers, expansion of renewable energy generation and transition to cleaner transport modes, in addition to the renovation of homes, schools and hospitals. The EGD is designed to be implemented through aligning investors and beneficiaries so as to achieve considerable societal gains. In practice, it links a low carbon future to sustainable and more equitable development for the EU [1,2].

Such a complex strategy that involve several sectors, agents and institutional levels deserves an extensive set of policy instruments to be implemented simultaneously [3], since the Tinbergen rule [4,5] will be violated if the policy strategy is directed to multiple objectives while the number of instruments is underestimated. Together with this theoretical explanation, there are additional reasons for using multiple instruments, given the potential complementary effects and the creation of positive synergies emerging from the implementation of the EGD.

Moreover, given that the EGD is clearly designed to accomplish multiple objectives, such as effectiveness, efficiency and equity, it is clear that a one size fits all approach might produce a policy strategy that is ineffective at least for one of the three objectives. The instruments might be also thought of as a way to compensate for the non-optimal level of the key policy instruments if, for instance, the final design is constrained by compromises between stakeholders or inefficiencies of the institutional and economic system [6,7].

There are several examples of both qualitative and quantitative exercises aiming at emphasizing potential complementarities or trade-offs between multiple instruments adopted within the same environmental strategy.

Qualitative analyses are based on different approaches that share as a common element the theoretical foundation of transition studies. According to Geels et al. [8], the achievement of ambitious decarbonisation targets is limited by the policy design itself, since the instruments adopted so far are not able to activate a systemic reaction from all agents. On the other hand, along with an evolutionary approach, interactions between technologies and societal groups should be used as the basis for policy design, instead of being assessed ex-post as an outcome of instruments' interaction. In the same line, Rogge and Reichardt [9] propose a set of characteristics of the policy mix that can help assess the potential capacity of instrument design to reinforce societal interactions and exploit complementarities. Systems thinking (ST) is often used to carry out qualitative assessments in the context of sustainability, recently predominantly in the context of green economy [10] and green growth [11], but also for circular economy [12]. Examples also exist for project-specific analysis, at the asset level and for project finance decisions [13,14].

Quantitative analyses are often based on partial or general equilibrium models that allow us to compute the different effects, often in a dynamic perspective, associated with alternative structures of the policy mix design. Recent examples of these exercises are applied to the computation of the potential double dividend arising from energy taxation [15] or to the design of counteracting instruments for reducing the rebound effect determined by gains in energy efficiency [16]. Elements of potential trade-offs emerged, in particular, for two issues. The first one is related to the potential inefficiency of a carbon policy designed to jointly support energy efficiency and renewable sources [17], since efficiency gains could be a source of reduction for the demand of renewables, thus bringing additional uncertainties for investors. The second concern regards the potential carbon leakage effect associated with a unilateral climate policy that can lead in the long term to a substantial reduction in economic competitiveness as well as a partial replacement at the global level of carbon emissions [18].

While the overall decarbonization goal of the EGD is clear and easily measurable, the other objectives are largely interlinked with several potential trade-offs emerging from the many outcomes they generate, and how these are interlinked. Accordingly, there emerges a need for further efforts in developing integrated tools that must address complexity and dynamically inform the policy design evolution [19]. So far, most proposals for enriching quantitative models with deeper knowledge of agents' interactions are based on soft-linking CGE models with bottom-up sector-based technology models with recent applications for the energy and transport sectors [20,21]. On the other hand, to the best of our knowledge there are no contributions proposing to use qualitative approaches to refine selected elements in CGE models.

This paper constitutes a first step to fill this knowledge gap by developing an integrated qualitative-quantitative methodological framework with a soft-linking exercise, combining systems thinking (ST) with a computable general equilibrium (CGE) model to assess the outcomes of the EGD. Systems thinking is used to identify the main indicators of the system analysed, conceptualize the interconnections existing among these indicators and explore emerging dynamics of change with the use of feedback loops. The improved systemic understanding achieved with ST informs the development of the CGE model, and the formulation of scenarios, in addition to supporting the interpretation of quantitative results.

The proposed approach provides an assessment of the social, economic and environmental outcomes of the implementation of the EGD, also in the context of the COVID-19 pandemic and recovery strategies. As such, it contributes to policymaking by providing indications on synergies and trade-offs emerging from the implementation of green investments, supporting the creation of a roadmap toward the goal of decarbonization by 2050. The introduction of COVID-19 into the modelling exercise allows consideration of potential benefits arising from the transition process toward a cleaner energy system in the EU as a way forward to recover from the economic crises.

The rest of the paper is organized as follows: Section 2 describes the two modelling tools, stressing the channels used for linking them, and the scenarios developed for the simulation exercise; Section 3 presents main results from the CGE simulations on effectiveness and efficiency of the EGD; Section 4 concludes by discussing the novelties of the methodological framework, the main results and policy implications and suggesting some insights for further development of methods for optimal policy mix design.

2. Materials and Methods

The transition to a low carbon economy has significant impacts on future energy systems and is likely to affect the entire economy. A rapid decarbonization pattern is also likely to affect the multiple linkages across different sectors of the economy, which deserve to be deeply analysed with a detailed representation of the relationships between different agents at different implementation levels [22]. At the same time, the interactions among agents belonging to a specific economic system might be influenced by the linkages across different economic systems, in a global general equilibrium approach which provides a consistent representation of interactions of different economic sectors in different countries.

The inclusion of both aspects, agents' interaction and feedback loops on the one side, and global relations into a market equilibrium approach on the other side, is hard to implement in a single model as different logics and behaviours drive the two elements. On the other hand, a soft-linking approach might help exploit the advantages of both tools by informing each other. In this paper we propose a one-way linkage approach, where the agents' interaction is defined with a system thinking approach, and the direction of linkages are used to develop a dynamic CGE model and formulate policy scenarios.

In particular, CGE models provide reliable results in a long-term perspective but they are affected by a strong rigidity in modelling assumptions, as for instance fixed technical coefficients, homogeneous agents and no feedback loops that can change behavioural parameters, such as demand elasticity to price and income, substitution elasticity across inputs in the production function, or substitution elasticity in consumer (households) basket expenditure.

All these sources of rigidity might be smoothed by first applying a ST approach to draw a complete picture of the complexity of the dynamic linkages arising from the policy issue under investigation. Then, parameters and coefficients in the CGE model can be updated or modelled as exogenous shocks on the basis of the ST indications, and simulation results are selected and interpreted from the point of view of the evolution of complex systems.

Figure 1 presents a flow diagram for the approach used to develop the research presented in this paper. First, a literature review was performed, considering the overall strategy of the EGD, policy provisions envisaged and expected outcomes. The review of data and historical trends as well as policy ambition and expected impacts resulted in the creation of the CLD. Two versions were created, one focused on system dynamics and one included policy intervention options. The former was used to support simulation designed for the CGE model, while the latter was used to perform policy analysis and support the interpretation of the results of the CGE model. The quantitative analysis includes both the parametrization and calibration of the pre-existing GDynEP model, as well as the creation of scenarios and resulting simulation of the model. Finally, the results of the study are a combination of insights originating from the use of systems thinking (CLD) and quantitative modelling (CGE), where key systems' variables were identified and numerical results interpreted.

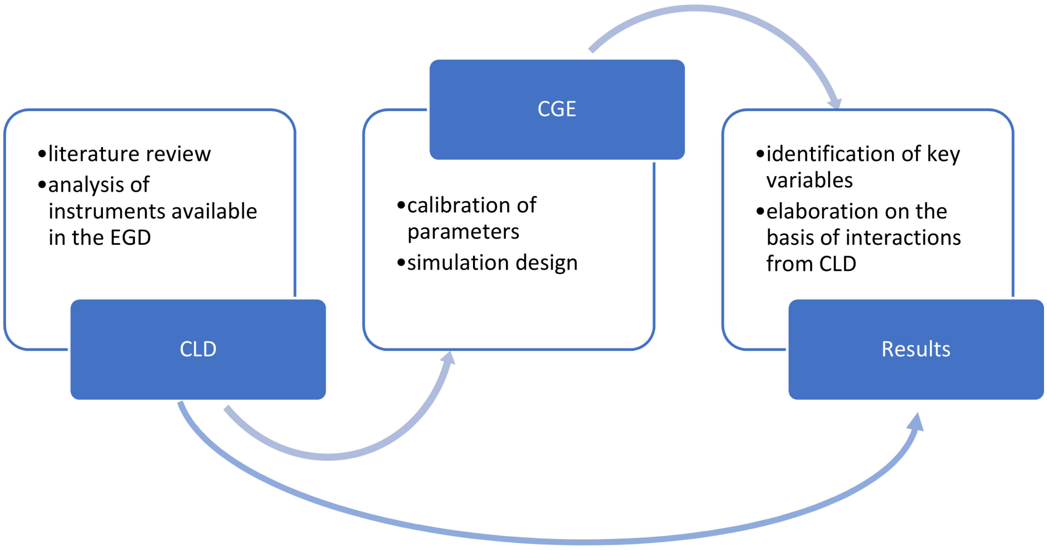

Figure 1. Soft-linking diagram procedure.

2.1. Systems Thinking

The starting point for the systemic analysis is the review of past drivers of change and the dynamics these have triggered. With an understanding of the known patterns of change that brought us to the need for the introduction of the EGD it will be possible to identify stated entry points for intervention, and their direct, indirect and induced outcomes. The use of ST provides a simplified system map (or causal loop diagram, CLD) to understand how the key variables of our socioeconomic and environmental system are interrelated, and how policy intervention can shift the dynamics experienced historically, leading to a more sustainable future. The CLDs presented in this paper were created with the software Vensim. Figure 2 shows that when GDP increases, a stable trend in the past decades, with only a few exceptions, two main outcomes emerge: (a) consumption increases, leading to higher GDP directly and indirectly via production (reinforcing loop R1), and (b) investment increases, leading to more innovation and cost competitiveness, in turn increasing production and GDP (reinforcing loop R2). It is these reinforcing loops (R) that trigger economic growth, also through employment creation and trade.

On the other hand, economic growth has given rise to various balancing factors (or balancing loops). One of these is the growing need for mobility, resulting in congestion. Congestion increases time spent in traffic and away from work and families (B1), creating societal costs. It also reduces the potential to grow for productivity, production and value added (B3). It further leads to air pollution (B2) resulting from energy use (both for transport, industries and in buildings), which affects labour productivity via health. Finally, the increase in energy use resulting from higher investment and income has led to higher vulnerability to market dynamics, price volatility and extreme weather events impacting the supply of energy (B4), which has negative impacts on production. Production, in turn, leads to the generation of waste, which impacts water pollution and food quality, creating societal costs both in urban and rural areas (B5). These are only a few examples of growing costs to society, those highlighted in the EGD. In addition, these costs are not emerging in the same measure in all countries and regions. As an example, urban areas are being impacted more strongly by air pollution than rural areas.

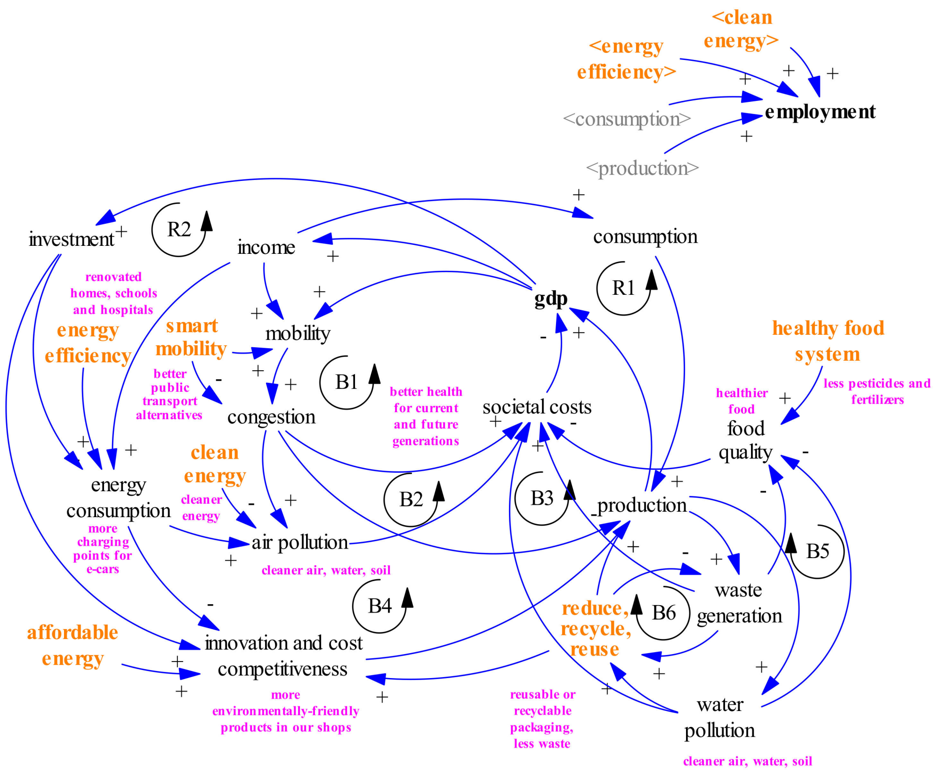

Figure 2. A simplified representation of the dynamics triggered by the European Green Deal (EGD). Legend: All key areas of intervention are covered in the causal loop diagram: energy, buildings, industry, mobility (https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6714, accessed on 1 March 2021); Pink: EU Green Deal benefits for future generations (https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6717, accessed on 1 March 2021); Orange: all key intervention options (areas) (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=EN, accessed on 1 March 2021).

When considering historical trends, it emerges that the reinforcing loops R1 and R2 have been dominating the dynamics of the system. This is because GDP, consumption and investment have grown over time, as have congestion and societal costs. On the other hand, the reinforcing dynamics have been stronger and have dominated the economy over the balancing ones. In 2009, after the financial crisis of 2008, GDP and investments decreased by 4.3% and 11.7%, respectively, for the EU27+UK. However, between 2015 and 2018 GDP increased by 2–2.5% each year, while investments also grew by 2.3–4.9% during the same period. Moreover, consumption expenditure increased by 9.8% from 2008 to 2018 on the basis of information on national accounts provided by Eurostat [23]. On the other hand, thanks to energy efficiency improvements, little change has emerged for energy consumption and emissions, as well as for waste generation, indicating relative decoupling. Gross inland energy consumption was relatively stable between 1990 and 2017, increasing only by 1.6% according to the national energy balances [24] while greenhouse gas emissions were around 22% lower than 1990 levels as emphasised by the statistics provided by the European Environment Agency (EEA) [25]. According to Eurostat, waste generation, excluding major mineral waste, slightly increased from 779.5 million tonnes in 2004 to 785.0 million tonnes in 2016 [26], thus revealing that deeper investigation on specific environment-related themes might unveil inefficiencies in the sustainability of the development trajectory. Overall, this highlights that the emergence of balancing loops has been countered by energy efficiency, the use of renewable energy, collection, sorting, recycling and reuse of waste. Limiting these balancing factors has allowed GDP to continue growing at 1.5–2.5% in the last decade, but more should be done both to support the economy via reinforcing loops and reducing constraints to growth via balancing loops.

The EGD is designed to use various strategies (in orange in Figure 2) to influence energy, buildings, transport and food production. The expected outcomes (in pink) include cleaner air, water and soils (through interventions on energy efficiency, clean energy, waste reduction, improved agriculture practices), also resulting in better human health, better transport alternatives and access to distributed power generation options (and so better access to more modern and resilient services).

Specifically, energy efficiency, clean energy and affordable energy are designed to reduce energy consumption and air pollution, as well as to stimulate innovation and increase competitiveness. As a result, these interventions strengthen reinforcing loops R1 and R2 via GDP, consumption and investment. At the same time, balancing loops B2, B3 and B4 will become weaker, further stimulating economic growth by reducing societal costs and making production more effective. Investments to realize these opportunities include renovated homes, schools and hospitals (energy efficiency), renewable energy use, installation of charging stations for e-vehicles, and adoption of environment-friendly technologies (clean and affordable energy). Smart mobility via better public transport and non-motorized transport will make B1 and B2 weaker, by reducing congestion, energy use and emissions, leading to lower societal costs (e.g., health costs) and more effective production activities. Outcomes include better health for current and future generations, via cleaner air, water, soil (also in conjunction with waste reduction, recycling and reuse). Waste reduction, recycling and reuse affect primarily B5 and B6, which then indirectly affect R1 and R2. As a result, reducing waste both unlocks opportunities for existing drivers of growth, and stimulates new paths for sustainable growth by stimulating innovation and competitiveness. Healthy food systems are expected to increase food quality by reducing the use of fertilizers and pesticides. This reduces societal costs (B2, B3), increasing labour productivity, lowering public and private costs, resulting in a stimulus taking place through R1 and R2.

Practically, the EGD aims at making balancing factors weaker, so that the economy can continue to grow, but in a more sustainable and resilient way. This results in lower costs for society, higher productivity, and improved well-being.

The inclusion of the COVID-19 pandemic crisis in the analysis requires the addition of several variables to the CLD, representing (i) impacts of the outbreak (e.g., consumption) and (ii) response measures (e.g., public stimulus). These additions introduce new dynamics and feedback loops (Figure 3), namely:

- reduction of GDP via the reduction of production (due to demand and limited labour force availability);
- reduction of GDP via the reduction of consumption (due to social distancing, avoided travel);
- reduced economic performance due to the higher cost of doing business and insurance premiums;
- reduced country performance due to the increase of country risk and public costs (higher country risk leading to higher debt costs, higher public costs related to health and stimulus packages).

These four dynamics affect two existing reinforcing loops (R1 and R2), having a negative impact on GDP via consumption and production, possibly triggering a vicious cycle and hence a recession. The introduction of a public stimulus instead adds reinforcing loops R4 and R5. The former represents the short-term solution implemented by governments, to stimulate investments. The latter represents the expectation that, once the economy starts growing again, it will generate additional growth that allows the reduction of the debt accumulated in the short-term. The dynamics triggered by the increase of debt are represented by the balancing loop B4. Higher debt will reduce the potential for new investments in the future, due to the higher cost of debt servicing and to budget constraints related to financial stability.

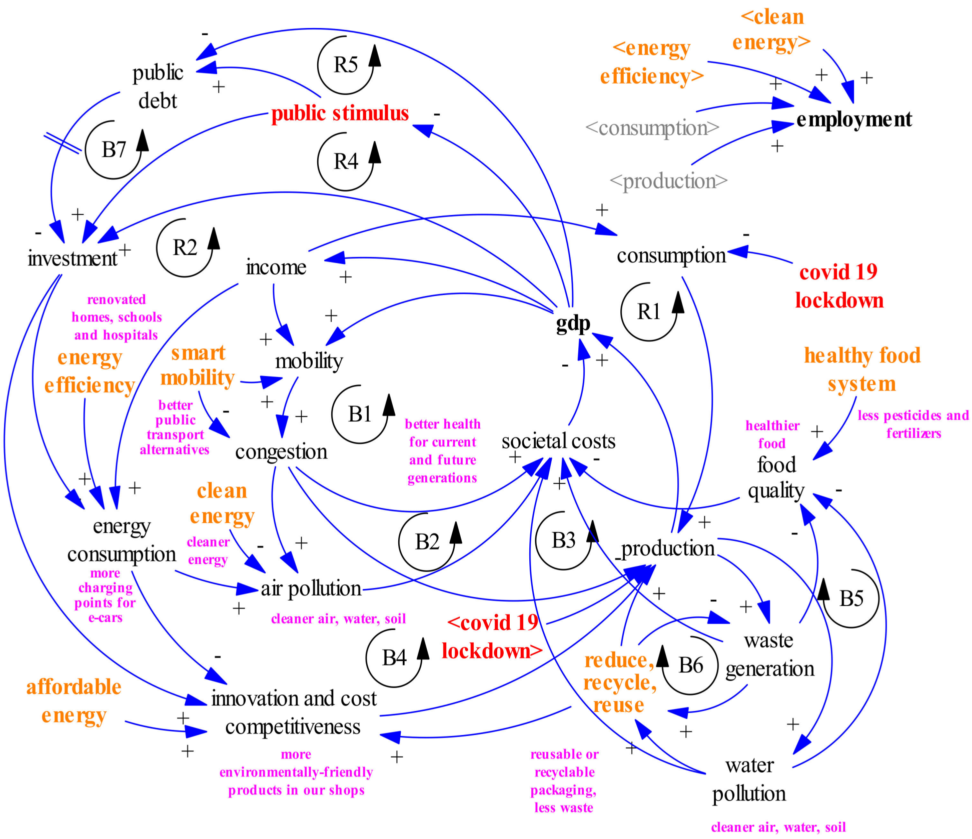

Figure 3. A representation of the dynamics triggered by the European Green Deal (EGD) including COVID-19 pandemic.

It has emerged that COVID-19 has temporarily turned two drivers of growth (R1 and R2) from virtuous to vicious, making them causes of recession rather than growth. This triggers balancing loop B7, which highlights the limited (finite) amount of financial resources available to governments. The expectation is that, if the stimulus is allocated well (R4), after the lockdown ends and the economy recovers, it will kick start production and consumption to levels that will stimulate employment, increase government revenues (R5) and limit the constraints posed by medium and long-term debt (B7).

Concerning environmental performance, the reduction of economic activity reduces energy consumption and air pollution, and hence societal impacts, driven by R2, as well as by B1, B2, B3 and B4. With economic recovery the opposite dynamics return, as described earlier. As a result, little change is expected to these dynamics, unless permanent impacts emerge (e.g., smart working remains common practice with a structural impact on transport modes).

2.2. The GDynEP Model

By focusing on the behavioural aspects related to the energy system, some of the linkages and loops obtained by the ST approach can be simulated into a dynamic CGE model hereafter called GDynEP. The model we develop for this purpose is based on RunDynam software designed for GTAP-type models. The specific GTAP-type version of the model is called GDynEP and all details on the modelling approach are provided in [27,28]. With respect to the previous GDynEP model version, there are some novelties related to the construction of the base year, the emissions data and the regional aggregation.

The base year relies on the GTAP 10 database, meaning that the starting point is the year 2014, with updated values for Leontief input-output matrices for the factor costs of sectors included. The GTAP 10 database is a consistent representation of the world economy for a pre-determined reference year [29].

Together with combustion-based CO_2 emissions as in all standard GTAP-E models, the GDynEP also introduces non-CO_2 emissions associated with the use of energy commodities in the production and consumption activities. In detail, the new version of GDynEP includes three energy-related data sources.

The GTAP-E 10 database provides carbon dioxide (CO_2) emissions data distinguished by fuel and by user for each of the 141 countries/regions and the 65 sectors in the GTAP10 database. GTAP-E data is based on: GTAP 10 and extended energy balances compiled by the International Energy Agency (IEA). A complete description of all features in the GTAP-E database is provided by [30].

The GTAP-Power 10 database is an electricity-detailed extension of the GTAP 10 database including seven base load technologies (nuclear, coal, gas, hydroelectric, oil, wind and other power technologies), and four peak load technologies (gas, oil, hydroelectric, and solar) for 2014 [31]. Moreover, an updated version of the methodology allows output of the electricity and heat generation sector to be split using electricity generation data together with heat generation volumes [32].

The GTAP-NCO2_V10a database is based on the methodology developed by [33] and is integrated in GDynEP with three major non-CO_2 groups of gases, CH4, N2O, and fluorinated gases (F-gases), including CF4, HFCs, and SF6. Emissions come from three emissions drivers: consumption (by consumers and firms), endowment use (land and capital), and output. With respect to the emissions associated with consumption by firms and households the original GTAP file has been transformed in order to be compatible with the structure of combustion-based CO_2 emissions used in GTAP-Power with 76 sectors. Accordingly, the new emissions database contains the sum of combustion-based CO_2 emissions and non-CO_2 emissions associated with the use of energy inputs including the chemical sector.

The regional aggregation: takes into account the Brexit process and the United Kingdom is excluded by the EU aggregate, while the sector aggregation is based on the technological content as well as the energy intensity of the production process. Details on aggregation are provided in Appendix A, Tables A1–A3.

With respect to the time frame, the starting point is 2014, so the first period is 2014–2015, while the following periods are five-year steps up to 2050 with a total of eight periods. Details regarding the software adopted, the aggregation files, the elaboration of shocks are available in the Supplementary Material file.

2.3. Simulation Setup

Scenarios are based on a business as usual reference case (BAU) that is alternatively tested with and without the economic crisis due to COVID-19 pandemic. This helps us better investigate the role played by investments in clean energy technologies (CETs) in contributing also to exiting the crisis. By comparing the GDP growth rate with COVID-19 shock with growth patterns associated with a general economic recovery based on GDP levels, it is possible to highlight the magnitude of investments required to escape from the crisis in a short-term perspective. By adding the financial support to CETs associated with the implementation of the EGD targets, we can emphasize the additional impact played by longer term investments.

The source on which scenarios are based is divided between the current period 2014–2020 and projections for the time span 2025–2050. The different variables on which the baseline and the policy scenarios are based are listed.

2.3.1. Model Calibration to Current Baseline

For what concerns the calibration for the current period 2014–2020, we provide details on the procedure adopted for each variable.

- Population: for the reference period (2014) data are taken from the GTAP10 database while for updates 2015–2020, data come from Eurostat and World Development Indicators (WDI) from the World Bank;

- CO_2 emissions: for the reference period on combustion-based CO_2 emissions (2014) data are taken from GTAP-E while for updates 2015–2020, data come from Eurostat, IEA CO_2 emissions highlights and WDI;
- GDP: for the reference period (2014) data are taken from the GTAP10 database while for updates 2015–2020, data come from Eurostat and WDI;
- Non-CO_2 emissions: for the reference period (2014) data are based on GTAP-NCO2V10a updated with change in 2015–2020 based on Eurostat and IEA energy balances;
- Labour force: for the reference period (2014) data for skilled and unskilled labour force are calculated as the share of total labour force from CEPII information applied to GTAP population data and for the period 2015–2020 they are also calibrated with ILO information on labour force and CEPII statistics;
- Production of electricity from renewable sources (RSELE) in the electricity sector: for the reference period (2014) data on RSELE are taken from GTAP Power version 10 and for the period 2015–2020 data comes from growth rates computed on Eurostat and IEA energy balances;
- Production of electricity from fossil fuels (FFELE): for the reference period (2014) data on FFELE are taken from GTAP Power version 10 and for the period 2015–2020 data come from growth rates computed on Eurostat and IEA energy balances.

For the projections in the time span 2025–2050, the baseline case (called BAU) is computed on the basis of the combination of data from different sources:

- Data on GDP, population, GHG emissions and production of electricity divided into RSELE and FFELE are based on the reference case used by the JRC model (Keramidas et al., 2020) for all regions in the model setting except for the EU region;
- data on GDP, population, GHG emissions and production of electricity divided into RSELE and FFELE only for the EU members with country-based information are based on the reference case developed by the European Commission for the PRIMES model [34];
- Data on labour force divided into skilled and unskilled are based on CEPII projections [35].

The baseline is calibrated with shocks associated with GDP, population, skilled and unskilled labour force and CO_2 and non-CO_2 emissions that are considered as exogenous and are calibrated with the increase in production and consumption efficiency. This is a requirement for the GTAP modelling exercise because otherwise emissions are not bounded, and they proportionally follow the GDP and population trends without any assumptions on technological improvements that will reduce carbon intensity of economic dynamics.

A further element for building the BAU case is reflected in the energy balances for all regions, and in particular the proportion of renewable and fossil fuel sources in the electricity production process. On the basis of the projections available from the JRC model and the EU reference case for PRIMES, the two electricity sub-domains have been treated as exogenous, thus calibrating the BAU case at the end of 2050 with a share of RSELE on total electricity for the EU compatible with the JRC baseline case. The shocks in BAU are based on the evolution over time of the production of electricity by the two sources expressed in GWh, where the starting point is 2014 according to the value of electricity production provided in the GTAP-Power database in GWh. The calibration has also been compared with the composition of the energy mix on the consumption side with respect to the reference case of the EU models, in order to obtain an overall energy consumption at the EU level compatible with expected values simulated with the help of bottom-up technology scenarios.

2.3.2. Model Calibration for Policy Scenarios—Paris Agreement

For the projections in the time span 2025–2050 related to the policy case, we consider as a starting point the decarbonization process for the EU27 region according to the implementation of the Paris Agreement with an emissions pattern to 2050 compatible with the EU targets associated with the increase in global temperature by a maximum of 1.5 °C with respect to pre-industrial levels. The emissions target designed for the Paris Agreement scenario for the EU is equivalent to the net zero emissions target described in the EGD with the updated target by 2030 of cutting emissions by 55% with respect to 1990 levels. Accordingly, there is a common CO_2-eq emissions trend in all policy scenarios for the EU.

Given that the GDynEP model is an economic-energy model without enough technological details to simulate the role played by LULUCF and CCS activities, the final emissions in 2050 account for gross emission levels without the impacts of carbon sinks. This results in an apparent overestimation of emissions with respect to the EU reference scenario that is fully explained by the absence of sinks. Accordingly, while in the EU reference case emissions in 2050 are around 2% of the BAU case, in GDynEP in 2050 emissions are around 9% of the BAU case. The remaining 7% is supposed to be absorbed by carbon sinks to reach the target of net zero emissions by 2050.

In order to obtain the first policy scenario in which the EU will respect the abatement target for the full implementation of the Paris Agreement, resulting in an emission reduction by 2050 of 91% with respect to the BAU case (called EU-PA), a policy instrument based on a Pigouvian carbon tax is adopted. According to the model version in Bassi et al. (2020), by considering the EU as an aggregated region it is worth mentioning that the cost effectiveness criterion is fully respected, since the value at the margin of the carbon tax is perfectly equivalent to a carbon price level if an emission trading system is applied. The only difference between the EU-ETS and the modelling approach we adopt is that in GDyn-EP all sectors are involved in the carbon policy with the same instrument, without differentiated treatment for energy-intensive and non-energy intensive sectors [28]. This assumption allows consideration of carbon tax and carbon price as fully equivalent market-based environmental policy instruments. Accordingly, in the following sections we will consider carbon tax and carbon price as if they are synonymous.

In order to calibrate the model with respect to the emissions trend, we take CO_2 emissions as exogenous only for the EU, with a specific trend that is compatible with the PA target. On the contrary, emissions for the rest of the world are left as endogenous, considering a case in which the other regions are not respecting their NDCs under the PA. This is consistent with a notion of unilateral policy, and in a comparative exercise perspective, it is the only way to compute the economic impacts of a specific policy in an ex-ante evaluation with a counter factual benchmark. If, on the other hand, we adopt a multilateral perspective in which all regions implement abatement targets, it is no longer possible to single out the economic impact of the EGD [36].

Together with the calibration of emissions with exogenous shocks, we also control for the energy mix at the EU level, with particular attention to electricity production. More specifically, we consider electricity production, both from fossil fuels and for RES as exogenous, following the production trends available in GECO 1.5 °C policy case. This is a requirement because electricity is a carbon free energy source in a sense that consuming electricity is not associated with CO_2 emissions. This leads to an overestimation of electricity consumption in a policy scenario with no control for electricity production. In other words, the model cannot consider for instance technical constraints to substitutability between sources related to competition to inputs (capital and labour mainly), or diffusion obstacles, for example, associated with the absorptive and distribution capacity of the power grid.

2.3.3. Model Calibration for Policy Scenarios—European Green Deal

In order to make an economic assessment of the impacts associated with the EGD, on top of the first policy scenario (EU-PA), based on a simple carbon pricing instrument, we associate an additional instrument based on a revenue recycling mechanism for financing the development, deployment and diffusion of CETs. The recycling mechanism is based on the hypothesis that part of the revenues collected from carbon pricing (CTR) by the government can be reused for sustaining green energy technologies.

In detail, given that GDynEP has a standard production structure where sectors are classified according to the ISIC codes, without a specific sector producing technology, we compute an elasticity parameter with which investment flows in R&D are directly transformed into benefits on the consumption and production side.

We test different shares of CTR to be allocated to finance CETs through an ideal innovation fund that can be compared with real figures available in the estimation provided for the ETS innovation fund by the European Commission. It is worth mentioning that in our model, given that a carbon price (equivalent to an equilibrium carbon tax) is paid by all sectors (as if the ETS has been applied to the whole economy without free allowances), from the one side the higher the abatement target the higher the cost, given by the carbon price, but on the other hand a higher carbon price is associated with a larger CTR and consequently to a higher amount of the innovation fund for CETs.

In GDynEP it is possible to account for the efforts in development and diffusion of two technology options: energy efficiency, both in the production processes and in the households' consumption patterns; and production of electricity with renewable sources.

In order to quantify the contribution of public support to CETs, we need two parameters related to elasticity of substitution that are required for developing evolutionary scenarios of technological trajectories for clean energy technologies sustained by public support [37]. We compute them on historical data for the last ten years of R&D public investments in the EU for energy efficiency (obtained in all sectors) and renewable sources in electricity with respect to the starting date of GDynEP (2014). In this model we consider two assumptions: (i) energy efficiency uniformly influences productivity across all sectors independently from the specific share of energy used within the input mix, (ii) the diffusion of innovation is not influenced by additional technical barriers different from those already accounted for with the historical estimation.

The model is programmed in order to use R&D investments to increase input augmenting technical change for the use of energy as an input in the consumption (households) and production (firms) function. For a given amount of public budget invested in energy efficiency, the effect consists of a reduction of the energy intensity with respect to the reference case, with a lower cost for saving energy [38].

Concerning renewable sources in electricity generation, by promoting renewable energies by capacity investments (rather than by generation subsidies) the impact of uncertainty for demand conditions and capacity availability is substantially reduced. Accordingly, the elasticity is computed considering the public R&D investment in renewable sources for electricity generation provided by the IEA R&D database and the corresponding increase in installed capacity in renewable electricity in EU countries during the same period (1994–2014 Eurostat energy balance dataset available online). The estimated parameter comprises an output-augmenting technical change, meaning that the R&D efforts have the main effect of reducing the production cost of electricity from renewables with respect to fossil fuel sources. The economic rationale behind this modelling choice is simple: given a certain number of inputs used for producing RES (mainly capital and labour), the investments in RES allow the system to transform the same amount of inputs into a larger amount of output (electricity in this case) [39].

It is worth mentioning that the investments in RES are combined with the exogeneity of RES production in the EU-PA policy case. This means that the amount of RES produced are exogenously determined but the production cost is endogenously driven by the amount of investments directed to technical change from the CTR. Accordingly, the higher the share of CTR invested into the innovation fund, the higher the output augmenting technical change, the lower the unitary production cost. In order to compare model results with the EU energy strategy pillars, in the case of RES it is possible to compare the amount of energy, and in particular of electricity from RES as a share of total consumption of electricity. Given that the production cost is lower, in the EU-GD scenario it is likely to obtain an increase in the share of electricity from RES consumed than in the EU-PA policy scenario.

2.3.4. Scenarios Accounting for COVID-19 Crisis

Together with these three scenarios we introduce the economic impact of the crisis due to the COVID-19 pandemic to the BAU case as follows. Starting from the BAU case we implement a policy shock in 2020 with an exogenous reduction of GDP w.r.t. the BAU case with an impact associated with the main regions according to [40] compatible with the IMF and the World Bank estimates at the world level, recently provided by the updated report [41]. The average reduction at the world level is estimated around 6% in 2020 w.r.t. BAU and around 3% w.r.t. the GDP level in 2019.

The economic impacts of COVID-19 are many and varied and growing by the day. Following the outbreak, financial conditions have worsened at an unparalleled speed, weakening economies worldwide. Emerging dynamics include the increased risk of defaults of private companies due to weaker demand, higher volatility in the stock market due to future uncertainty on the profitability of businesses and impacts on the solidity of national finances due to growing expenses and reduced revenues. These impacts depend on both global and local dynamics, with local consumption as well global trade being impacted by the number of infected countries and the duration and severity of epidemiological shocks. The uncertainty of impacts, effectiveness of policy responses, and duration of current challenges leads to consideration and creation of various scenarios for a possible recovery.

The assumption is that once the shock has been assigned to the 2020 policy scenario, then the GDP is left to be determined endogenously by the model. Accordingly, it is possible to obtain changes in GDP from 2025 according to a path dependence approach related to the dynamic recursive nature of the model. It is worth mentioning that in the case of a COVID-19 shock without any recovery measure, the GDP growth pattern can be lower than in the case of a BAU pre-crisis case because the amount of capital stock for the economic system is dependent on savings produced in the previous period in a system of national account methodology.

The BAU case that accounts for the shock which occurred in 2020 assumes that no additional shocks will occur, but the endogenous solution provides GDP values for the period 2025–2050 that incorporate the negative impacts due to capital stock reduction and a demand decrease that persists over time. This BAU case with the COVID-19 shock with no recovery measures is named BAU no-recovery.

A second scenario is built with an exogenous shock that allows GDP in 2025 to turn back to 2025 original BAU values before the COVID-19, hereafter called BAU full-recovery. This means that the shock is calibrated in order to give impulse to the economic system to completely recover from the negative impacts in the medium-term (5 years). In order to make sure that the amount of resources is compatible with policy feasible solutions, we have computed the endogenous increase in capital formation required to recover from the crisis. As a benchmark, we looked at the resources that the EU is allocating in different forms during 2020 amounting to a recovery package of around €750 billion, that corresponds to around 5% of the EU GDP in 2020 from GDyn-EP without COVID-19. In 2025, according to the full-recovery scenario, the total resources to be invested along a 5-year period required to go back to a GDP pre-COVID-19 amount to around 9.5% of GDP in 2025. Considering that in the years 2021–2025 additional resources could be invested within the Next Generation EU fund according to the recovery plans presented by Member States, together with additional private resources, a total of 9.5% of GDP in the form of capital investments is reasonable. The same mechanism is applied to all regions belonging to the GDyn-EP, with examples of resources invested in other large economies as 4% of GDP in China and 8% in the US.

On the basis of the two additional BAU scenarios that include COVID-19 GDP shock with and without recovery, we are able to compute the new emissions trend for the two BAU cases. Different from the original BAU where emissions are exogenously projected according to bottom-up energy scenarios, in the two BAU cases with COVID-19 emissions are left free to move endogenously, following the GDP shocks in 2020 and in 2025 (only in the case of full-recovery), and the endogenous GDP patterns from 2025 on. Accordingly, together with the GDP, CO_2-eq emissions will also be changed with respect to a BAU pre-crisis, and on this new reference case the two policy options associated with the simple carbon pricing and the additional measures planned within the EGD are implemented and evaluated. As a final calibration check, emissions endogenously determined with the BAU no-recovery and BAU full-recovery GDP shocks have been compared with emissions provided by the bottom-up model by the International Energy Agency available in the World Energy Outlook 2020 [42].

3. Results

3.1. Economic Impacts with COVID and Unilateral European Union Carbon Pricing

The BAU case represents a baseline to be used as a benchmark for policy impact evaluation under different scenarios and assumptions. The introduction of the economic shocks associated with the COVID-19 pandemic is represented for the EU in Figure 4 and for the rest of the world (ROW) in Figure 5.

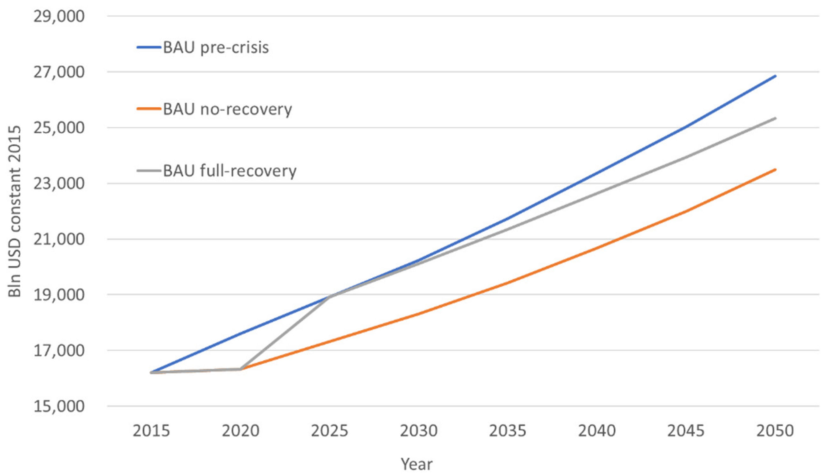

Figure 4. Gross domestic product (GDP) pattern in EU27 in reference cases (own elaboration on GDynEP results).

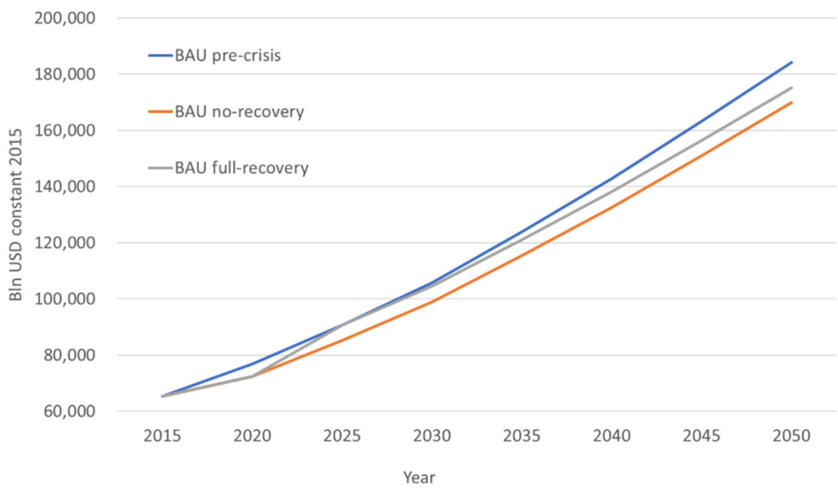

Figure 5. Gross domestic product (GDP) pattern in rest of the world (ROW) in reference cases (own elaboration on GDynEP results).

The difference highlighted by the two alternative patterns is explained by the introduction of a generally designed recovery package that is supposed to be implemented over five years, from 2020 to 2024, in order to obtain a full recovery in 2025. After 2025 the GDP pattern is endogenous again and the recursive nature of the dynamic CGE implemented here demonstrates that without a long-term perspective in the design of the implementation of investments under the recovery measures, the positive impulse to GDP is large in the short-term but loses weight in the medium to long term. The reason behind this result is that from 2020 to 2025 a considerable portion of capital stock has been lost, and the resources implemented for a short-term recovery are not sufficient for ensuring a return to the same GDP growth pattern. Practically, reinforcing loops R1 and R2 (see Figure 3) will not be strong as in the BAU scenario in the medium and long term, despite the stimulus offered by R4. Possible reasons, in addition to loss of capital, include the future cost of the recovery package (e.g., cost of financing) and the economic growth pattern being largely aligned with the carbon intensity and the creation of externalities of the BAU scenario.

According to the modelling choice described in Section 2.3.4, together with the GDP pattern that is endogenously modelled from 2025 on, the CO_2-eq emissions included in GDynEP are also left free to evolve according to the economic patterns at the regional level and the feedback loop mechanisms automatically activated as shown. As a result, the reduction in economic activities even in the case of a full recovery in 2025 will bring emissions in the BAU case to decrease, both in the case of EU (Figure 6) and ROW (Figure 7).

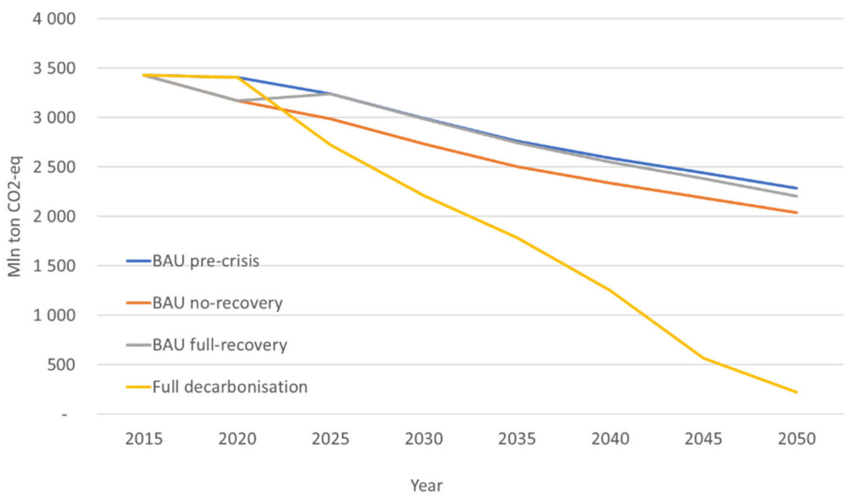

Figure 6. CO_2 emissions pattern in EU27 in reference cases (own elaboration on GDynEP results).

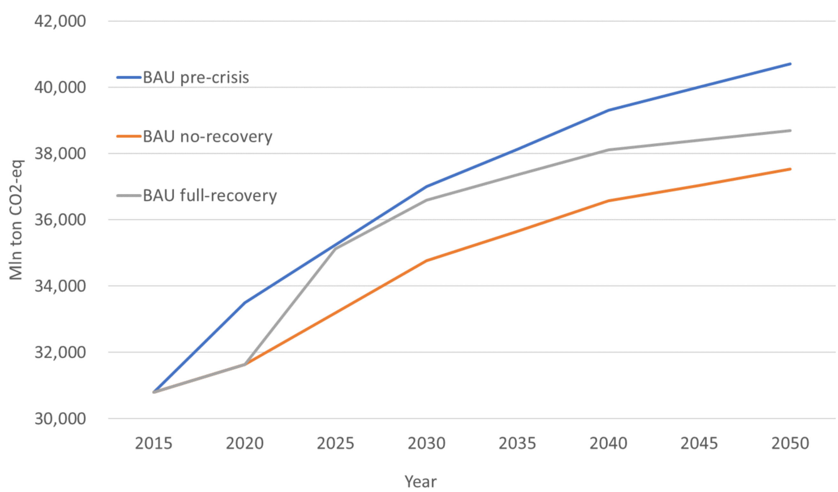

Figure 7. CO_2 emissions pattern in rest of the world (ROW) in reference cases (own elaboration on GDynEP results).

In Figure 6 we compare emission trends for the EU in the different BAU cases with the projection of the full decarbonisation strategy by 2050. Emissions decline in the decarbonisation scenarios as a result of the implementation of intervention options that reduce energy use and stimulate fuel switching (see Figure 3, specifically, orange variables and feedback loops B2, B3 and B4).

It is worth mentioning that, although in both post-COVID reference scenarios the CO_2 level will drop, the emission gap with the mitigation target is still large. The implementation of a unilateral carbon policy by the EU will instigate a reaction at the global level with an increase in emissions level, as a typical carbon leakage effect [25]. This means that the efforts taken by the EU in reducing emission levels that correspond to around 2000 Mt CO_2-eq abated in 2050 w.r.t. BAU are partly cancelled out by the increase in emissions by the rest of the world (estimated around 1000 Mt CO_2-eq), with a carbon leakage rate (computed as the ratio between the change in emissions of the ROW and the absolute value of emission reduction by the EU) by 2050 that is around 51%. In other words, if the emission reduction by the EU is implemented by adopting a carbon pricing instrument alone, without any additional public support for speeding up the technological transition of the energy sector, the reaction of foreign producers will be to increase their demand for fossil fuels to produce goods and services thanks to their increased competitiveness on external markets with respect to the EU companies. Furthermore, whatever BAU is considered, the achievement of the emissions level respectful of the EU decarbonisation target obtained by a pure carbon price policy without any support to efficiency and innovation has relevant costs for the EU, with a substantial drop in GDP level (Figure 8). This is not surprising, as the final target for the year 2050 is a reduction of 90% in emissions w.r.t. to 2050 emissions in BAU, corresponding to a net zero emission goal for the EU, with a carbon price that is prohibitive in all scenarios without any financial support to CETs.

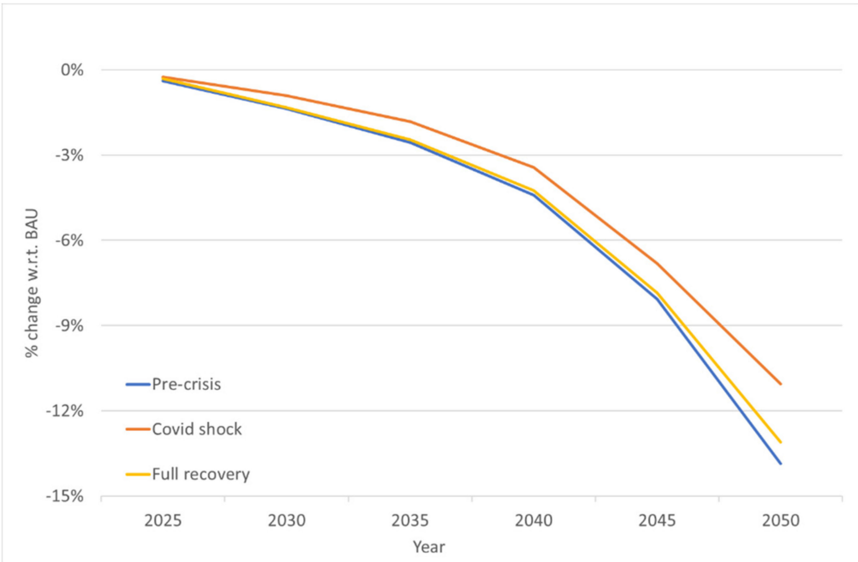

Figure 8. Gross domestic product (GDP) change in EU w.r.t. baseline with carbon pricing alone (own elaboration on GDynEP results).

Competitiveness losses are obviously more evident for energy intensive sectors, as those included in the EU ETS. By looking at the relations with the ROW, changes in emission patterns are disentangled across sectors and computed as the difference in emissions produced by each sector by all other regions forming the ROW with respect to the decrease in EU emissions for the same sectors associated with the implementation of the climate policy. It is worth noting that the chemical, energy and transport sectors are the leading players in the leakage effect (Figure 9). The reaction by foreign countries to the EU climate policy when implemented only with a market-based instrument without support to CETs is to increase the volume of production activities to fill the gap provoked by the reduction in EU output. Indeed, the market-based mechanism brings a substantial competitiveness loss to EU firms, and an increase in comparative advantages with resulting offshoring effects that undermine the benefits from the EU climate policy.

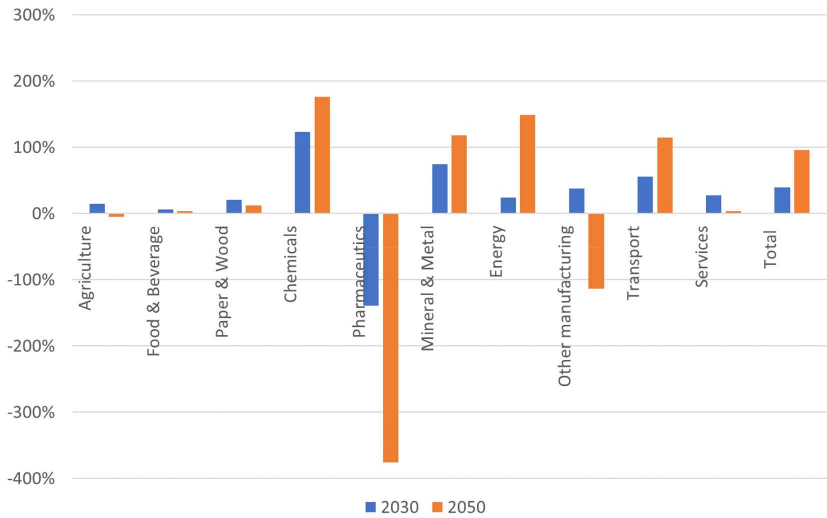

Figure 9. Sector carbon leakage rate with EU carbon pricing policy (own elaboration on GDynEP results).

Together with a sector disaggregation of the leakage effect, it is relevant to investigate if and to what extent there are selected trade partners that are involved more than others by this offshoring mechanism. Given the structure of GDynEP, it is not possible to disentangle to what extent the offshoring effect is associated with a delocalization process of EU firms that moved abroad or to an increase in production activities decided at the local level by foreign firms. Accordingly, results must be interpreted as a delocalization of the source of emissions that are embedded into EU imports rather than into EU domestic production, with only a partial reproduction of the mechanisms and linkages related to innovation and competitiveness highlighted with the ST approach (Figures 2 and 3, reinforcing loop R2), which primarily represent the extent to which the adoption of new technology and the reduction of externalities will support innovation and competitiveness in the EU. The quantification of this offshoring mechanism with a bilateral trade dimension is graphically represented in Figure 10.

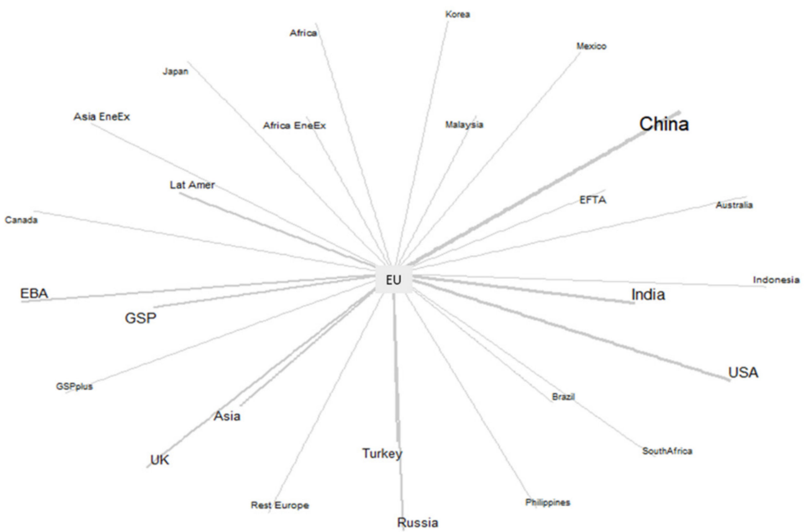

Figure 10. Difference in emissions embedded in bilateral EU imports by 2050 w.r.t. baseline (own elaboration on GDynEP results).

Putting the EU in the middle of the import network, the dimension of the name of each region and the thickness of the arc connecting the EU with each partner is proportional to the difference between the emissions embedded in bilateral import flows in the policy scenario w.r.t. the reference case. Accordingly, a large share of the offshoring effect in producing emissions abroad to satisfy the EU internal demand for final goods and intermediate inputs is associated with few regions, namely China, India, USA, GSP UK, EBA and Russia, here listed according to their relative relevance, and representing more than 60% of the total emissions embedded into EU imports.

3.2. Economic Impacts with Full Implementation of the EGD

When the unilateral carbon pricing mechanism is complemented by the public support to CETs' deployment and diffusion, the overall cost of achieving the target is considerably lower and the situation changes. In this simulation we test the impact of an innovation fund mechanism that is financed by 50% of 100% of the pricing mechanisms in the form of carbon tax revenue (CTR) derived from the collection of the Pigouvian tax (remembering that it is equivalent to a carbon price in an ETS covering the whole economy with no free allowances).

The final economic impact measured by GDP pattern under the two CTR share scenarios reveals that GDP level increases with respect to the reference case, and this positive outcome is proportional to the share of resources devoted to financing CETs. When the maximum share is tested, we can notice that the increase in GDP assumes a positive and stable trend resulting in a constant increase in GDP w.r.t. the BAU case (Figure 11).

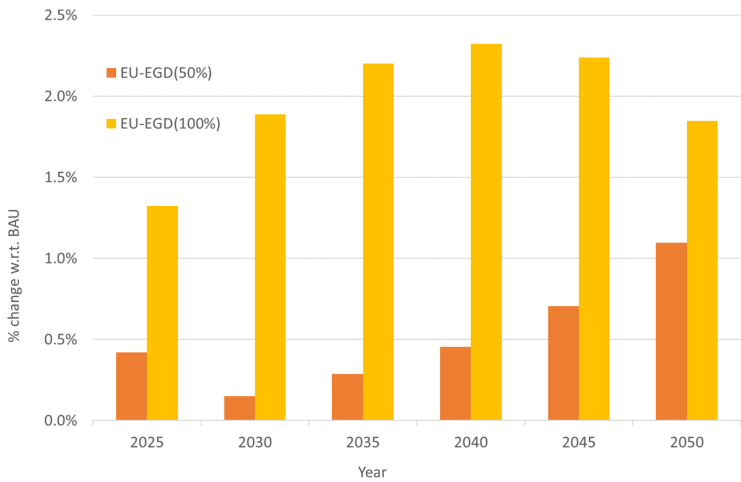

Figure 11. Difference in emissions embedded in bilateral EU imports by 2050 w.r.t. baseline (own elaboration on GDynEP results).

By considering the reaction in structural composition of the global economy, differences in technologies and emission intensities across regions explain the changes in emissions of ROW as a consequence of international outsourcing or offshoring [43]. Contrary to the case when only a carbon pricing mechanism is implemented, when the full EGD is tested, the leakage effect is reversed and becomes slightly negative when the 100% share of CTR is simulated (Figure 12). A possible explanation of this result is associated with trade-induced positive knowledge spillover effects, in the form of a direct transfer of carbon-neutral technologies to foreign producers or an improvement in the environmental quality of EU goods exported in the global market and used as intermediate inputs [44].

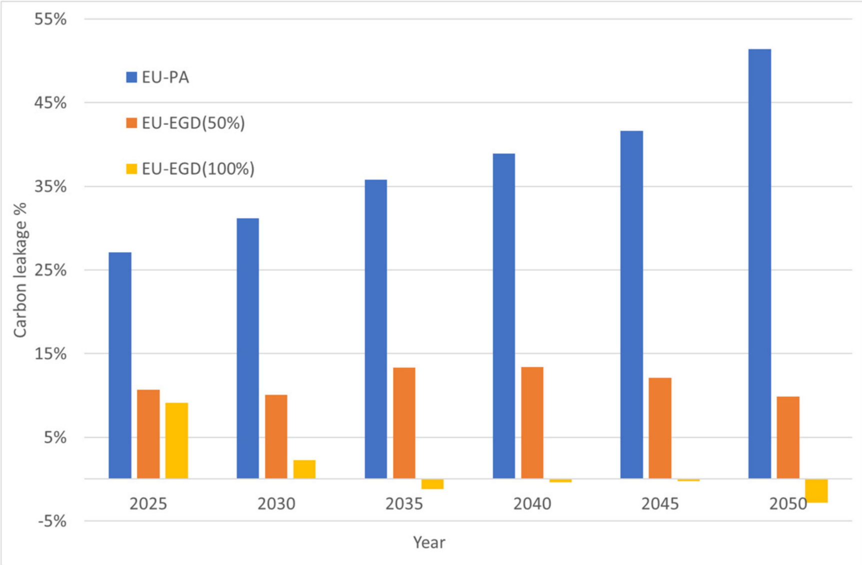

Figure 12. Carbon leakage rate under different shares of carbon tax revenue (CTR) financing clean energy technologies (CETs) (own elaboration on GDynEP results).

4. Discussion

The first key result we obtain from interpreting the CGE outcome with a ST approach is that the efficiency gains determined by the full implementation of the EGD allow the transformation of EU climate policy into a development opportunity, with a complete decarbonisation target achieved with noticeable economic benefits, revealing that a sustainable energy transition is not only feasible but also profitable. This results from the synergies created in simultaneously strengthening reinforcing loops (e.g., R1 and R2) and making balancing loops weaker (e.g., B1 through B6) in Figures 2 and 3.

Indeed, the unitary abatement cost of one ton of CO_2-eq by 2050 is more than halved when the carbon tax revenue is recycled for CETs improvement. In addition, it is worth mentioning that a higher share of revenue devoted to CETs is a key element for cost competitiveness for the EU as the unitary carbon price is inversely correlated with the share of CTR recycled.

The second result we stress refers to the contribution of this complex multi-method approach in interpreting potential trade-offs into instruments' interaction. According to the CGE outcomes, given that the amount of resources invested in clean energy technologies via the innovation fund is endogenously determined by the abatement target, that in turn influences the carbon price level, the reduction in carbon price obtained with a higher revenue share also results in a relative reduction in the proportionality of the amount of the innovation fund. Consequently, the higher the share of carbon tax revenue the higher the innovation fund but with a decreasing proportionality. This is a clear example of the multiple linkages that should be considered under a complexity approach, as the final value of the investment fund is simultaneously affected by a positive impact related to the increase in the share of revenue recycled and by a negative impact associated with the reduction in carbon price. The lower the carbon price the smaller is the revenue collected from carbon pricing, and consequently the amount of resources to be invested in the innovation fund. Such a trade-off might be well explained by the feedback loops activated by joint effects played by the carbon pricing instrument and the public support to innovation deployment related to the revenues collected by the government.

The third noteworthy result refers to the additional elements provided by a general equilibrium approach to the interlinkages that can be detected at the domestic level. The positive effects associated with the loops activated by the EGD within the EU countries are followed by additional benefits at the global level thanks to positive knowledge externalities creating a race to the top effect in trade relationships and the adoption of cleaner technologies also in extra-EU countries.

This analysis and the results obtained are far from perfect. Nevertheless, the emergence of synergies from the use of multi-methods is evident. The qualitative analysis of key drivers of change, with a dynamic approach, can support the creation of a quantitative assessment, as well as improve the interpretation of the results obtained. Identifying the best entry points for intervention, so as to maximize efficiency and value for money for policy interventions is critical, especially when new investments are implemented to emerge out of an economic crisis.

The CLDs, being qualitative and not constrained by data availability, allow for the creation of a shared understanding of the dynamics of the system analysed. In our work, we use CLDs as a blueprint for model and scenario formulation as well as for the interpretation of results. First, CLDs highlight how policy outcomes may materialize in the form of synergies or side effects; second, being more comprehensive than a CGE model, CLDs extend the quantitative analysis with dimensions and dynamics that cannot be quantified (e.g., either due to the characteristics and limitations of the CGE, or any other quantitative model, or due to the qualitative nature of certain dynamics, possibly related to behavioural choices and emerging patterns of behaviour). As a result, both qualitative and quantitative approaches provide much needed information to policymakers, reaching beyond the typical limitations of each approach taken alone (i.e., quantification is required, but it is often narrowly focused, or not as all-encompassing as reality is).

This multi-method approach allows formulation of a key policy implication that has been scarcely addressed by previous quantitative studies. The adoption of multiple market-based instruments, typically in the form of demand and supply-side policies (represented in this case by the carbon pricing and the support to R&D activities, respectively), even if they are well balanced [45], might generate inefficiencies in the exploitation of marginal gains in technological opportunities. A better knowledge of the multiple qualitative linkages occurring in society between stakeholders might inform the policy making process in activating corrective measures that might maximise the returns to investments in clean energy technologies.

Despite the limitations of a such multi-method framework, mainly related to the rigidity of the CGE structure that cannot follow all linkages provided by the CLD, we see great potential of such an approach to be applied to other scenario analyses.

Indeed, the methodological improvement provided by such a soft-linking exercise is well represented by the calibration and interpretation of changes in CGE results when including the macroeconomic effects provoked by an external shock, as in the case of COVID-19. The additional effects and feedback loops obtained with a pandemic-corrected CLD are key inputs for both setting the scenario in the CGE model, but more importantly for immediately highlighting those quantitative results that are mainly affected by this shock.

Such an exercise could be adapted to further shocks, such as large changes in energy prices due to unpredictable events (e.g., due to a conflict occurring in large fossil fuels suppliers or to a disruptive innovation discovery radically shifting the technological trajectory) that could be hardly modelled in a precise way with a CGE model alone.

As a result, although this work is at an early development stage, it constitutes the basis that can stimulate further efforts in developing complex, systems models.

As an example, the soft-linkage framework can help designing additional fiscal policies that can help turn decreasing marginal returns to scale of knowledge creation in clean technologies into increasing gains thanks to the maximisation of positive loops across stakeholders. Such effects can be used to inform the CGE framework by introducing assumptions that allow positive externalities to dynamically influence returns to scale of innovation, such as those related to knowledge co-creation in a typical smart specialisation policy design.

It is our hope that the proposed approach will be used to better design quantitative analysis and better interpret its results, with broader boundaries. The soft-linking of ST with quantitative models can be applied at different levels and for several assessments, from macroeconomic (as presented in this study) to sectoral (e.g., energy planning) to specific investment and policy decisions (e.g., asset-level analysis for project finance decisions).

5. Conclusions

This work is a first attempt to analyse, with a systemic approach, the effectiveness of policy interventions required to achieve different but interconnected targets by combining a qualitative and a quantitative method. The mixed-method utilised, primarily serving as a framework for knowledge integration, allows for a better calibration of scenario design and consequently provides a more complete interpretation framework of policy outcomes. This holistic approach effectively supports policy formulation and evaluation, especially in light of the growing complexity brought about by COVID-19 and related policy responses. It does so by reducing the drawbacks encountered when using sectoral models with limited boundaries (because these normally focus on a single theme or sectoral dimension and do not allow to create an analysis with the breadth of the EGD), as well as by reducing the complexity of several hard-linked models (where several assumptions have to be made for the simulation of different models that use different equation solving methods and treatment of time). As a result, we find that the approach proposed of soft-linking ST and an existing CGE model both leverages existing knowledge and models, as well as improving the analysis carried out with such models, making the analysis better aligned with the complexity of our socio-economic systems.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. GDynEP aggregation of endowments.

No.	Model Code	Description
1	Land	Land
2	SkLab	Skilled labour force
3	UnSkLab	Unskilled labour force
4	Capital	Capital
5	NatRes	Natural resources

Table A2. GDynEP aggregation of economic sectors.

No.	Model Code	Description	Sector Code
1	rice	Rice	pdr, pcr
2	cer	Cereal grains	wht, gro
3	o_prim	Other primary	osd, pfb, ocr, wol
4	veg	Vegetable and fruit	v_f
5	liv	Livestock	ctl, oap
6	r_meat	Rumin meat	cmt
7	o_meat	Other meat	omt
8	fish	Fishery	fsh
9	dai	Dairy	rmk, mil
10	bev_t	Beverages and tobacco	b_t
11	food	Processed food	vol, ofd
12	sug	Sugar	c_b, sgr
13	tex	Textile	tex, wap, lea
14	pap	Paper and publishing	ppp
15	wood	Wood	frs, lum
16	chem	Chemical	chm, rpp
17	phar	Pharmaceutics	bph
18	min	Mineral	nmm, oxt
19	mot	Motor vehicles	mvh
20	tr_eq	Transport equipment	otn
21	elect	Electronics and electronic eq	ele, eeq
22	metal	Metal product	fmp
23	mach	Machinery	ome
24	fer	Ferrous metal	i_s, nfm
25	o_man	Other manufacturing	omf
26	coal	Coal	coa
27	oil	Oil crude	oil
28	gas	Natural gas and LNG	gas, gdt
29	ely_f	Electricity from fossil fuels	NuclearBL, CoalBL, GasBL, OilBL, OilP, GasP
30	ely_rw	Electricity from renewables	HydroBL, HydroP, OtherBL, SolarP, WindBL
31	oil_p	Oil products	p_c
32	r_transp	Road and railway transport	otp
33	a_transp	Air transport	atp
34	w_transp	Water transport	wtp
35	serv1	Service private	TnD, ofi, ins, rsa, obs, whs, cmn, trd, cns, afs
36	serv2	Service public	ros, osg, hht, edu, wtr, dwe

Table A3. GDynEP aggregation of regions.

No.	Model Code	Description	Region Code
1	AFDC	Africa developing countries	cmr, zwe, bwa, nam
2	AFEX	Africa energy exporters	egy, xnf
3	AFNorth	Africa North	mar, tun
4	AS1	Rest of East Asia	aze, geo, isr, jor, xws
5	AS2	Asian countries (rest of)	twn, xea, brn, khm, sgp, tha
6	ASEX	MiddleEast &Asian energy exp.	kaz, bhr, irn, kwt, omn, qat, sau, are
7	Australia	Australia	aus
8	Brazil	Brazil	bra
9	Canada	Canada	can
10	ColPeru	Colombia and Peru	col, per
11	China	China plus Hong Kong	chn, hkg
12	EBA	Everything but arms countries	lao, xse, bgd, npl, xsa, ben, bfa, gin, sen, tgo, xwf, xac, eth, mdg, mwi, moz, rwa, tza, uga, zmb, xec, xsc
13	EFTA	EFTA countries	xna, che, nor, xef
14	EU27	European Union members	aut, bel, bgr, hrv, cyp, cze, dnk, est, fin, fra, deu, grc, hun, irl, ita, lva, l tu, lux, mlt, nld, pol, prt, rou, svk, svn, esp, swe
15	GSP	GSP countries	xoc, vnm, tjk, xsu, civ, gha, nga, xcf, ken, mus
16	GSPplus	GSP plus countries	mng, pak, lka, bol, kgz, arm
17	India	India	ind
18	Indonesia	Indonesia	idn
19	Japan	Japan	jpn
20	Korea	South Korea	kor
21	Malaysia	Malaysia	mys
22	Mexico	Mexico	mex
23	NewZealand	New Zealand	nzl
24	Philippines	Philippines	phl
25	RestAndean	Rest of Andean countries	chl, ecu, ven, xtw
26	RestEurope	Rest of Europe	alb, blr, ukr, xee, xer
27	RestLatAmer	Rest of Latin America	xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, jam, pri, tto, xcb
28	RestMercosur	Rest of Mercosur	arg, pry, ury
29	Russia	Russian Federation	rus
30	SouthAfrica	South Africa	zaf
31	Turkey	Turkey	tur
32	UK	UK	gbr
33	USA	USA	usa

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sustainability

Article

The Role of Strategic Autonomy in the EU Green Transition

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Abstract: The European Green Deal (EGD) is the cornerstone of a strategic package (EGD Strategic Framework; EGDSF), which aims to make the EU a climate-neutral and competitive economy by 2050. The green transition planned by the EGD has been affected by relevant external shocks, which have highlighted Europe's vulnerabilities in key strategic sectors. In this context, EU strategic autonomy (SA) has increasingly become a recurring element of the EGDSF. This article aims to provide a better understanding of the role of SA within the EGDSF and investigate whether it supports the EGD's environmental ambitions. Based on an in-depth qualitative analysis of the EGDSF, it examines the specific purposes that, via SA, the EU wants to achieve and provides a categorisation of the related implementation measures. It emerges that SA objectives embedded into the EGDSF have been shaped in support of EGD goals but that some trade-offs may arise depending on the implementation measures selected to meet the former. In particular, current measures that promote self-sufficiency and the extension of environmental requirements to foreign businesses/products accessing the EU market raise some environmental, economic, and social concerns, which can be partly addressed through a stronger and more comprehensive EGD external dimension.

Keywords: strategic autonomy; green transition; European Green Deal

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1. Introduction

The European Green Deal (EGD) [1] is the cornerstone of a comprehensive strategic package (EGD Strategic Framework—EGDSF), which aims to transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases (GHG) in 2050 and where economic growth is decoupled from resource use. The achievement of the EGD ambition requires the development of deeply transformative policies, with wide effects on the whole economy and society.

The green transition planned by the EGD has been affected by several external shocks (the COVID-19 pandemic, Russia's invasion of Ukraine, and the subsequent energy crisis), which have highlighted Europe's vulnerabilities in key strategic sectors and have resulted in the adoption of dedicated recovery policies [2]. In this context, also characterised by the increasing tendency of major powers, such as China, the US, and India, to self-reliance and protectionism [3–6], the debate about EU strategic autonomy (SA) has received renewed attention, and SA has become a recurring element of the EGDSF. SA was officially mentioned for the first time, at the EU level, by the European Council conclusions on common security and defence policy of December 2013 [7]. Since 2020, the scope of EU SA has been widened to virtually all policy areas, while the expression has often been qualified by the adjective 'open' or replaced by its multiple correlated 'derivations', such as 'strategic sovereignty', 'resilience', 'capacity to act', etc. [3]. Although SA is currently defined in different and evolving ways [8,9], it may be broadly interpreted as the EU's ability to decide and act, free of foreign interference, in accordance with its rules, principles, and values [3,10–12]. These undoubtedly include environmental protection, which has progressively moved in EU treaties from being a sectoral policy to one of the core, transversal principles of the EU legal order [13] and, according to the EGD, a fundamental driver of economic growth [1].

SA is becoming a substantial issue in the green transition and cannot be any more relegated to the sphere of rhetorical concepts. The present paper focuses on the role of SA within the EGDSF. Based on an in-depth qualitative analysis of the EGDSF policy design, it investigates the objectives that, via SA, the EU wants to achieve in the green transition and the related implementation measures. The ultimate purpose of the work is to identify the main potential frictions between SA and EGD goals and suggest possible ways to reduce them. Overall, it emerges that SA objectives embedded into the EGDSF have been shaped in support of EGD goals but that some trade-offs may arise depending on the implementation measures selected to meet the former. In particular, current measures aimed at improving the resilience of strategic supply chains by promoting self-sufficiency and the extension of environmental requirements to foreign businesses and products accessing the EU market raise some environmental, economic, and social concerns and should be used on a case-by-case basis, preserving market openness. A stronger and more comprehensive EGD external dimension that is not limited to the projection of the EU domestic environmental strategies into multilateral/bilateral cooperation but also addresses all the external and geopolitical consequences of these strategies may help to manage some of the above-mentioned concerns.

The present work contributes to improving existing knowledge about the operalisation of SA in a relatively new area of application, namely environmental policy, which, as highlighted by the literature review in Section 2, is still quite an unexplored topic. Moreover, this result is not achieved via case studies but by systematically examining how SA is translated into the EGDSF, i.e., the EGD and the about 30 strategic documents already published by the European Commission accordingly.

The remainder of the article is structured as follows. Section 2 provides a short literature review, focusing on the area of research covered by the article. Section 3 describes the materials and methods used for analysis. Section 4 illustrates the results of the research work, which are then discussed in Section 5, while Section 6 concludes.

2. Literature Review

As SA is an evolving and ambiguous concept, scholars have tried to reconstruct its meaning based on political/institutional declarations by the EU and the Member States [9,12,14]. Recently, the European Parliamentary Research Services [15] (p. 3) defined SA as 'the capacity of the EU to act autonomously (that is, without being dependent on other countries) in strategically important policy areas'. Moreover, SA has been compared with similar notions. In particular, the relationship between SA and strategic sovereignty has been interpreted in different ways [11,16–19], while academics have taken more similar views on what the 'open' component adds to SA. This adjective indeed highlights that the twin aims of achieving SA and preserving an open economy are not incompatible, although characterised by an inherent tension [20]. Open SA may therefore be described as a balancing act on a spectrum ranging from absolute self-sufficiency or autarky to full dependence [21,22].

Several research works investigate the reasons behind the rise of the EU SA and its implications. The current geopolitical landscape and the crisis of the liberal international order, which make EU countries especially vulnerable to external pressures, threatening EU security, economic health, and freedom of action, have been identified as key explicative factors [23,24]. Although in this context (open) SA is often stated as a need [18,19,23], it has also been recognised that it involves risks and trade-offs, such as further fragilising multilateralism, higher barriers for cross-border trade and investment (with negative impacts especially on developing countries), wider divisions within the EU and undue concentration of power within the single market [8,18,25,26].

Another issue that has been discussed by scholars is how to make SA operative. In general, advancing in EU political autonomy is underlined as a fundamental enabler [17,23], and suggestions have been made to improve the EU's own capacity for SA while preserving 'openness'. These include, e.g., expanding the EU trade defence toolbox while making it compliant with WTO and institutionalise its 'last resort nature'; maintaining fair competition within the single market; strengthening alliances with like-minded partners; and fostering a strong, fair, and rules-based multilateral trading system [20,25]. However, proposed changes and recommendations also depend on the policy area under scrutiny. Indeed, it has been observed that (open) SA is not an end in itself and that a critical reflection on how to turn this concept into concrete action cannot avoid questions about the specific objectives that via SA are pursued, the capacities needed to achieve them, and the dependencies from which autonomy is sought [11,27]. Purposes, dependencies, and capacities may vary across policy areas.

The progressive extension of the scope of EU (open) SA has been widely studied. There is a growing research interest in security and defence policy, i.e., the realm from which SA originates [11,28–30]. But scholars have also analysed the application of (open) SA to further policy areas that have security implications, mainly trade [14,20,24,31,32], strategic technologies and digitalisation [11,33–35], and energy [9,36].

A few works specifically focus on the role of SA within the green transition, arguing that 'the environmental dimension constitutes a key aspect of open SA on an equal footing with the geopolitical, technological, and social spheres' [37] (p. 3) and that a SA approach is already enshrined, to a certain extent, in the EGD [38]. This topic is increasingly attracting EU institutions' attention [15,39,40]. Moreover, a part of the abundant literature on the EGD [41] already addresses issues that are critical to the (open) SA discourse. Several works on the energy transition and climate mitigation investigate the related geopolitical repercussions, including the problem of technological and critical raw materials dependency; the impact on third countries of specific EGD measures, such as the Carbon Border Adjustment Mechanism (CBAM); and the social factors (for instance energy poverty and skills shortage) that may influence global strategic decision [42–49]. Other researchers analyse the so-called EGD external dimension and examine the measures aimed at decreasing the EU's contribution to the global ecological footprint and those to promote international cooperation to achieve the ambitions of the Paris Agreement and the 2030 Agenda [50–52]. In this context, the need for a more integrated external dimension, able to manage all the geopolitical issues raised by the EGD (both those having a competitive and cooperative nature), is often stated [53,54].

3. Materials and Methods

In this paper, the expression 'SA' is understood as the EU's ability to decide and act, free of foreign interference, in accordance with its rules, principles, and values [3,10–12], and it is used hereinafter to make reference to both 'strategic autonomy' and its correlated terms (such as 'open strategic autonomy' and 'strategic sovereignty'). All these expressions are considered interchangeable, although they are generally interpreted in different ways. In particular, 'sovereignty' is conceived as a more comprehensive concept than 'autonomy' (which has been originally linked to security and defence) [14,18,22,28], while 'open' has been later added to 'autonomy', as the latter elicits fears of unilateralism and autarky [20,27,55,56].

In order to investigate the role of SA within the green transition, an in-depth qualitative analysis has been carried out of the EGDSF, i.e., the EGD and the about 30 strategic documents already published by the European Commission accordingly (the full list of the documents that have been examined is provided by Table 1). The methodology that has been applied is illustrated by Figure 1.

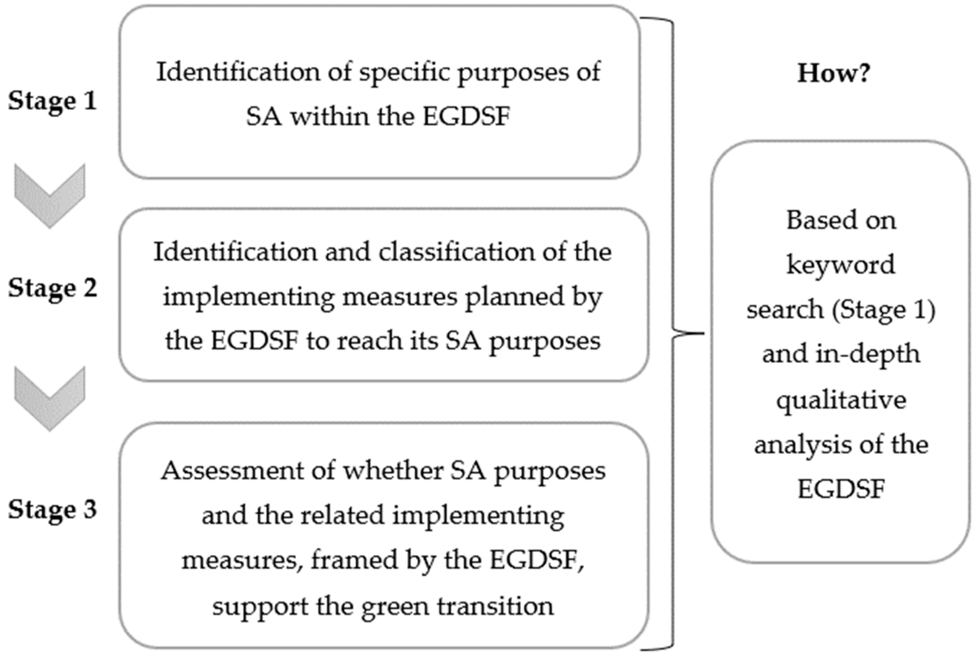

Figure 1. Methodology.

Based on the analytical framework developed by Fiott [11], the following questions have been addressed:

- Given that SA is not an end in itself [27], which are the specific purposes that, via SA, the EU strives to achieve in the green transition?
- How is SA being operationalised? What kind of policy measures have been planned by the EGDSF and are being adopted to reach the desired autonomy?

To answer the question on SA purposes, the EGDSF was screened to single out the strategic documents that embed an SA aspiration and to identify the objectives connected to such an aspiration. This task was performed, as a starting point, via a keyword search. Keywords that have been searched in the documents belonging to the EGDSF are the following: autonomy, sovreignity, self-sufficiency, resilience, vulnerability, security, dependence/independence, and diversification/concentration. Also, words (such as adjectives or verbs) drawn from the above-mentioned keywords were taken into account. Keyword search was complemented by a broader qualitative assessment of the EGDSF. The latter was useful to both refine the former (leaving out records that were not really linked to SA) and to take into account the implicit relationships between the EGDSF and SA. Within the EGDSF, three specific SA objectives were detected, namely the following:

1. Enhancing the resilience of supply chains that are key to the green transition, especially by making them less dependent on imports from third countries and less exposed to the related geopolitical risks. This objective pertains to the idea of SA as a spectrum that represents different degrees of autonomy and dependency [11].
2. Promoting environmental protection and resilience beyond EU borders. Climate change and environmental degradation pose challenges (e.g., conflicts, food insecurity, changes in the availability of critical assets, population displacement, and forced migration) likely to influence almost any initiative on SA [37]. Moreover, the lack of environmental commitment/results by third countries could undermine the EU's efforts in the face of global environmental problems, with potentially severe economic and social consequences both within and outside the EU. Since all EGDSF documents plan environmental actions, this work only focuses, from an SA perspective, on those measures that are specifically aimed at reducing environmental degradation and increasing resilience to environmental risks in third countries.

3. Ensuring a level playing field (firstly on the EU market) for EU businesses and products that must comply with environmental requirements. This objective reflects the European model of economic growth, which is based on 'sustainable competitiveness' [57] and the fact that the EGD is, at the same time, a growth and environmental strategy [1]. 'Green' EU business/products are needed to accelerate the EGD transition, but if they are not competitive, EU dependence on third countries will increase.

The questions concerning the operationalisation of SA were addressed by preparing an inventory of the most important implementation measures that the EGDSF has scheduled to reach its SA objectives. Relevant legislative proposals of the European Commission were also considered. In the first place, implementation measures were classified into three groups according to the SA objective they mainly serve. A single EU initiative may, indeed, support the achievement of several SA goals (which are, in turn, interrelated). For instance, bilateral and regional cooperation initiatives often aim to meet multiple objectives, which can e.g., include the promotion of environmental protection and the opening up of new markets to diversify EU's imports of strategic materials/technologies. Secondly, implementation measures belonging to the same group were further classified into different types, as illustrated by Table 2. With regard to the measures that, under objective 1, contribute to reducing dependences on imports, only environmental measures that have a direct impact on the import by the EU of critical materials, products, and technologies were taken into account.

As a last step of the research process, it was discussed whether the specific SA objectives and the related implementation measures stated within the EGDSF support the EGD's environmental ambitions by highlighting the most relevant synergies and trade-offs. Possible ways to manage trade-offs are also suggested (see Section 5).

The analysis is updated to July 2023. Part of the work is related to the activities of the European Topic Centre on Circular Economy and Resource Use (ETC/CE), funded by the European Environment Agency under a framework agreement for the period 2022–2026.

4. Results

4.1. SA Objectives within the Green Transition

Based on a keyword search beyond the EGD, 14 policy documents belonging to the EGDSF have been found to explicitly set a SA aspiration. Further, 13 documents implicitly embed SA objectives as they plan measures to achieve them (see Table 1).

Overall, about two-thirds of the above documents establish the goal of enhancing the resilience of supply chains that are key in the green transition, especially by making them less dependent on imports from third countries and less exposed to the related geopolitical risks. The underlying assumption is that the greater the dependency on specific strategic sectors, the more vulnerable and unable the EU is to pursue its environmental interests [58]. EGDSF documents setting this goal include, e.g., the main EGD energy strategies [59–61], the strategies concerning energy-intensive sectors (such as transport, textiles, and fisheries) [62–64], as well as the Action Plan on critical raw materials (CRMs) [65]. The EU currently imports 60% of its energy [66]. Boosting renewables while contributing to climate neutrality is expected to shift dependencies: dependence on the import of fossil fuels will be reduced, while there will be more in strategic materials and technologies (e.g., for the production of batteries and electric vehicles) with respect to which the EU is generally a net importer [37]. This is why, according to the European Commission, for both environmental and security reasons, Europe should have more SA, in particular when the sources of supply (as for some CRMs) are highly concentrated and at high risk of supply disruption [65]. Moreover, ensuring the security of supply is also a core objective of the Farm to Fork Strategy, addressing food systems [67] and of the Chemicals Strategy for Sustainability [68], which underlines that SA should be aimed mainly at those chemicals that have fundamental uses for our health and for achieving a climate-neutral and circular economy (CE).

The EGD has a strong external dimension, which will be crucial for its implementation. Most EGDSF documents, therefore, contain chapters on global issues and schedule actions beyond EU borders, e.g., [67,69–71]. This relates to SA in different ways. According to the Treaty on the European Union (Art. 3 par. 5), sustainable development is among the key values and interests that the EU should uphold and promote in the wider world. There are several global problems, such as climate change and biodiversity loss, which cannot be solved by the EU acting alone. Moreover, environmental and climate risks, wherever they take place, may have security implications for the EU by affecting the availability of water, food, and resources; worsening existing socio-economic inequalities; and generating cascading and spillover effects on trade and migration. The EU Strategy on adaptation to climate change, for instance, recognises that international climate resilience is not only a matter of solidarity but also of SA [70].

Ensuring a level playing field for EU businesses and products that must comply with environmental requirements is a third SA objective embedded in about half of the EGDSF documents, see, e.g., [62,72–74], which mainly focus on the EU market. In order to protect the environment, the EU needs to set environmental regulatory and economic measures within its borders, but to safeguard its interests, it should also be able to preserve the competitiveness of its companies implementing those measures (otherwise, EU vulnerability and dependency on third countries will increase). It is worth pointing out that EU interventions aimed at supporting international competition and reciprocity are also often promoted outside the EGDSF. These actions, however, are not analysed by the present work.

The three above-mentioned SA objectives are strongly interlinked. For instance, ensuring a level playing for EU companies can also be achieved via external action (e.g., by promoting more stringent environmental policies/standards at the international level), and it is pivotal to strengthening the EU manufacturing capacity of critical emerging technologies and materials (making the related value chains more resilient).

4.2. Measures Implementing SA Objectives

Many measures have been scheduled by the EGDSF to achieve its SA ambitions. The present section provides an overview of these measures, which have been grouped according to the SA objective they mainly serve and then classified into different types (as reported by Table 2). Obviously, implementation measures are different in nature, also depending on the corresponding SA purpose. For instance, most of the measures promoting environmental protection in third countries belong to the so-called 'Green Deal diplomacy', focused on convincing/supporting others to take on their share in the green transition [1]. Instead, environmental requirements are mainly applied to imported products and to certain foreign companies accessing the EU market via regulatory (e.g., product-making requirements) and economic (e.g., the Carbon Border Adjustment Mechanism; CBAM) [75] tools.

4.2.1. Measures to Enhance the Resilience of Value Chains That Are Key in the Green Transition

Measures to Reduce the Dependence on Imports from Third Countries

The first set of EGDSF measures aims to increasing the domestic sourcing/processing of critical resources and the production of strategic goods/technologies. The proposed CRMs Act [76] and the Net-Zero Industry Act (NZIA) [77] play a key role in this regard. The former establishes domestic capacities targets (at least 10% of the EU's annual consumption for extraction and 40% of the EU's annual consumption for processing) to be achieved by 2030 and, with the aim of accelerating them, introduces an EU time limit to the issuing of permits for relevant industrial projects. The latter identifies 'strategic' net-zero technologies, sets a benchmark for their manufacturing capacity to meet at least 40% of the EU's annual deployment needs by 2030, and introduces a 2030 target for spurring the development of carbon capture and storage technologies. To reach these targets, the NZIA shapes a governance system based on the selection by Member States of Net-Zero Strategic Projects, which, inter alia, have to be granted priority status at the national level and fast-tracked in permitting procedures. On the same line, but moving to agriculture, the Commission has recently adopted a legislative initiative on new genomic techniques, which, as they will be applied to a large range of crop species, are expected to contribute to SA by decreasing the Union's dependence on critical feed materials and fostering EU-grown plant protein [67,78].

The resilience of strategic supply chains will undoubtedly benefit from a strengthened implementation of specific environmental measures. For instance, to reduce the EU energy import dependency and address the energy crisis, REPower EU has proposed to further increase to 13% the binding target in the Energy Efficiency Directive and to 45% the target in the Renewable Energy Directive [60,79]. Similarly, improving the collection and recycling of CRM-rich waste is fundamental to ensure the EU's access to a secure supply of these materials. For this reason, the proposed CRMs Act [76] requires that, by 2030, at least 15% of the EU's annual consumption come from domestic recycling. Promoting the uptake of low-input practices in agriculture is expected to reduce EU dependency on fertilisers [67]. Eco-design, resource efficiency and CE practices generally contribute to SA by lowering the use of primary raw materials and are, therefore, mentioned by various EGD strategies [61,63,65] as relevant supporting tools.

Measures to Diversify Imports from Third Countries

The external dimension of the EGDSF has progressively been geared towards securing the supply of critical materials and strategic technologies via source diversification. In this way, dependency on dominant or unreliable suppliers is reduced, as well as the risk of total backlog. In particular, both the REPower EU package (via its External Energy Strategy) [80] and the Action Plan on CRMs [65], along with the proposed CRMs Act [76], schedule some actions to increase the EU SA by diversifying the supply of, respectively, energy and CRMs. The EGDSF [68] also addresses the problem of the limited number of suppliers for some chemicals used in essential societal applications.

Measures to Manage Critical/Emergency Situations

The EGDSF provides for the adoption of emergency plans and measures (e.g., strategic reserves and stockpiling) aimed at risk management to ensure that strategic supply chains/services can continue to operate unaffected in case of a crisis. Such initiatives are, e.g., scheduled by the Farm to Fork Strategy [67], the Chemicals Strategy for Sustainability [68], and the Sustainable and Smart Mobility Strategy (both with regard to freight and passenger transport) [62].

4.2.2. Measures to Promote Environmental Protection and Resilience to Environmental Risks beyond EU Borders

Measures Promoting Environmental Protection and Resilience in Third Countries

The EU makes use of multilateral agreements and fora to promote its EGD external action. For instance, the United Nations (UN) proposes or supports the adoption of relevant conventions (such as the agreements on plastics and on marine biological diversity of areas beyond national jurisdiction) [71,72] and standards (e.g., for chemicals) [68], as well as the launching of new partnerships (e.g., the Global CE Alliance) [72] and the establishment of observatories (e.g., the global soil biodiversity observatory and the international methane emissions observatory) [74,81]. Moreover, environmental protection is channelled via regional and bilateral cooperation (e.g., the NaturAfrica initiative to protect wildlife and key ecosystems, the EU–India Clean Energy and Climate Partnership, the Africa–EU Green Energy Initiative, etc.) [71,80]. The EU's long-term budget 2021–2027 has allocated EUR 110.60 billion (in current prices) to the heading 'Neighborhood and the world', and for some of the related funds, a climate contribution target has been set. In particular, the target is set at: 30% of the EU's Neighbourhood, Development and International Cooperation Instrument, which has a budget of EUR 80.59 billion; 16% of the pre-accession assistance, which has a budget of EUR 14.16 billion; and 20% of the Overseas Countries and Territories

Programme, which has a budget of EUR 500 million [82]. The EU's participation in international cooperation is often aimed at meeting multiple objectives and generating co-benefits, including creating a level playing field on the global market and, in some cases, diversifying the suppliers of materials/technologies that are pivotal to the green transition.

Specific Measures to Reduce the EU Environmental Footprint beyond EU Borders

The EU is committed to reducing its environmental footprint in third countries. This can partially be achieved as a positive side-effect of shaping EU environmental requirements, which, e.g., apply to EU products exported to third countries and to EU companies operating within global value chains. The EGDSF, however, has scheduled the introduction of specific measures to meet this objective. For instance, based on the current revision of the Waste Shipment Regulation [83], the shipment outside the EU (particularly to non-OECD countries) of waste having harmful environmental impacts will be subject to stricter requirements and the Zero Pollution Action Plan [69] has proposed to restrict the export to third countries of certain products which are no longer allowed in the EU market.

4.2.3. Measures to Ensure a Level Playing Field on the Single Market for EU Business and Products That Must Comply with Environmental Requirements

Measures Setting Environmental Requirements Applying to Imported Products and/or to the Related Production Processes

The EU prevents domestic products from suffering a competitive disadvantage because of higher environmental standards than other global players by imposing the same environmental requirements on all the products placed on the EU market (including imported ones). These measures may also have a positive impact on the environment of third countries. Indeed, EU environmental regulations, via market mechanisms, are often 'externalised', as they are sometimes emulated in other legal systems and contribute to shaping the international business environment (so-called 'Brussels effect') [53,84,85]. The EGDSF has scheduled the introduction of new or more stringent environmental requirements across all the environmental policy areas. When considering product requirements, for instance, a new regulation has been recently adopted [86], which establishes that from 2035, all new cars and vans registered in the EU must have zero emissions, and other ongoing legislative initiatives are aimed at extending the eco-design requirements beyond energy-related products [87]; setting new sustainability and safety requirements for batteries, packaging, construction products, vehicles, and toys [88–92], as well as for plant and forest reproductive materials [93,94]; and developing stricter emissions standards (Euro 7) for all petrol for cars, vans, lorries and buses [95]. Even more interesting is the planned extension of the environmental requirements related to production processes, including, e.g., the regulation on the placing of products associated with deforestation or forest degradation on the EU market [96] and the legislative proposal shaping the obligation to detect and repair methane leaks in the energy sector, which should apply from 2024 also to imported fossil energy [97]. Within this context, the CBAM [75] deserves special attention. This tool is designed to complement the Emission Trading System by putting a price on the carbon emitted during the production of carbon-intensive goods that enter the EU. It will be gradually applied to selected products at high risk of carbon leakage (cement, iron and steel, aluminium, fertilisers, electricity and hydrogen), but it has already faced severe scrutiny from EU trade partners (e.g., Brazil, South Africa, India, China, and the United States) and scholars [47,48,98–100] about its effectiveness in achieving its objectives, its compatibility with WTO rules, and its expected impacts on developing and least developed countries that have historically contributed less to global warming.

Measures Setting Environmental Requirements Applying to Non-EU Companies and Investors

The European Commission has proposed a Corporate Sustainability Due Diligence Directive (CSDDD) [101], which should revise and extend the scope of the current Non-Financial Reporting Directive (NFRD) [102]. The CSDDD introduces a framework to integrate sustainability into corporate governance and management systems of large companies that operate in a single market by identifying, preventing, mitigating, and accounting for their adverse environmental impacts throughout global value chains. It applies to both upstream and downstream activities, as well as direct/indirect business relations in the global value chains. Moreover, the directive covers large companies from third countries meeting specific requirements (companies from third countries: (i) with 500+ employees and a net turnover over EUR 150 million generated in the EU or (ii) with 250+ employees and a net turnover over EUR 40 million generated in the EU, operating in defined high-impact sectors, such as textiles, agriculture, and the extraction of minerals). The CSDDD, in turn, will complement the Sustainable Finance Disclosure Regulation (SFDR) [103] and the Taxonomy Regulation [104], which have established a parallel regime for investors and also address non-EU investment managers marketing specified funds in the EU, as well as those who manage/advise EU-domiciled funds. Companies and asset managers within the scope of the NFRD and the SFDR will have to disclose to what extent they are aligned with the EU Taxonomy, which shapes a classification system for sustainable economic activities.

Measures to Improve the Implementation/Enforcement of Environmental Requirements

Some EGDSF documents set measures to improve the application and enforcement of the above-mentioned EU environmental requirements, focusing especially on imported products. For instance, according to the Action plan for the development of organic production [105], guidance will be provided to the Member States on reinforced import controls to tackle fraudulent practices, while the Strategy for Sustainable and Circular Textiles [63] aims at strengthening market surveillance via better coordination between all relevant actors (customs and market surveillance authorities, industry, etc.) and by encouraging the use of digital tools.

As stated in Section 4.1, relevant EU interventions aimed at ensuring international competition and reciprocity (with positive impacts on the green transition) are also promoted outside the EGDSF. Interesting tools include, for instance, the recently adopted regulations on foreign subsidies distorting the internal market [106] and on the access of third-country economic operators, goods and services to the EU public procurement and concession markets [107]; the legislation concerning the exercise of the EU's rights for the application and enforcement of international trade rules [108] and the proposal for an anti-coercion legal instrument to deter third countries from pressing the Union or a Member State into making a particular policy choice by implementing trade or investment measures against them [109]. All these measures, however, do not fall within the scope of the present work.

Table 1. EGDSF documents and their connection to SA.

EGDSF Document and Reference	SA Explicitly Mentioned	Examples of Measures to Enhance the Resilience of Supply Chains	Examples of Measures to Promote Environmental Protection Outside the EU	Examples of Measures to Ensure a Level Playing Field for EU Business/Products in the EU Market
Circular Economy Action Plan [72]		Supporting CE practices (e.g., resource efficiency and recycling) to make supply chains more resilient	Restricting the export of waste having harmful impacts in third countries; supporting the global agreement on plastic	New eco-design requirements for several products; new product-information requirements to empower consumers in the green transition
Hydrogen Strategy [59]	x	Diversification of imports of renewable electricity/hydrogen; increasing the production of renewable hydrogen to reduce EU dependency on the import of fossil fuels	Promoting hydrogen standardisation/ regulation; cooperation on renewable hydrogen (e.g., with Southern–Eastern neighbourhood partners and the African Union)	
Renovation Wave Initiative [110]		Improved energy efficiency to make the EU less dependent on energy import		New sustainability and eco-design requirements for construction products
Biodiversity Strategy [71]			Adoption of a post-2020 global framework under the Convention on Biological Diversity; NaturAfrica initiative to protect wildlife and key ecosystems.	Adoption of stronger sustainability criteria for bioenergy
Farm to Fork Strategy [67]	x	Setting up a food crisis response mechanism; new rules to reduce the dependency on critical feed materials by fostering EU-grown plant proteins and alternative feed materials	Proposal of green alliances on sustainable food systems in bilateral, regional, and multilateral fora	Fighting food fraud via better import controls; reviewing import tolerances for substances with a high level of risk to human health
Action Plan on CRMs [65]	x	CE practices and increased domestic sourcing/processing to reduce dependency on CRM import; diversifying CRM imports	Promoting responsible mining practices for CRMs outside the EU via legislation and int. cooperation	
Methane Emissions Reduction Strategy [74]			Establishment of an int. methane emissions observatory under the UN framework	Introducing methane emission reduction requirements on fossil energy consumed in the EU

Table 1. *Cont.*

EGDSF Document and Reference	SA Explicitly Mentioned	Examples of Measures to Enhance the Resilience of Supply Chains	Examples of Measures to Promote Environmental Protection Outside the EU	Examples of Measures to Ensure a Level Playing Field for EU Business/Products in the EU Market
Chemicals Strategy for Sustainability [68]	x	Strengthening EU chemical production capacity; diversifying imports of essential chemicals; identifying strategic dependencies; emergency mechanisms	Setting global strategic objectives for managing chemicals beyond 2020; introducing/adapting criteria/hazard classes in the UN globally Harmonized System of Classification and Labelling of Chemicals	New requirements for chemicals to protect the environment and human health (e.g., to take account of the combination effects of chemicals in toys, cosmetics, food additives, etc.)
Strategy on offshore renewable energy [111]	x	Increased RES production to make the EU less dependent on the import of fossil fuels; CE practices to increase CRM supply chain resilience	Engagement with int. partners to develop offshore renewable energy	
Sustainable Mobility Strategy [62]	x	Making strategic value chains (batteries, raw materials, hydrogen and renewable/low-carbon fuels) more resilient; preparing crisis contingency plans to ensure business continuity	Proposing high environmental transport standards in int. fora (IMO, ICAO, etc.)	Euro 7 emission standards for cars/vans/lorries/buses; CO_2 emission performance standards for new passenger cars/vans; rules to address the effects of foreign subsidies in the internal market
EU Adaptation Strategy [70]	x		Supporting partner countries in developing adaptation strategies (e.g., in Africa); increasing int. climate finance for adaptation via EU funds	
Action plan for the development of organic production [105]				Measures to tackle fraudulent practices (e.g., provision of guidance to Member States on reinforced import control)
A new approach for a sustainable blue economy in the EU [112]			Conclusion of a binding agreement on marine biological diversity in areas beyond national jurisdiction and of a global WTO agreement to ban harmful fisheries subsidies	
Zero Pollution Action Plan [69]		Supporting practices for pesticides and nutrients reduction by promoting innovations and exchange of knowledge	Enhancing actions under the Basel, Rotterdam, Stockholm, and Minamata Conventions on WEEE, hazardous chemicals, POPs, and mercury	
Fit for 55 [73]		Improved energy efficiency and increased RES production to make the EU less energy import-dependent.		CBAM to be gradually introduced for selected products at high risk of carbon leakage

Table 1. *Cont.*

EGDSF Document and Reference	SA Explicitly Mentioned	Examples of Measures to Enhance the Resilience of Supply Chains	Examples of Measures to Promote Environmental Protection Outside the EU	Examples of Measures to Ensure a Level Playing Field for EU Business/Products in the EU Market
EU Forest Strategy [113]				Regulation on the placing on the EU market of products associated with deforestation or forest degradation
EU Soil Strategy [81]			Supporting the establishment of the global soil biodiversity observatory as proposed by FAO	
Communication on Sustainable Carbon Cycles [114]			Proposing an accounting framework for the int. carbon market	
EU External Energy Strategy [80]	x	Diversifying imports of energy and CRMs; accelerating the green energy transition; prioritising energy efficiency	Pushing forward the Global Methane Pledge (to reduce the collective methane emissions of participating countries by at least 30% from 2020 levels by 2030)	Reshaping the EU's regulatory framework for hydrogen to ensure a level playing field for imported and domestically produced hydrogen
Strategy for sustainable and circular textiles [63]	x	CE practices and bio-innovation to make the EU textile sector less dependent on imported fossil fuels and virgin raw materials.	Enforcing the restrictions on exports of textile waste to non-OECD countries; developing criteria for distinguishing waste from second-hand textile products	Proposing measures addressing textiles under the Ecodesign for Sustainable Products Regulation and the revision of the REACH and Ecolabel Regulations; strengthening market surveillance
EU Solar Energy Strategy [61]	x	Reducing the import of fossil fuels via increased RES production and that of CRMs via CE practices; diversifying CRM imports.	Increasing the production of solar energy and renewables in third countries based, e.g., on EU-India Clean Energy and Climate Partnership and the Global Gateway EU-Africa investment package.	Proposing the application of the Ecodesign Directive and Energy Labelling Regulation to photovoltaic systems
REPower EU Plan [60]	x	Reducing the import of fossil fuels via increased RES production and improved energy efficiency; diversifying energy imports		
EU 'Save Energy' Communication [115]	x	Improving energy efficiency to make the EU less dependent on energy import		

Table 1. *Cont.*

EGDSF Document and Reference	SA Explicitly Mentioned	Examples of Measures to Enhance the Resilience of Supply Chains	Examples of Measures to Promote Environmental Protection Outside the EU	Examples of Measures to Ensure a Level Playing Field for EU Business/Products in the EU Market
Towards a strong and sustainable EU algae sector [116]	x	Upscaling regenerative algae cultivation and production in the EU to contribute to food security and reduce the dependency on feed materials		
Energy transition of the EU fisheries and aquaculture sector [64]	x	Improved energy efficiency/increased RES production to make the EU less dependent on energy import and the EU fisheries and aquaculture sectors more resilient	Promoting work on the energy transition for the fisheries and aquaculture sector in int. organisations (e.g., OECD, IMO, FAO)	
EU Action Plan on sustainable and resilient fisheries [117]			The EU should hold its vessels to at least the same standards when they fish on the high seas or in the exclusive economic zone of non-EU countries	
Resilient and sustainable use of natural resources [118]		Development of new genomic techniques to, inter alia, decrease EU's dependence on critical feed materials		Proposing new sustainability requirements for plant and forest reproductive materials

Note: every example of a planned measure is mentioned in the Table under the SA objective it mainly serves, even if the same measure may be set to achieve multiple SA objectives. 'Int.' means international, 'POPs' means persistent organic pollutants, 'REACH' is the regulation on the registration, evaluation, authorisation, and restriction of chemicals, 'RES' means renewable energy sources, and 'WEEE' means waste electrical and electronic equipment. Source: own elaboration.

Table 2. SA objectives and classification of measures planned by the EGDSF to achieve them.

1 Enhancing the resilience of supply chains that are key in the green transition, especially by reducing dependence on imports from third countries and the exposure to the related geopolitical risks
• Measures to reduce the dependence on imports from third countries. ◦ Measures to increase the domestic sourcing, processing, and production of key resources/products; ◦ Specific environmental measures. • Measures to diversify imports from third countries. • Measures to manage critical/emergency situations.
2 Promoting environmental protection and resilience beyond EU borders
• Measures promoting sustainability and environmental protection in third countries. • Specific measures to reduce the EU environmental footprint beyond EU borders.
3 Ensuring a level playing field in the EU market for EU businesses and products that must comply with environmental requirements
• Measures setting environmental requirements applying to imported products and/or to the related production processes. • Measures setting environmental requirements applying to non-EU companies and investors operating in the EU. • Measures to improve the implementation/enforcement of the above environmental requirements.

Please note that SA objectives are reported in the Table in italics in the grey rows, followed by the related types of implementation measures in the white rows. Source: own elaboration.

5. Discussion

Although the SA concept has been discussed in the EU since 2013, it has been applied to environmental policy over the past few years. With the EGD, the shift to climate neutrality has, hence, become a priority on the EU agenda and has been recognised as a strategic driver of economic growth and competitiveness. The implementation of SA within the EGDSF has received a huge boost for the recently changed geopolitical context, which has, on the one side, confirmed the need to accelerate the green transition while highlighting, on the other, the related supply chain risks for critical and strategic materials, products, and technologies. The late integration of SA into an already complex strategy, affecting all environmental policy areas and all economic sectors, is challenging in different respects. This situation is compounded by the multiple visions that EU policymakers and Member States have about what SA is and how to achieve it [8,119]. National divergences also reflect the uneven distribution of the costs associated with SA implementation across the EU-27. Recent SA policies have been estimated to create income losses in the EU of between 0.08% and 0.15% of EU-27 Gross Domestic Product, with smaller countries faring worse compared to larger ones because of their greater openness to and reliance on trade with non-EU countries [25]. As the SA agenda takes shape and is put into practice, the lack of a common understanding of the related objectives means, and resources could result in its failure [20].

Overall, the three core SA goals embedded into the EGDSF have been set in support of EGD goals. The green transition indeed cannot take place if the EU is not able to improve the resilience of the related key supply chains, preserve the competitiveness of the EU business and products that must comply with environmental requirements, and promote environmental protection on a global scale.

Frictions, however, may arise depending on the implementing measures planned to meet SA goals. Some implementing measures are certainly beneficial from both SA and EGD perspectives. For instance, energy efficiency and CE contribute to reducing dependencies, and, in general, more sustainable supply chains have proven to be more resilient [10]. In other cases, instead, trade-offs tend to emerge. Identifying and managing these trade-offs is crucial for the success of the EGD. Setting wrong SA policies today may have long-term negative implications for the green transition.

In the following section, some preliminary reflections are provided on selected trade-offs affecting the current integration of SA within the EGDSF policy design and suggestions are formulated to address them. The increase in domestic sourcing and production of key resources and technologies to make the EU supply chains more resilient is the cause of growing criticism. In the first place, geopolitical resilience comes with a price tag [120]: improving self-sufficiency is a cumbersome process that requires 'political will, long-standing executive action and more than a mere contribution from the EU budget' [3] (p. 8). This does not fit well with the EU commitment to be climate-neutral by 2050 and the urgency to efficiently transform Europe's energy system [121]. Furthermore, the costs of resilience are not acknowledged by the proposed CRMs Act and the NZIA [76,77], and there is no new EU-level funding strategy accompanying the EGD Industrial Plan [122], which basically repurposes current EU programs to fund the green transition [120,123]. Second, the way this objective is being operationalised raises environmental and social concerns. In order to meet the targets they established, the CRMs Act and the NZIA [76,77] introduce faster permitting procedures, even if permitting alone is unlikely to substantially speed up strategic project development. Indeed, the main obstacles to cleantech investment in the EU are skills and access to funding [121], and the prolonged lead times for CRM extraction projects are primarily attributed to the exploration and project preparation phase, which falls under the responsibility of mining companies [120]. Moreover, fast-track permit processes, along with other features of the two proposed regulations (such as the lack of limits to the EU consumption of CRMs and the definition of net-zero technologies only based on their GHG emissions, without any consideration for their further environmental impacts), risk weakening social and environmental safeguards [124–126]. The idea that improved self-sufficiency could come at the expense of environmental/social protection blows beyond EU industrial policy, affecting, e.g., the recent Commission proposal on new genomic techniques (NGTs) [78]. This legislative initiative, which also aims at guaranteeing EU food security, loosens existing rules for genetically modified plants produced by certain NGTs [127,128]. In light of the above and considering that international supply chains are often more efficient and diversified and, hence, more capable of rapid adaptation to new shocks than local ones, the EU should carefully evaluate on a case-by-case basis whether and for which products self-reliance is a valuable approach [38,129]. Before opting for reshoring/developing new industrial capacities, available alternatives should be explored, most notably diversification and coordination of supply chain risks with trade partners [20].

It also has to be added that labour markets represent a dimension of SA that has been underrated by the EGDSF. For instance, actions scheduled by the CRMs Act [76] do not seem to adequately address skills shortages in the mining sector, which is unfashionable to young generations and traditionally perceived as damaging to the environment and hard physical work. More in general, if the EU does not take appropriate and timely measures, given its population projections, it will need to rely on external labour to sustain its economic prosperity (as well as the green transition) and, as a consequence, its SA may be compromised in the future [37].

Another sensitive issue is the ongoing extension of the EU environmental requirements applying to imported products, the related production processes, and certain foreign companies accessing the EU market. These measures may generate environmental benefits beyond EU borders, as highlighted by the 'Brussels effect' [53,84,85]. However, the direct cost that they impose on the EU's trading partners may discourage the latter from exporting to the EU, which, in turn, plays against the EU's efforts to diversify its sources of imports [130]. Large compliance costs for third countries businesses could also make Europe comparatively less attractive for foreign investments. Some of the proposed initiatives (like the CBAM) [75] are often perceived as a distortion to international trade or as unequal since they mostly impact the least developed countries that are especially vulnerable to climate change [48,131]. Although they may have environmental (and not protectionist) aims, the new requirements could lead to undesirable countermeasures and directly affect the EU's openness to trade and investment [20]. In using these tools, the EU should, therefore, remember that its strength remains its market openness and that tackling climate change and other environmental challenges can only be carried out via global engagement and cooperation [10,99]. Finally, greater coherence and balance should be achieved between environmental requirements/rules applying to EU products exported to third countries and third countries' products imported into the EU. For instance, the EU is currently exporting to third countries chemicals and pesticides that are banned within its borders (but then, the EU imports from third countries food and textiles with residues of the banned substances) [132].

The above brings us to the importance of the EGD external dimension. Third countries suffering from negative economic repercussions because of the EU green transition may see the EGD as a threat. This is why the EGD needs a stronger external dimension that is not limited to the projection of the EU domestic environmental strategies into multilateral/bilateral cooperation but that also addresses all the external and geopolitical consequences of these strategies. This includes, e.g., supporting oil-gas exporting third countries (such as North African countries) in shifting to renewable energy and green hydrogen (which could in the future be exported to Europe) and providing targeted financial and technical assistance to developing/least developed countries that incur high costs to adjust to new EU environmental requirements [46,53,54]. The EGDSF already sets some measures to manage some EGD geopolitical issues, but they are generally designed and implemented in a fragmentary way. A more integrated approach could make the EU's external action more effective, taking full advantage of the existing synergies across different policy objectives, areas, and measures. Moreover, in the context of the EGD external dimension, it will be crucial to shape a comprehensive strategy to support import diversification. On this issue, indeed, most of the relevant legislative initiatives (such as the proposed CRMs Act) [76], as domestic regulations, remain largely declaratory and vague [120,133].

6. Conclusions

The present paper analyses the role that SA plays within the EU green transition. In particular, it focuses on how this concept has been integrated into the policy design of the EGDSF to evaluate whether the specific SA objectives and the related implementing measures support the EGD goals.

It concludes that SA objectives embedded into the EGDSF have been shaped to achieve the EGD goals but that some trade-offs may arise depending on the implementation measures selected to meet the former. With this regard, it emerges that current measures that promote self-sufficiency and the extension of environmental requirements to foreign businesses/products accessing the EU market raise some environmental, economic, and social concerns. Therefore, the EU should carefully consider on a case-by-case basis whether and for which products self-reliance is a valuable approach, exploring available alternatives, such as the diversification and coordination of supply chain risks with trade partners. Moreover, the costs for third countries' products/businesses of complying with EU environmental requirements, as well as the related implications on trade openness and international cooperation, should not be understated. Multilateralism is a defining feature of the EU's internal constitution and external identity. The EU needs the support of reliable partners to improve the resilience of its strategic supply chains and to address global environmental challenges. A stronger and more integrated EGD external dimension may be extremely useful to manage all the geopolitical consequences of the EU green transition.

The above considerations are preliminary in nature, as some policy measures scheduled by the EGDSF could remain unimplemented, and several legislative initiatives have not been adopted yet so their building blocks could substantially change in the decision-making stage. It also has to be added that the debate on SA and how it is conceived/applied will undoubtedly be led, in the next future, by the upcoming European Commission. Further research is needed, therefore, to monitor this process and, especially, to assess whether the EU has the capacity to apply the SA implementing measures designed by the EGDSF, along with their effectiveness and implications.

Overall, this article contributes to expanding existing knowledge about how the SA concept has been so far operationalised in a new area of application, namely EU environmental policy. It also provides EU policymakers with some reflections on the negative implications that selected SA implementing measures, set by the EGDSF, may have for the green transition.

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Abbreviations

CBAM	Carbon Border Adjustment Mechanism
CE	Circular Economy
CSDDD	Corporate Sustainability Due Diligence Directive
CRMs	Critical Raw Materials
EGD	European Green Deal
EGDSF	European Green Deal Strategic Framework
EU	European Union
FAO	Food and Agriculture Organisation
GHG	Greenhouse Gas
ICAO	International Civil Aviation Organisation
IMO	International Maritime Organisation
NGTs	New Genomic Techniques
NFRD	Non-Financial Reporting Directive
NZIA	Net-Zero Industry Act
OECD	Organisation for Economic Cooperation and Development
POPs	Persistent Organic Pollutants
REACH	Regulation on the registration, evaluation, authorisation, and restriction of chemicals
RES	Renewable Energy Sources
SA	Strategic Autonomy
SFDR	Sustainable Finance Disclosure Regulation
UN	United Nations
WEEE	Waste Electrical and Electronic Equipment
WTO	World Trade Organisation

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Institutional Quality, Trust in Institutions, and Waste Recycling Performance in the EU27

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Abstract: This paper addresses the role of institutional quality and trust in institutions for the performance in waste recycling of the EU27 countries. While survey-based works have highlighted the role of these factors for waste recycling attitudes and performance at the micro level, econometric analyses of recycling in Europe at country and regional levels have mostly looked into the role of waste policies, and not the role of institutional factors, in driving progresses in waste recycling. This paper tries to fill this gap through a panel econometrics analysis of recycling rates of municipal solid waste at the national level for the EU27 countries for the period 2005–2020. The proxies for institutional quality and trust in institutions, as the variables of interest, are introduced into a model that includes controls on a set of socio-economic variables, and on a set of EU waste policy variables, in particular the Waste Framework Directive (WFD) and its revision, and the first Circular Economy Action Plan of 2015 (CEAP 2015). Our results support the hypothesis that the quality of institutions can influence waste recycling performance. Moreover, our results provide evidence on the negative role of institutional trust on recycling rate at country level. Similarly, we find that the EU WFD and CEAP 2015 have been significant in driving recycling performances; the latter finding, however, is a necessary condition in appropriate institutional and socio-economic environments at the national level.

Keywords: waste recycling; quality of institutions; trust in institutions; circular economy action plan

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1. Introduction

The EU is pursuing a large-scale sustainability transition through the European Green Deal (EGD), which is driven by the target of achieving the Net Zero of greenhouse gases emissions by 2050 [1]. This ambitious challenge has been confirmed by Next Generation EU (NGEU), the European post-pandemic recovery program, which includes specific constraints on allocation of funding to climate objectives [2]. Together with the focus on climate change, both the EGD and NGEU encompass the decoupling of economic growth from resource use, in which waste management and circularity have a key role, in particular through the new Circular Economy Action Plan 2020 embodied into the EGD strategy.

The circular economy paradigm is opposed to the predominant paradigm of the linear economy 'take, make, and dispose' and focuses on closing the cycle of materials and energy through the structural change of the whole production system [3,4]. The current linear economic model risks exceeding the environmental capacity to absorb the externalities and by-products of the economy and the regenerative capacity to produce enough materials and ecosystem services to sustain further development. The alternative is a shift to a more circular system, in which the decoupling of the economic activities is also achieved by reducing waste generation and increasing the reuse and recycling of materials, thus also benefitting ecosystems through reduced anthropogenic pressures from the extraction of virgin materials (e.g., loss of biodiversity, loss of ecosystem services).

Circularity can be achieved through increased material efficiency by using fewer resources for the same output, or reducing waste per unit of output, or reusing and recycling secondary materials avoiding the extraction of virgin materials and pressures on the ecosystem [5,6]. Key aspects of circularity are technological enhancement, environmental policies, and industrial changes, together with social participation in sustainable consumption behavior and minimized waste disposal.

Waste management is of primary importance within the circularity paradigm: it increases the amount of secondary material reintroduced into the economy, thus closing the material loop and avoiding the extraction of primary material and its impacts. Therefore, increasing recycling rates is at the very core of circularity progresses in accordance with the EU's main objectives of sustainability transition.

Municipal solid waste (MSW) amounts to around 10% of total waste generation in European countries [7–9]. Within the waste management systems of EU27 countries, recycling has gained a prominent role during the past few decades. On average, a European citizen produces 534 kg of waste of which 220 kg are recycled, 141 kg are treated in incinerators, and the remaining 173 kg are landfilled. However, even though all EU countries share a common legal EU framework that is pushing them to converge to the highest level of circularity, they show heterogeneous recycling performances within their own national and regional waste management models [10,11].

Many authors have investigated the role of EU and national policies, demographic factors, and socio-economic aspects as main drivers of waste recycling performances at national or regional levels (see [12–14]). While these analyses have often explored the role of specific waste policies for the observed changes in waste management in the EU countries, the factor which often has been overlooked is how the quality of institutions and the trust in institutions can influence waste management trends, and in particular the pattern of recycling activities. While it is expected that specific waste policies, for example landfill bans, can have a specific direct role in triggering positive changes in waste management, these policies are in any case implemented within national and local economic and social frameworks, in which the specific institutional environment and its capacities can have a critical role in the effectiveness of waste and recycling policies.

Institutions are the 'rules of the game' of a society and are important because they can push individual behavior towards collective actions that would not take place without them. Institutions enhance the cooperation of citizens through monitoring, coercion, and sanction systems that can prevent market failures or policy failures. The quality of institutions is linked to good governance with important impacts on socio-economic interactions within the society [15]. Moreover, trust in institutions, considered as the citizen's perception that these institutions can be trusted, can increase cooperation and participation in collective actions because citizens are confident that free-riding behaviors will not occur due to the presence of trustable institutions [16]. Institutions and institutional trust can affect how citizens participate in and cooperate within society, also determining the socio-economic performance of a country. Therefore, the impact of institutions on waste management and recycling is worthy of interest [17].

Some authors have analyzed the role of institutions in waste management with micro analyses using survey data [16,18] or sub-regional analysis in a single country [19]. All those studies have provided evidence on the effect of institutions on the recycling attitudes of citizens, but cross-country studies at the European level analyzing the effect of institutions on recycling are still lacking.

The aim of this paper is to investigate the role of the quality of institutions and institutional trust in the recycling performance of MSW in the EU27 by using an econometric approach to a cross-country panel dataset from Eurostat from 2005 to 2020. We aim to fill the gap in the literature by providing an econometric exercise on the main socio-economic determinants and the role of institutions in the MSW recycling rate of the EU27 countries along a time frame of 15 years.

The paper is structured as follows. Section 2 provides a background on recycling in the EU27 and a literature review on the quality of institutions and recycling. Section 3 provides the description of the data and method used in this study. In Section 4, the main results are presented and discussed in Section 5. The concluding remarks are presented in Section 6.

2. Background

2.1. Waste Policies and Recycling Performance in the EU27

Waste policies are among the oldest European policies for the environment. The first Waste Framework Directive of 1975 introduced the general approach to waste management based on the Waste Hierarchy, which gives the highest level priority to prevention and reuse (or preparation for reuse), followed by material recycling and then energy recovery, with landfill classed as the least preferred option (see Zoboli et al. [20] for a discussion). Important steps of the EU waste policies took place in the 1990s and early 2000s with the directive on packaging waste (1994) and the landfill and incineration directives (1999), together with the other directives on specific flows of waste (ELV, WEEE, and batteries) [21,22]. In the past two decades, the EU waste policies have been largely aimed at reinforcing the existing legal framework and at introducing more ambitious targets for the whole waste management system. Two major policy steps in the past fifteen years have been the new Waste Framework Directive of 2008, which was amended in 2018, and the First Circular Economy Action Plan (CEAP) of 2015, updated in 2020 within the European Green Deal package.

The new EU Waste Framework Directive (WFD) of 2008 updates the basic concepts and criteria of waste management policies and regulations, such as definitions of waste, recycling, and recovery to reflect decades of waste policy implementation and outcomes. The WFD also confirms the principles of Waste Hierarchy [23,24]. The aim of the WFD is to promote strategies for waste prevention prioritizing the reduction, reuse, and recycling of waste over disposal in landfill [25]. This policy vision and strategy was reinforced in 2015 with the First Circular Economy Action Plan (CEAP) [26]. While framed in the new dominating paradigm of the circular economy, the CEAP 2015 confirms the strategy of reducing the production of waste while closing the loops of material use in the EU economy [26]. Recycling is then a key strategy to move from a linear to a circular economy, and the recycling rate can be considered as a good proxy of measurement to assess the closure of the material loop within the economy [27,28]. In 2018, the WFD was amended by introducing new definitions and new targets for the recycling and reduction of municipal solid waste, together with other new provisions, for example, on the end-of-waste and on Extended Producer Responsibility (EPR). In particular, the preparation for reuse and the recycling of municipal waste should be increased to a minimum of 55% by weight by 2025, to a minimum of 60% by 2030, and to a minimum of 65% by 2035 [29]. The new CEAP (2020) focuses on product design for waste prevention, the extension of EPR to new sectors, e.g., single-use plastics, reuse, and recycling in the textile sector, and the improvement in the performance of secondary materials markets [20,30].

In general, the average recycling rate of MSW as a share of the total managed MSW in the EU27 countries has grown steadily over the last 25 years, from 12.3% in 1995 to 39.7% in 2020. Figure 1 illustrates the main waste management patterns in the EU27 countries. The average landfill rate of MSW experienced an important reduction in the past 25 years, from 70.2% of the total MSW in 1995 to 32.9% in 2020, while the average incineration rate has increased, but at a relatively slower rate compared to the recycling rate, reaching 32.9% of the total MSW in 2020.

Figure 2 shows the changes in the recycling rate for all EU27 countries from 2000 to 2020 and highlights important differences among countries in terms of recycling performances: only eight countries in 2020 recycled more than 50% of their total MSW production (Germany, Austria, Slovenia, Netherlands, Belgium, Denmark, Luxembourg, and Italy), thirteen countries recycled between 45% and 30% of their MSW (Lithuania, France, Slovakia, Finland, Ireland, Latvia, Poland, Sweden, Spain, Bulgaria, Croatia, Czechia, and

Hungary), and six countries recycled less than 20% of their MSW (Estonia, Portugal, Greece, Cyprus, Romania, and Malta).

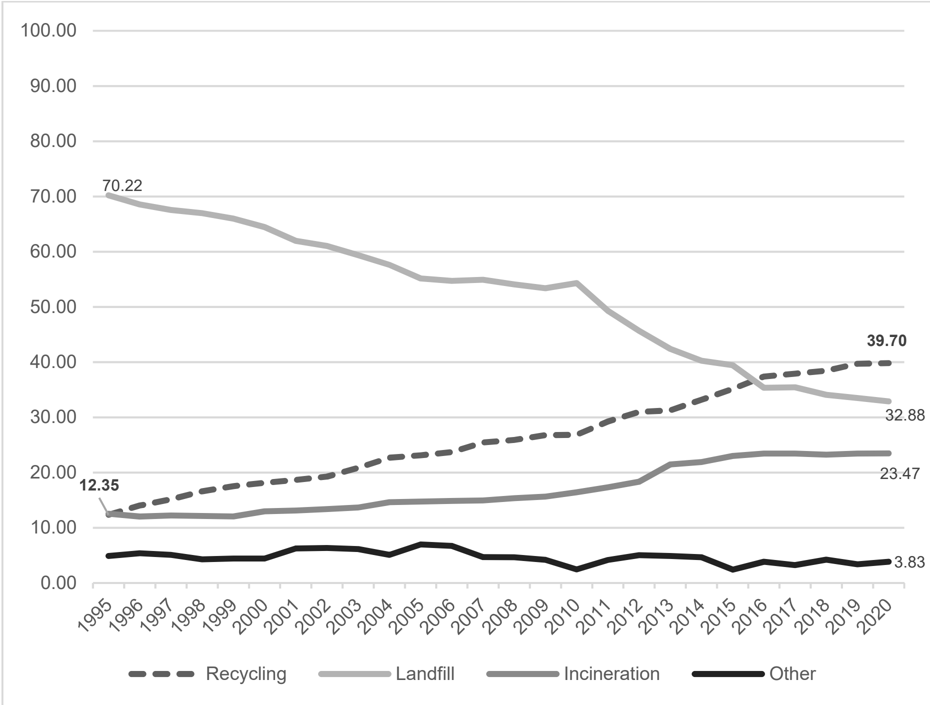

Figure 1. MSW treatment rate by category of treatment. Source: Authors' elaboration from Eurostat data.

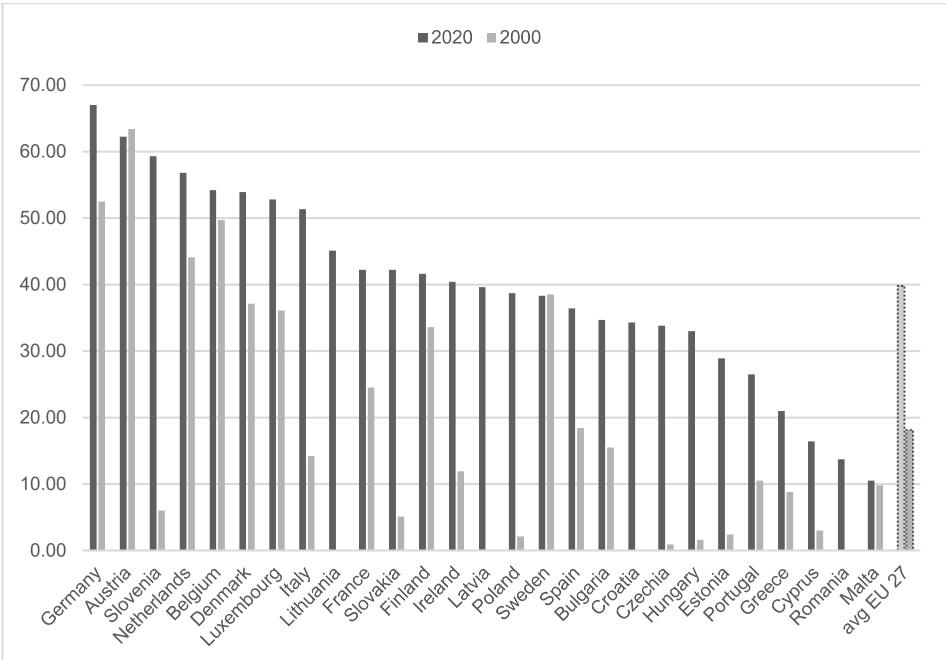

Figure 2. Recycling rate of MSW in the EU27 countries in 2020 and 2000 (in order of recycling rate in 2020). Source: Authors' elaboration from Eurostat data.

European countries, despite the common legal framework that includes binding targets of waste management performance to all EU members, have shown important heterogeneities in terms of recycling patterns. This has been due to the different strategies for the diversion of MSW from landfills adopted by EU members during the past thirty years in which the landfilling, material recovery (mainly recycling and composting), and incineration of MSW were guided by different national and local structural socio-economic factors (i.e., the stage of economic growth, demographic and social aspects, investments in specific technologies creating lock-in effects, etc.) [10,13,14]. These differences in national, and local, patterns and performances are due not only to structural factors, but also to the specific institutional environment in which the policy impulses were received and processed to achieve the requested changes of the MSW management system. This role of the 'institutional environment' is the specific object of the rest of this paper.

2.2. Quality of Institutions, the Environment, and Waste Management

An important branch of economic research has studied institutional quality as a determinant of economic performance, highlighting the role of governance and institutions as important accelerators of economic development [31–38].

The quality of institutions is strictly related to good governance because it can reflect the ways in which authority is exercised in a country, including the political process by which governments are selected and monitored, their ability to implement appropriate policies, and the way they govern socio-economic interactions between the members of a country. Kauffman et al. [17] define 'governance' as "*(a) the process by which governments are selected, monitored and replaced; (b) the capacity of the government to effectively formulate and implement sound policies; and (c) the respect of citizens and the state for the institutions that govern economic and social interactions among them*".

Institutions are a fundamental factor of good governance and can be interpreted as the "rules of the game" of a society. They work as external systems of control that can drive the decision of individual members of the society toward the overall benefit for the society itself [15,39]. Formal institutions shape the relationships among individuals and reflect the government structure of a society [37,40], with important impacts on political, social, and economic relationships within the society [15].

Studying the effects of institutions on economic processes can be difficult because finding effective proxies for institutional quality is not an easy task. Governance is connected to various aspects which are not always observable, such as the rule of law (e.g., the enforcement of property rights), political stability (e.g., riots, violence), characteristics of political regimes (e.g., elections, constitutions, executive powers), social capital (e.g., civic participation), the control of crime and corruption, and other socio-cultural characteristics (e.g., income distribution, ethnicity, religion diversity, historical background) [41]. A robust approach is the one proposed by Kauffman et al. [17], who suggested a way to measure the quality of governance by articulating institutional quality around six dimensions that can have different impacts on growth and other socio-economic indicators: (1) voice and accountability; (2) political stability and absence of violence and terrorism; (3) government effectiveness; (4) regulatory quality; (5) rule of law; and (6) control of corruption [42].

'Trust in institutions' can be defined as the perception of and confidence of citizens in the credibility, fairness, competence, and transparency of institutions. Institutional trust is experiential in the sense that it depends on people's experiences with representatives of institutions (e.g., public employees such as bureaucrats and police officers) [43]. It is evident that general social trust, institutional trust, and institutional quality are correlated with important feedback effects on each other [39,43].

Differences among countries in the quality of institutions can lead to different outcomes in economic performance (i.e., a weak institutional framework can increase transaction costs, limiting the efficiency of markets, business, investments, and technological innovation) [41,44]. Therefore, the quality of institutions can also influence waste management at the country level.

'Institutional quality' and 'trust in institutions' can be even more important in waste management if recycling is considered as a special case of large-scale collective action dilemma or social dilemma [45]. A social dilemma can occur when in a collective action situation (e.g., the provision of a public good, the internalization of externalities, or the management of the commons), the payoff of individuals for refusing action is higher than the cooperative actions, regardless of what other members do [45]. This leads to a final outcome of market failure depending on the type of problem (e.g., the public good is not provided, the externality is not internalized, or the commons collapse). Therefore, all individuals receive a lower payoff if they all refuse than if they all cooperate, but there is not a mechanism that allows the solution of the 'prisoner's dilemma' because the individual pay-off is larger than the social utility gained by the solution of the collective action problem.

In this framework, recycling takes the form of a public-good provision problem in which the successful provision of the public good itself (or of the shared commons) depends on the cooperation of a large number of individuals. In fact, individual participation in the schemes of advanced separate collection for recycling can influence the overall outcome of the recycling process: individual decisions, which depend mainly on individual incentives (i.e., economic, social, and other types of incentives), can affect the final level of total material recycled by the society as a whole [16,46]. People cooperate in collective actions if they have some confidence that others will also cooperate, and this may partly depend on general social trust, which can be considered as the expectations on others and on the reliability of their actions when there is no or little information about them [43]. In some cases, general social trust alone cannot guarantee the success of the social dilemma when the number of participant is large [47].

The higher the number of actors involved in a collective action problem, the higher the chances to end up in a situation far from the best social solution, as in the collective action problem explained by Hardin's '*Tragedy of the Commons*' [48]. The more actors are involved, the greater the demand for a third-party enforcer (e.g., the state or a lower level of government) to coordinate and facilitate collective actions, typically through the use of economic incentives, regulations, and control activities [18,39].

The introduction of third parties into collective action problems can prevent the failure of public good provision by increasing general trust in other members as well as trust in the institutional framework that enables the management of the collective action problem itself [49]. In the case of recycling, general trust in the institutions that manage the recycling process can increase the compliance and cooperative behavior of individuals by reducing incentives of free-riding through coercion, monitoring, and enforcement activities [16,18]. In other words, non-cooperation incentives which can increase defections from collective actions are lower with the participation of institutions in the process due to the general idea that institutions can manage and coordinate the contribution of all citizens to the public good.

Various studies highlighted the effect of institutional quality as a driver of good environmental performances of countries and regions, considering mainly air pollution and the management of natural resources [50–59], but few studies have focused on waste management.

Some authors specifically investigated the effect of the 'quality of institutions' and 'institutional trust' on the recycling behavior of citizens, finding that the trustworthiness of institutions increases cooperation in collective action problems, and in those cases, increasing participation in recycling activities. These studies have been mainly based on micro-level surveys.

Sønderskov [47] analyzed whether general social trust can determine recycling, finding evidence that people characterized by higher generalized social trust recycle more than those with low trust, and identifying how in large collective action problems, the idea of generalized social trust increases the level of cooperation when individuals believe that others will do the same.

Rompf et al. [16] tested the relationship between institutional and social trust and the recycling attitudes of citizens, also focusing on the interactions between these two components of trust, and identifying a different process of reciprocity in determining cooperative behavior. They found that an increase in institutional trust (which increases trust in the punishment of free-riders) prompts citizens toward an automatic norm-compliant behavior, affecting cooperation in recycling as a public good [16]. They also showed that when trust in institutions is high, the individual private costs and benefits do not affect the participation in recycling as a collective action.

Harring et al. [18] analyzed the link between institutional quality and trust and individual self-reported recycling behavior in different European countries, using cross-sectional survey data at the micro level. Moreover, the authors tested the hypothesis of a curvilinear relation between the self-reported recycling activities of citizens and their declared trust in institutions, which indicates a negative relationship between institutional trust and recycling. They argued that institutional trust at its highest levels, such as in developed countries, could affect cooperation negatively, because above certain high levels of trust, individuals no longer cooperate with the collective action problem. They do that by passivity or rational calculations, as their contribution appears to be less important since the state is assumed to take care of the public good regardless of individual actions [18]. In their empirical work, the researchers found that institutional quality, general social trust, and institutional trust all strongly increase recycling behavior, but failed to show an inverse relation between institutional trust and recycling activities.

Argentiero et al. [19] investigated the relationship between social trust and the quality of institutions on recycling behavior in Italy using data at NUTS 3 level to exploit the strong heterogeneity among Italian provinces in terms of institutions and social capital They consider social trust as a proxy of social cohesion and social capital. Moreover, they studied the interactions between social trust and the quality of institutions to consider potential mediating factors in influencing recycling attitudes. They found that both social trust and the quality of governance positively affect recycling, but their results also revealed a decreasing marginal effect of social trust when institutional quality is high, with a strong degree of substitution between trust and the quality of institutions [19]. This means that social trust for collective action is more important where institutional quality is low.

3. Methods and Data Description

3.1. Research Hypotheses

Our main interest is to understand and measure the effect of the 'quality of institutions' and 'institutional trust' on the recycling rate at country level for the EU27. Previous studies based on surveys, as reviewed above, confirmed a positive relation between institutional quality and recycling, which implies that the institutional environment positively affects the participation in and cooperation of households with recycling activities [16,19]. Our main hypothesis follows those findings and econometrically tests them for the EU27:

H1. *The stronger quality of institutions increases the level of recycling in the EU27 countries.*

This would imply a positive sign in the regression of the proxy for the quality of institution.

The study of Harring et al. [18] added institutional trust to the analysis of determinants of recycling behavior, assuming an unknown relation between the two variables and hypothesizing that a negative effect may also occur. This is explained in relation to a less civic participation when institutional quality is high because people believe that their contribution is useless since institutions 'take care of everything'. We partially follow their approach in defining our second hypothesis to be econometrically tested:

H2. *Institutional trust influences the recycling rate in the EU27 countries, but the direction of the effect is uncertain as it can be either an increase or a decrease in the recycling activities of citizens.*

This implies that a statistically significant coefficient of the proxy for institutional trust is required to test H2, but the sign of the coefficient cannot be defined a priori.

3.2. Data Description

All our data are from waste and socio-demographic datasets of Eurostat [60,61], and the time frame of analysis is 2005 to 2020 to circumvent missing data in many control variables in the years before 2005 in Eurostat data.

Our dependent variable RR is the recycling rate, measured as the total MSW recycled to the total MSW produced in each year considered in our analysis. Our key independent variables are QI and IT. The former (QI) is the quality of institutions, measured using the indicator on Government Effectiveness (GEE) from the World Governance Indicator (WGI) of the World Bank [42]. The WGI provides five other main composite indicators following the definition of the quality of institutions, as identified by Kaufmann et al. [17], namely, voice and accountability; political stability and absence of violence/terrorism; regulatory quality; rule of law; and control of corruption.

We focus only on the GEE indicator because all WGI indicators are strongly correlated to each other, thus preventing the possibility to use all of them together. The GEE indicator captures the citizens' perceived quality of public services, civil service, policy formulation, and implementation, the degree of independence from political pressures, and the credibility of the government's commitment to such policies [42]. Even if the WGI database provides a large selection of quality of institution indicators, we focused only on GEE because it is the closest indicator to be adapted to recycling and waste management. Furthermore, as the WGI indicators are set at world level, indicators other than the GEE (i.e., voice and accountability; political stability and absence of violence/terrorism; rule of law; and control of corruption) do not show great heterogeneity among European countries, since all EU27 countries have already converged towards high institutional quality standards for those aspects.

Our second key variable is institutional trust (IT) from Eurostat. Based on Eurobarometer surveys at a national level, it measures the confidence among citizens in a set of selected EU institutions (i.e., the European Parliament, the European Commission, and the European Central Bank). The variable represents the percentage of people positively declaring to trust in EU institutions on a three-grade answer ('tend to trust', 'tend not to trust', and 'don't know' or 'no answer') in each EU27 country. The institution we selected is the EU Parliament because it is the only elected institution among the three.

We identified the controls to be used in our model specification following previous analyses of recycling and waste management [7,12–14,24]. The data are from the Regional Eurostat database, and all the variables are registered annually considering the time frame 2005–2020. Our controls are as follows:

- Household size (*HH Size*). The dimension of the household can influence the level of waste generated and the amount recycled. Larger families can have more difficulty in recycling because of the higher amount of waste produced. The variable measures the average household size at country level.
- Low education (*Low Edu*). Recycling is expected to increase with higher levels of education which can influence more participation in large-scale collective actions because of more civic engagement or environmental concern. A higher number of citizens with low education can increase the level of non-compliance in recycling. This variable measures the percentage of 25–64 population with an education level lower than secondary (lower than primary, primary, or lower than secondary education) at country level.
- Immigration. A higher level of immigration is expected to reduce the level of recycling by several factors, for example, the unstable dwelling conditions of the immigrants; a low level of language comprehension; or the adherence to a traditional scheme of waste management, e.g., a culture of origin which does not consider recycling. The variable measures the total amount of immigrants resident in the country, using a natural logarithm to reduce the skewness of the distribution.
- Tourism. Recycling performance can be influenced by tourism flows in different ways, although the relationship between the two variables is not well defined. For example,

visitors may not be interested in participating in recycling activities because it is an action that requires effort in their free time, or they may not participate in recycling because they do not know how to comply with local recycling rules (e.g., the type of bins, or the type of selection of specific waste). This may reflect a negative sign of the tourism proxy in the regression. On the contrary, tourism flows may increase recycling activities due to the increased focus of local authorities on pro-environmental behavior, as tourists may have pro-environmental preferences, or they just prefer clean environments. Nevertheless, independently of the type or relation, in order to reduce distortions related to unobserved tourism activities, it is necessary to control for tourist activities. The variable measures the total number of tourist facilities (e.g., hotels, holiday and other short-stay accommodation, campsites, recreational vehicle parks, and caravan parks) per capita as a proxy for the total potential tourist accommodation, and it is calculated as the ratio between the total number of touristic establishments and the total population in a country.

- Population density (*Pop Density*). Several studies have already used this variable to control for economies of agglomeration and value of land that may substantially influence the cost of landfilling sites and therefore increase recycling activities because they reduce the overall cost of waste management [24]. Another aspect influenced by population density is the level of urbanization of a country which can directly affect the level of recycling through the economy of scale, integrated services, and the higher cost for other types of waste treatment. The variable measures the level of citizens per square kilometer living in a country, and we used the natural logarithm of population density to smooth the distribution.
- Age dependency ratio (*Age Dep*). The age structure of a country may influence the attitude towards recycling (e.g., younger citizens with greater environmental commitment may increase the overall recycling rate in a country). Although a clear relationship between the age of the population and recycling activities has not yet been established, it is necessary to control for this element as it could influence our estimation by biasing the results. The variable measures the age dependency ratio, as the percentage of the population in the non-working life stage divided by the population in the working life stage (i.e., the ratio of the population aged 0 to 19 and 65 or older to the population aged 20 to 64).
- Final consumption. One of the most important factors influencing waste generation is household consumption, which is also an important proxy for well-being and economic development, being strongly linked to gross domestic product per capita. Many other authors have used this variable in waste analysis, also considering its potential non-linearity in an environmental Kuznets curve hypothesis [12,13]. We follow this line of studies by adding the quadratic consumption term in our regression to consider non-linearity. The variable used is the household final consumption expenditure per capita at current prices at country level.
- Gini Index. Inequalities may affect recycling directly or indirectly. The first outcome can occur if different levels of recycling are due to inequalities within a country, which can result in differences in services provided (e.g., recycling services only in rich areas while poor areas are characterized by landfilling). The second outcome can depend on the overall institutional framework in poor areas, which can produce low recycling performances due to other institutional priorities (e.g., employment or welfare). The variable we employed is the Gini coefficient of equivalized disposable income before social transfers (pensions included in social transfers) expressed in a 0–100 range.
- High No-Waste Performances (*HNWP*). This variable can be interpreted as an indication of high performance in avoiding waste production, and it is used as a control for countries' profile and attitudes in limiting waste production. A country's recycling performance for MSW can be influenced by its idiosyncratic propensity to produce waste, which can be affected by various factors such as the consumption habits of the citizens, the overall circularity of the production system which reduces the parts of

goods becoming waste, or the pro-environmental behavior of the citizens. To consider these aspects, we used a dummy variable that takes the value 1 if waste production per capita is below the 10th percentile of the distribution of waste production per capita.

- Low No-Waste Performances (*LNWP*). This variable can be interpreted as an indication of a low performance in waste production per capita and it negatively mirrors the *HNWP* variable. We used a dummy variable taking the value 1 if the waste per capita is in the 90th percentile of the distribution. These last two variables (*HNWP* and *LNWP*) are used to control for lifestyle and efficient consumption management, and thus to consider the effect of the efficiency of consumption systems on recycling levels.

Table 1 provides a description of all the variables used in the econometric analysis.

Table 1. Descriptive statistics of the variables used in the econometric analysis.

Variable		Obs	Mean	Std. Dev.	Min	Max
Recycling rate	RR	432	31.622	17.256	0	67.2
Household size	HH Size	432	2.447	0.268	2	3
Low education	Low Edu	432	23.355	14.574	4.6	74.8
Log (Immigration)	Immigration	432	10.819	1.384	7.27	14.267
Tourism	Tourism	432	16,920.605	34,806.283	157	226,855
Log (Population density)	Pop Density	432	4.647	0.901	2.793	7.395
Age dependency	Age Dep	432	63.9	5.239	52.3	80.2
Final consumption	Consumption	432	12,780.787	6339.909	2120	31,770
Final consumption^2	Consumption^2	432	2.034×10^8	1.841×10^8	4,494,400	1.009×10^9
Gini Index	Gini Index	432	48.633	4.519	37.2	61.6
High No-Waste Performances	HNWP	432	0.079	0.27	0	1
Low No-Waste Performances	LNWP	432	0.109	0.312	0	1
Quality of institutions	QI	432	1.098	0.583	−0.36	2.354
Trust in institutions (EU Parliament)	IT	432	52.639	10.205	23	79
Waste directive	WFD	432	0.062	0.242	0	1
Circular directive	CEAP	432	0.062	0.242	0	1
Revision targets	Revision	432	0.062	0.242	0	1
Trend 1 (2005–2007)	Trend 1	432	0.375	0.858	0	3
Trend 2 (2009–2014)	Trend 2	432	1.312	1.994	0	6
Trend 3 (2016–2017)	Trend 3	432	0.188	0.527	0	2
Trend 4 (2019–2020)	Trend 4	432	0.188	0.527	0	2

3.3. Econometric Strategy

To test H1 and H2, we used a standard econometric panel data approach with a fixed effects model to consider unobserved heterogeneity and the potential endogeneity due to unobserved time-invariant variables which may bias our estimation [62]. To cope with potential autocorrelation and heteroskedasticity in our data, we used clustered standard error at country level [63,64]. Our main specification is outlined in Equation (1).

$$RR_{i,t} = \alpha + \beta_1 QI_{i,t} + \beta_2 IT_{i,t} + \sum_{m=1}^{k} \beta_m x_{m,\, i,t} + u_i + \varepsilon_{it} \quad (1)$$

where RR is the recycling rate (MSW recycling over total MSW produced), QI is the quality of institutions, IT is the institutional trust, x_m are other control variables, u_i is the individual fixed effect, ε_{it} is the idiosyncratic error, βi are the parameters to be estimated, i is the identifier for the country, t is the identifier for the year, and α is the intercept. Our dependent variable is RR, while our key independent variables are the 'quality of institutions' QI and 'institutional trust' IT.

In a second specification, we added two dummy variables to control for the European policy framework which can have affected the recycling rate in our time frame of analysis. We add a dummy variable for 2008 when the Waste Framework Directive was implemented, for 2015 when the first EU Circular Economy Action Plan (CEAP) was introduced, and for 2018 when the major EU targets for MSW were revised to become more ambitious. Moreover, to further control for EU policies and targets, which are expected to affect the recycling rate, and to consider the expected lagged effects of policies (i.e., the policy produces effects after its introduction and not in the year of implementation), we added a set of trends within our time frame:

- Trend 1 from 2005 to 2007, to control for the years before the introduction of the WFD;
- Trend 2 from 2009 to 2014, to check the effect of the WFD implementation before the introduction of the first CEAP;
- Trend 3 after 2015, to check the effect of the first CEAP before the revision of its targets which occurred in 2018;
- Trend 4 to check the effects of the target revision for the years after 2018.

The time frame of our analysis does not allow to consider a possible effect of the New Circular Economy Action Plan of 2020.

The second specification is described in Equation (2), in which the dummies for the EU policies and the trends ($\tau_1,\ \tau_2,\ \tau_3$) were added to the previous specification.

$$RR_{i,t} = \alpha + \beta_1 QI_{i,t} + \beta_2 IT_{i,t} + \sum_{m=1}^{k} \beta_m x_{m,\ i,t} + u_i + WFD_{i,t} + CEAP_{i,t} + Revision_{i,t} + \tau_{1(2005-2007)} + \tau_{2(2009-2014)} + \tau_{3(2016-2018)} + \tau_{4(2019-2020)} + \varepsilon_{it} \quad (2)$$

Finally, we used the specification shown in Equation (3) to test the hypothesis of Harring et al. [18], which states that trust in institutions can have a negative effect at high levels of waste management performance, since the individual contribution may be felt to be unnecessary as the institution itself is assumed to take care of the waste regardless of individual action.

$$RR_{i,t} = \alpha + \beta_1 QI_{i,t} + \beta_2 IT_{i,t} + \sum_{m=1}^{k} \beta_m x_{m,\ i,t} + u_i + WFD_{i,t} + CEAP_{i,t} + \tau_1 + \tau_2 + \tau_3 + \tau_4 + \beta_{k+1} HNWP_{i,t} + \beta_{k+2} HNWP_{i,t} * IT_{i,t} + \beta_{k+1} LNWP_{i,t} + \beta_{k+2} LNWP_{i,t} * IT_{i,t} + \varepsilon_{it} \quad (3)$$

The last specification shown in Equation (3) is defined as before, but in this specification, two interaction terms were added to better identify how institutional trust operates in affecting recycling attitudes. We used the interaction between institutional trust and the dummies of high and low waste production performances (*HNWP* and *LNWP*), indicating the mediating effect of institutional trust with countries that have both high and low levels of waste production performances. By doing this, we could identify the effect of institutional trust on countries in the 10th and the 90th percentile in terms of 'no-waste' performance: this can suggest whether institutional trust might negatively affect recycling at high levels of 'no-waste' performance. To confirm this, we expected that the interaction between *IT* and *HNWP* (i.e., countries that have a high level of 'no-waste' performance) would be statistically significant and negative. This effect should not be relevant for the interaction between *IT* and *LNWP* (i.e., the interaction between trust in institutions and the dummy of low 'no-waste' performance countries should not be statistically significant).

4. Results

The results of our analysis are shown in Table 2. The quality of institutions (*QI*) using WGI's government effectiveness indicator, is always statistically significant alone (90% level) and in combination with *IT* (95% level), with a positive coefficient indicating that a high level of institutional quality increases the recycling rate (Column 2 to 4). In terms of marginal impacts, the quality of institutions increases the recycling rate by 7.6% and 8.3% % for the specifications in columns 2 and 3 (respectively, in model 2 without *IT* and model 4 with *IT*).

Table 2. Results of the econometric analysis. Effects of the quality of institutions (QI) and institutional trust (IT) on the recycling rate (RR).

	(1)	(2)	(3)	(4)	(5)
Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
HH Size	−11.75	−9.988	−9.632	−7.572	−8.012
	(−1.519)	(−1.323)	(−1.282)	(−1.028)	(−1.090)
Low Edu	0.125	0.115	0.121	0.109	0.0915
	(0.612)	(0.575)	(0.616)	(0.575)	(0.484)
Immigration	0.217	0.0732	0.528	0.396	0.552
	(0.217)	(0.0731)	(0.546)	(0.413)	(0.578)
Tourism	0.000184 ***	0.000180 ***	0.000187 ***	0.000183 ***	0.000183 ***
	(7.528)	(8.316)	(8.194)	(8.507)	(9.031)
Pop Density	−18.49	−10.35	−25.38	−17.09	−19.68
	(−0.758)	(−0.428)	(−1.106)	(−0.761)	(−0.872)
Age Dep	0.0571	0.124	0.0133	0.0819	0.113
	(0.162)	(0.373)	(0.0397)	(0.263)	(0.359)
Consumption	0.00510 ***	0.00496 ***	0.00499 ***	0.00483 ***	0.00460 ***
	(3.768)	(3.803)	(3.987)	(4.143)	(4.107)
Consumption^2	-1.18×10^{-7} **	-1.15×10^{-7} ***	-1.02×10^{-7} **	-9.80×10^{-8} ***	-9.22×10^{-8} ***
	(−2.661)	(−2.784)	(−2.643)	(−2.874)	(−2.804)
Gini Index	−0.0893	−0.0649	−0.132	−0.109	−0.0747
	(−0.692)	(−0.487)	(−0.991)	(−0.827)	(−0.566)
HNWP	−1.335	−1.657	−0.684	−0.984	18.90 **
	(−0.641)	(−0.848)	(−0.332)	(−0.509)	(2.659)
LNWP	−2.490 *	−3.170 **	−2.792 **	−3.549 ***	−3.874
	(−1.952)	(−2.382)	(−2.387)	(−2.982)	(−0.531)
QI		7.653 **		8.271 **	8.374 **
		(2.356)		(2.422)	(2.462)
IT			−0.169 **	−0.181 **	−0.165 **
			(−2.285)	(−2.623)	(−2.300)
HRP*IT					−0.353 **
					(−2.739)
LRP*IT					0.00264
					(0.0196)
WFD	−2.253 ***	−1.970 **	−2.380 ***	−2.084 **	−1.962 **
	(−3.002)	(−2.681)	(−3.053)	(−2.755)	(−2.724)
CEAP	4.745 ***	4.852 ***	2.642 *	2.604 **	2.286 *
	(3.696)	(3.821)	(1.985)	(2.080)	(1.870)
Revision	4.688 ***	5.030 ***	3.589 ***	3.878 ***	3.630 ***
	(3.405)	(3.596)	(3.174)	(3.419)	(3.166)
Trend 1	−0.600 **	−0.502 **	−0.361	−0.238	−0.229
	(−2.738)	(−2.148)	(−1.650)	(−0.911)	(−0.840)
Trend 2	0.415 *	0.430 *	0.114	0.109	0.0424
	(1.871)	(2.053)	(0.482)	(0.493)	(0.198)
Trend 3	3.292 ***	3.450 ***	2.421 ***	2.528 ***	2.357 ***
	(4.553)	(4.883)	(3.718)	(4.027)	(3.712)
Trend 4	3.388 ***	3.803 ***	3.028 ***	3.449 ***	3.280 ***
	(3.196)	(3.631)	(3.166)	(3.692)	(3.540)
Constant	95.74	42.72	132.0	77.38	86.65
	(0.720)	(0.320)	(1.074)	(0.631)	(0.703)
Observations	432	432	432	432	432
R-squared	0.647	0.660	0.661	0.675	0.682
Number of Id	27	27	27	27	27

Robust t-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0$.

Institutional trust (*IT*) is also significant in all specifications with a statistical significance level of 95% (model 3 and 4), but the effect of this variable is negative in all specifications, with a magnitude of −0.17 in the specification without *QI* (model 3) and −0.18 with QI (model 4). This result indicates that institutional trust reduces the recycling rate at the national level, with a reduction between −0.17 and −0.18 for each additional percentage of the population declaring to trust in the European Parliament, depending on the model specification. This suggests that increasing levels of institutional trust can have a negative effect at its highest level, thus reducing the recycling activities of citizens, as hypothesized by Harring et al. [18].

To confirm this, we ran an additional regression in which we inserted in the specification two additional elements which can be useful to identify how the effect of institutional trust operates in affecting recycling attitudes. The results of this econometric exercise are shown in model 5 where we added the interaction between institutional trust and the dummies of high and low waste production performances (*HNWP* and *LNWP*).

In this last specification, the signs and magnitude of *QI* and *IT* remain stable and statistically significant (both at the 95% level with a magnitude, respectively, of 8.37 and −0.16), confirming their main effects on the recycling rate. Moreover, we found a statistically significant negative effect of the interaction between *IT* and *HNWP* with a magnitude of −0.353. This suggest that for a high level of 'no-waste' performance at country level, the effect of institutional trust may reduce the overall recycling performance. This result further confirms the hypothesis of Harring et al. [18] that, at a high level of institutional quality, an individual can turn away from cooperative behavior, producing a sub-optimal outcome in a large-scale collective action problem, because an excessive trust in the institutional system can boost non-cooperative attitudes. This is confirmed by the positive sign, the low magnitude (0.00264), and the statistical insignificance of the coefficient of the interaction term between institutional trust and *LNWP*.

Considering the control variables, *Tourism* is always statistically significant at 99% in all specifications, which means that the tourism economy can push towards higher rates of recycling, but the magnitude of the coefficient prevents us from giving this variable a relevant economic role for the recycling rate (the coefficient is a five-digit number). The effect of the household size (*HH size*) is negative, as expected, but the estimated coefficient is never significant.

Household final consumption is positive and strongly significant in all models (99%). It is interesting that the non-linear effect of household final consumption is confirmed since the quadratic value of the variable (*Consumption*^2) is negative, which indicates a decreasing marginal effect of household final consumption on recycling activities along an inverse U-shaped curve. Although the magnitudes of the two coefficients are low, the effect of final consumption on the recycling rate has to be considered in terms of the marginal increase in the recycling rate due to each additional euro spent on average on consumption by households in the EU27: each additional euro spent on consumption by an average EU27 household increases the recycling rate by 0.005%; when considering the non-linearity, the negative effect of the quadratic term on the marginal increase in the recycling rate due to consumption activities is negligible (8-digit coefficient).

All other controls showed no statistical significance. They contributed to the correct specification of the econometric models, but we do not comment on them.

Among the waste policy variables, all yearly dummies used for waste policies are statistically significant in almost all specifications. The coefficient of the WFD is negative, indicating that in 2008, a slight reduction in the recycling rate occurred, whereas in 2015, with the introduction of the CEAP, and in 2018, with the revision of the waste targets, the recycling rate increased since the coefficients are all positive. It should be noted that the variables we used are basically dummy variables for the years 2008, 2015, and 2018, in which the three policies were introduced; therefore, those results should be taken cautiously since there may have also been other aspects affecting the recycling rate occurring in that specific year. Clearer evidence on the effects of waste policies should be further studied using specific econometric analysis (e.g., difference in differences, matching estimations).

Nevertheless, additional evidence of the effects of waste policy implementation can be derived from the analysis of the coefficients of the time trends we used for the years between the introduction of each policy: they show stable signs in all specifications and are statistically significant in many of them, thus being consistent with the results of the policy-introduction dummies.

These trends can be meaningful in interpreting the results for policies, because the actual effects of the introduction of waste policies are subject to lags and their possibly successful implementation in each country occurs with a delay, even just technical in nature, usually displaying their effects only in later years. These time lags can also reflect the quality of national and local institutions, as well as the possible financial constraints to investments in industrial capacity for waste management and recycling.

The first trend (2005–2007) is negative in model 1 and 2, confirming that in the years before 2008, the trend of *RR* was in slight decline. After the introduction of the WFD in 2008, the *RR* started to increase as it is shown by the positive coefficient of trend 2 (in model 1 and 2). This highlights that the WFD may have positively influenced the recycling activities in the EU27 countries. The most interesting effects are shown by trends 3 and 5, which are always statistically significant at 99% with a positive effect on *RR*, suggesting that both the introduction of the first CEAP and the 2018 revision of waste targets produced positive effects on recycling activities in the years following their introduction. Considering the marginal contribution of the first CEAP in the year following its first introduction, the *RR* increased by 2.53% in 2016 and 2017, respectively, while the revision of the waste targets further increased the *RR* by 3.5% in 2019 and 2020, respectively (see Model 4).

5. Discussion

Our findings confirm, with a different approach, the results of Rompf et al. [16], Harring et al. [18], and Argentiero et al. [19], who highlighted that institutional quality (i.e., good government) can increase waste recycling performance. This suggests that good and solid institutions can improve performance in solving large-scale collective action problems in public goods management such as the recycling of waste and other environmental issues. From our findings, it is clear that a higher level of institutional quality can increase the recycling performance in the EU27 countries. This might depend on a better organization of waste management, like collection, which is within the competences of the public sector in many countries, a higher level of control, punishment, coercion, and other incentives which can guide individual decision making toward cooperative actions, thus helping in solving collective action problems.

While the positive influence of institutional quality on recycling activities is fairly straightforward to understand, our findings on the effect of institutional trust are less clear. Our results indicate that institutional trust has a negative impact on the rate of recycling, suggesting that for a high level of institutional quality, institutional trust can reduce citizen participation in collective action problems, potentially limiting the social outcome when social dilemmas for the provision of public goods are at play.

Other authors have analyzed the effects of institutional trust on recycling activities, finding results that are different from those of our analysis. Sønderskov [47] found a positive effect of institutional trust as an increasing factor of social trust on recycling behavior. The focus of the author was more related to social trust, while the role of institutional trust was deepened in his further studies but not in relation with recycling attitudes. Rompf et al. [16] found a positive relationship between institutional trust and recycling behavior (i.e., attitude toward recycling); they also found a mediating negative effect with private benefits in recycling (i.e., a higher level of institutional trust reduces the personal benefit to compensate personal recycling costs) and a positive mediating effect with the cost of recycling (i.e., the effect of recycling costs on recycling attitudes decreases with an increasing level of institutional trust). The authors clearly argue that institutional trust, considered as trust in the reliability, effectiveness, and legitimacy of public institutions, has an overall positive effect on recycling activities, and conclude saying that improving the quality of institutions and the citizens' perception of them as trustworthy can increase individual incentives to solve the collective action dilemma applied to waste recycling activities [16].

Instead, our findings are in line with the hypothesis of Harring et al. [18], who argue that institutional trust is not just positive in influencing the cooperative actions of individuals, but conversely, in high-trusting societies, above certain levels of trust, a continuous positive relationship between institutional trust and recycling appears to be far from obvious.

The authors suggest that a strong faith in the state's ability to solve complex issues may make personal contribution to be perceived as less important, which may lead to uncooperative behavior at a certain level, the latter depending either on a rational decision not to cooperate or just on individual passivity.

The overall outcome is that citizens in high-trusting countries, where the quality of institutions is high, can reduce their personal contribution to collective actions in the presence of large-scale social dilemmas. The authors clearly stated a very interesting and plausible hypothesis, but in their empirical analysis, they did not find any evidence of that [18]. The results of our analysis confirm the argument of Harring et al. [18]: our results indicate that for a high-quality institutional environment, as in most EU27 countries, the effect of institutional trust on recycling participation can be negative. This is also confirmed when we combined the *IT* variable with the dummies of the highest and lowest deciles of the distribution of waste generation per capita, with, respectively, a positive and non-significant effect for a high level of waste generation per capita and a statistically significant negative effect for a low level of waste generation per capita.

This combination of results can suggest that, in achieving higher rates of recycling, administrative capacity, as reflected in the variable *QI*, is important, but public trust in institutions, as reflected in *IT*, due to the high level of quality achieved by the institutional system, may reduce the individual contribution to large-scale collective actions. In other words, the quality of institutions, and thus good administration, may be a sufficient condition for good recycling performance, but as discussed above, trust in institutions may reduce the overall effect of good administration on waste recycling.

Furthermore, our results highlight the effectiveness of waste policies introduced by EU institutions. In fact, our trend analysis shows that after the introduction of the WFD and CEAP, the average rate of recycling increased in the countries under study in the years after the implementation of these new waste policies.

Therefore, our analysis confirms that increasing the quality of institutions can improve environmental sustainability in a problem area, like waste management, in which the active contribution of citizens is fundamental for achieving the policy objectives. EU policies can be important in driving national policies in terms of sustainability and circularity, but strong and efficient national institutions can positively affect citizen participation to achieve high recycling performance of the EU27 countries. Then, improving good governance may increase the perceived quality of citizens helping to overcome a social dilemma which prevents circularity. This may apply to other environmental sectors in which citizen participation is important to achieve sustainability (e.g., pollution, climate change, and adaptation strategies), and further studies may also investigate in that direction. Considering potential individual defections deriving from a curvilinear institutional trust, when institutions are good, in order to improve citizen participation to collective actions, EU member states should work together to increase the level of individual cooperative action by increasing the pro-environmental behavior of citizens using both social stimuli (e.g., social involvement in the ecological transition process) and economic incentives (e.g., by using financial stimuli, such as pay-as-you-throw tariff schemes). We analyzed recycling activities, but as pointed out by Fellner et al. [65], recycling does not consider the effective reuse of secondary materials within a country, and therefore further studies should consider more comprehensive measures of circularity in which the reuse of goods and materials is also considered.

6. Conclusions

Looking at recycling as a large-scale collective action problem, in this paper, we analyzed the effect of the quality of institutions and the trust in institutions on recycling rate dynamics in EU countries. Our study uses cross-country data from Eurostat and WGI for a fifteen-year timeframe (2005–2020), with a panel data econometric approach.

Our findings support previous survey-based evidence developed at the micro and local level, in which it was highlighted that the quality of institutions can increase the social participation of citizens in recycling activities [18,19]. In our framework, the significance of institutional quality also suggests the role of good administration in providing sufficient waste collection and management facilities and infrastructure to increase recycling performance. On the other hand, our findings do provide evidence of the possible negative role of institutional trust on the recycling rate at country level, resulting from non-linear dynamic interactions between the quality of institutions and the trust in institutions. The quality of institutions and institutional trust are dynamically linked (i.e., the quality of institutions increases institutional trust) [43], but they can have two different and opposite effects on recycling. Further studies should consider measures to better disentangle the link between the two processes, as well as designing policies able to compensate for the decreasing individual participation in large-scale collective actions due to the high level of institutional trust with a high quality of institutions, both in general and for the environment.

Similarly, when considering the impact of specific EU policies within the timeframe of our analysis (WFD and CEAP), we see that they have been significant for increasing the recycling rate at the EU27 level. The stimulus from specific policies can thus be seen as a driver of recycling, as emerging from other analyses, but it is mainly because policies trigger processes that call for the work of appropriate institutional and socio-economic environments to achieve the policy-desired results. In a way, strong waste and recycling policies, while activating significant changes in waste management and circularity, cannot be effective if they do not find appropriate institutional and administrative systems in the implementation phase. Given that the latter is mainly a national or local matter, and the processes leading to good institutions are slow and systemic in nature, the design of EU waste and recycling policies should pay more attention to a range of enabling factors beyond ambitious targets and detailed regulations, like measures aimed at creating better markets for recycling and reuse, and a better waste management infrastructure [30].

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Article

Policies as Drivers for Circular Economy in the Construction Sector in the Nordics

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Abstract: A circular economy (CE) represents the key alternative to the linear 'take-make-consume-dispose' economic model, that still predominates in the construction sector. This study investigates how policies support CE-focused businesses in the construction sector in the Nordics. A literature review, the creation of a database, a review of Nordic actors with a CE focus, and targeted interviews with actors across the value chain of the construction sector in Denmark, Finland, Norway, and Sweden enabled us to benchmark the CE policy landscape and assess how CE policies at different levels support CE business models in the construction sector. The results show that the construction sector is well represented in the CE policy frameworks and that many business opportunities are created when national and local policies are put into practice. The implementation of policies is mainly done via three key concepts, i.e., planning, requirements for sustainable constructions, and requirements for public procurement. It can be concluded that policies are drivers for the implementation of a CE and support CE business models in the Nordics.

Keywords: construction sector; circular economy; policies; recycling; reuse

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1. Introduction

In the past, and still today, the construction industry practices a non-sustainable, linear economic model, based on the idea of "take, make, dispose of" [1]. The linear model does not support constructions and elements being deconstructed and reused, but they become obsolete at the end-of-life of the building [2]. The linear model assumes that natural resources are abundant, but now the world is in some cases exceeding the planetary boundaries, showing the need for a transition to a circular economy (CE) [3].

Construction and demolition waste (C&DW) accounts for more than 30% of the waste generated in the European Union [4]. Today, the recovery rate of mineral C&DW (excluding waste soils) is rather high in all the Nordic countries (especially Denmark and Finland) [5]. However, high recovery rates are, to a large extent, based on a high degree of backfilling or low-grade recovery, such as using recycled aggregates in road sub-bases (downcycling) [3].

The transition to CE requires a change in both attitudes and the core structure of an industry [6]. Much is already known about the drivers and barriers for implementing the changes. Drivers and barriers related to recycling C&DW have been presented by, e.g., Williams 2020 [7], Wahlström et al., 2020 [3], Wahlström et al., 2019 [8], Bio by Deloitte et al., 2017 [9], Kirchherr et al., 2017 [10], Miljøstyrelsen 2019 [11] and previous European Union (EU) funded projects (EU HISER [12]; EU IRCOW [13]). The key barriers presented in these studies are related to the design and construction of buildings reusing materials and components, and recycling waste materials. The CE business models of the construction sector have been presented in earlier Nordic studies (Høibye & Sand 2018 [14]; Munck-Kampmann et al., 2018 [15]; Alhola et al., 2017 [16]). In these studies, policies have been identified as a key driver by setting the recycling targets for the sector.

In order to speed up the transition to a CE in the construction sector, more knowledge is needed on how companies can be supported in practice. There is limited literature on how companies with a CE business model benefit from the current policy framework and which policy instruments are seen by the companies as advancing their activities.

This study aims to understand the policy landscape and the role of policies in the transition toward a CE in the construction sector in the Nordics. More specifically, the objectives of the study were (i) to benchmark the national and local CE policy framework in the Nordic countries and investigate whether the construction sector is addressed, (ii) to build a database of CE actors along the circular value chain in the construction sector in the Nordics, to (iii) review actors with a CE business idea to identify links to national and local policies, (iv) to identify key drivers and barriers related to the successful implementation of CE business models, and finally (v) to evaluate if the national and local CE policies support the transition to a CE in the construction sector in practice.

The article is structured as follows: The introduction section describes the status and presents the knowledge gap of the field of CE in the construction sector. Additionally, the objectives of the study are presented in the introduction. The background section describes the lifecycle value chain of the construction sector, as well as the European CE policy framework, and how the literature presents the impact of policies on the operational environment in CE actors of the construction sector. The materials and methods section presents the CE policy framework in Denmark, Finland, Norway, and Sweden, the CE criteria used for benchmarking CE activities in this study, and also the evaluation criteria for selecting companies for identifying the links to policies, drivers, and barriers related to the business model. The results section contains the findings of the analysis on how the policies influence the implementation of CE concepts at different levels in the Nordics. Finally, the discussion section concludes the article with some remarks related to the methodology and results presented in previous sections.

1.1. Background

CE represents the key alternative to the linear 'take-make-consume-dispose' economic model, that still predominates in the construction sector [17]. The Ellen McArthur Foundation defines CE to be 'restorative and regenerative by design, aiming to keep products, components, and materials in a closed loop and at their highest value at all times, also distinguishing between the technical cycle (finite materials) and biological cycle (renewable materials)' [1]. The CE in the construction sector is presented from a material perspective by Afshari and Górecki [18], where after the end-of-life building materials should be reused and their components and parts deconstructed, to act as material banks for new buildings, keeping the components and materials in a closed loop.

When closing the loop, all stages of the value chain play an important role; from design to end-of-life. C&DW is generated throughout the life cycle of buildings, also indirectly via the planning and design phase; when there is a lack of consideration on waste management and waste reduction in earlier phases of a project, it will reflect the total waste generation during the whole life cycle [19]. Most C&DW is generated at the end-of-life, since most building materials and components do not have a potential for reuse [20]. This study considers the five stages of a building's life cycle used by the European environmental agency [17], i.e., (i) recycling and product manufacture; (ii) design; (iii) construction; (iv) use and maintenance; and (v) end-of-life and demolition.

Wahlström et al. [21] defines the key features of the five stages of the value chain as follows: (i) the design phase facilitates sustainable material use, maintenance requirement, easy change of intended use, and expected lifespan, (ii) the construction phase is key to material efficiency and construction waste management, (iii) the use and maintenance phase determines the lifespan realization, (iv) the end-of-life and demolition phase determines the fates of the generated waste materials, and (v) recycling and the production of construction materials and products closes the material loop of the construction sector.

1.2. The European Policy Framework

The basic principles and general ambitions for CE in the construction sector are defined in the European CE policy framework [22–24]. EU legislation and policies are transposed into national legislation and policies, thus forming the basis for the CE policy framework in EU Member States. EU policies set the framework both for recycling targets for waste [22] and for market demand for secondary materials [23].

The first Circular Economy Action Plan (CEAP) of the EU defines construction and demolition as a priority area in the EU for closing the material loops and promoting a CE [24]. The second CEAP of the EU calls for improved recyclability, but also for the use of secondary materials in products [23]. The ambition for increased recycling is transposed into the revised Waste Framework Directive (WFD 2008/98/EC, amended 2018/851) by setting a mandatory target for the recovery of C&DW of 70 per cent as of 2020 [22].

The European Green Deal lays down the key framework for the policies of the construction sector [25], and the Renovation Wave states key initiatives to, e.g., increase reuse and recycling in the construction sector [26]. Furthermore, the second CEAP presents initiatives to propose minimum mandatory green public procurement (GPP) criteria as a means to enhance circularity in the EU, as well as key principles for the construction sector to increase material efficiency and promote CE [23].

Aiming for sustainability in the building sector may increase recycling, as materials with recycled content are often given credit in environmental rating protocols. Examples of well-established protocols are: Level(s) from the European Commission [27], the Building Research Establishment Environmental Assessment Method (BREEAM) from the UK's BRE [28], and the US Green Building Council's Leadership in Energy and Environmental Design (LEED) [29]. The protocols can be used by investors, designers, general contractors and real estate operators for proving the sustainability of a building.

Achieving CE targets in waste management is often measured based on the recycling rate, which is calculated as the ratio of recycled waste to the generated waste [30,31]. There is no distinction between preparation for reuse, high-grade recycling, and downcycling (including backfilling) [30]. The Waste Framework Directive sets a target of recycling 70% (by weight) of non-hazardous construction and demolition waste [22]. By 2024, the Commission shall consider material-specific targets for key streams of C&DW [22]. A recycling target for an entire industry creates incentives to recycle materials that have a large impact on the recycling rate and risks reducing the incentives to recycle materials that have a small impact but may be more valuable [21].

1.3. Policy Impact on the Operational Environment

Local CE drivers are created through setting targets and responsibilities in local strategies, by formulating CE guidelines and by setting specific requirements for construction projects. Local policy documents are often a continuation of the national policy framework with similar targets, often including more detailed practices and responsibilities for reaching the targets. Local CE policies are based on local needs and local prospects, aiming to have a local impact, but also to contribute to reaching the targets set by national and EU CE policies. [32] Kirchherr et al. (2017) identifies four key barriers to the CE, i.e., regulatory, culture, technology, and market barriers [10]. However, the same study also identifies policy-makers as the key actors in breaking the barriers and facilitating the transition to a CE via CE-friendly policies.

Recycling targets for C&DW are set both in the Waste Framework Directive [22], transposed to the national legislation or the waste management plan of the Nordic countries [33–36]. Recycling targets are a key policy for increasing recycling, but also for the use of secondary raw materials and closing the material loop [14–16]. Policies can influence recycling rates via, e.g., taxes for landfilling, taxes on virgin materials, encouragement of

GPP, end-of-waste criteria, and extended product responsibility or product ownership, supporting the attaining of recycling targets, and other CE activities as well. [3]

Related to recycling and reuse, construction products containing recovered materials need to comply with product requirements, which do not differentiate between virgin and recovered materials. The Construction Products Regulation (305/2011/EU) requires that all construction products put on the market be CE-marked [37], requiring full knowledge of the material content. This can be hard to acquire for waste feedstock, which is considered one of the key barriers for these activities [14].

Green public procurement (GPP) has a significant leverage for addressing environmental challenges. The European Commission (EC) has supported this strategic approach by publishing a Communication [38], a GPP handbook [39], and EU GPP criteria to support sustainability in public tendering [40]. The EC has identified the construction sector as a priority sector for GPP; a sector where GPP can significantly contribute to improving the environmental performance [38].

GPP can facilitate sustainability in construction by promoting closed material loops via the reuse, remanufacturing, and recycling of products and materials, also avoiding their harmful environmental impact. GPP can set requirements on the use of waste-derived materials and thus promote the markets for secondary raw materials and reusable construction products. In demolition, GPP requirements on the reuse and recycling of construction and demolition waste in new construction products will boost the market for recovered materials. [16] The public sector is the key property developer in the Nordics [14], and by using GPP criteria, the public sector can have a great impact on the competitiveness of CE-focused companies [16].

As an example, to support innovative and sustainable public procurement in Finland, the Finnish Government launched KEINO, a competence centre for sustainable and innovative public procurement. KEINO aims to improve the effectiveness and quality of public procurement and public services [41]. In Finland, a guideline for Public Green Procurement in demolition was published in 2019 by the Finnish Ministry of the Environment, intended to be used by municipalities to improve the recycling of C&DW arising from the demolition of public buildings [42].

2. Materials and Methods

2.1. CE Criteria and Indicators

CE criteria presented in Table 1 are employed to enable the identification of CE policies and business models. CE criteria also enable benchmarking policies in relation to CE focus to give an overview of the CE policy framework in the Nordics. The indicators presented in this study are chosen and modified to best fit the construction sector and excludes topics related to investments, markets, and trade, with a focus on material streams in the construction sector. The CE indicators presented in Table 1 are collated from indicators used by the European Commission [43], EUROSTAT [44], and Moraga et al. [45].

2.2. Policy Framework

In order to set the scene and benchmark the Nordic countries, national strategies for CE were shortly reviewed to compare the national policy framework in the Nordics, as well as to check the transposition of EU's CE policies into national policies in the Nordics. Although Norway is not a Member State of the EU, many policies are transposed from the European policy framework into Norwegian policies and legislation.

The CE policies in the Nordics aim to transpose the European CE policy framework. Waste management and waste prevention plans are mandatory, as stated in the Waste Framework Directive [22]. Finland, Norway, and Sweden have integrated the Waste Prevention Plans into the Waste Management Plans [46–48]. Other strategies with a CE relevance or relevant to the construction sector and CDW represent several different types of documents. The national CE policy frameworks were examined through 24 policy documents, such as strategies and roadmaps. The list of policies is presented in Table 2 in the results section.

Table 1. CE criteria and indicators used for the assessment of the CE focus of policies and business models.

CE Criteria	CE Indicator
1. Reducing use of resources	1.1 Sharing of facilities/adaptive use of facilities prevents the need for additional buildings
	1.2 Increasing the utilization rate of buildings to prevent the need for additional buildings
	1.3 Choice of material or product for options requiring less material for the same performance
	1.4 Saving of materials in production, optimizing cut-offs
	1.5 Reducing material consumption at construction site by using products pre-cut to size
2. Waste prevention	2.1 Extending life span by renovating old buildings instead of building new ones
	2.2 Preventing premature demolition by changing the use of a building 2.3 Repair and maintenance to prevent premature demolition
	2.4 Use of demountable construction components enabling the reuse of construction components and reconstruction of buildings
3. Increasing recycling rates	3.1 Sorting, separating, and recycling activities 3.2 Enabling recycling through selective demolition 3.3 Use of waste-derived/recycled materials in new products 3.4 Use of waste-derived materials in construction
4. Use of biobased/renewable materials	4.1 Biobased construction materials or products, such as wood, cellulose, cotton
5. Use of recyclable materials	5.1 Using materials that are recyclable at end-of-life 5.2 Enabling clean dismantling and recycling at end-of-life by not mixing materials at the installation phase

Table 2. The national CE policy framework in the Nordic countries. Finland and Norway have integrated the Waste Prevention Plans into the Waste Management Plans. Other strategies with a CE relevance or relevant to the construction sector and CDW are not specifically defined and can represent several different types of documents, and thus the list is not exhaustive.

Focus of National Strategies	Focus on the Construction Sector *		CE Criteria Focus **				
	1.	2.	1.	2.	3.	4.	5.
Denmark							
National Waste Management Plan [49,50]	x	x			x		
National Waste Prevention Plan [51]	x	x		x			
Other strategies with a CE relevance or relevant to the construction sector and CDW							
• Strategy for circular economy [52]	x	x			x		
• Strategy for intelligent public procurement [53]						x	x
• The Government's action plan on plastics [54]		x		x	x		
• Strategy for digital construction work [55]	x	x			x		
Finland							
National Waste Management Plan [46]	x	x		x	x		
Other strategies with a CE relevance or relevant to the construction sector and CDW							
• National circular economy programme [56]	x			x	x		x
• Material efficiency programmes [57,58]	x	x	x	x	x		
• Demolition guidelines [42,59]	x			x	x		
• Plastics roadmap [60]	x	x	x		x		
• Wood Building Program [61]	x	x				x	

Table 2. *Cont.*

Focus of National Strategies	Focus on the Construction Sector *		CE Criteria Focus **				
	1.	2.	1.	2.	3.	4.	5.
Norway							
National Waste Management Plan [47]	x	x		x	x		
Other strategies with a CE relevance or relevant to the construction sector and CDW							
• National action plan for construction and demolition waste 2017–2020 [62]	x	x		x	x		
• Circular economy recommendations from the industry [63]		x			x		
• Governmental CE policy framework [64]			x	x	x	x	x
Sweden							
National Waste Management Plan [48]	x	x		x	x		
Other strategies with a CE relevance or relevant to the construction sector and CDW							
• Circular economy strategy [65]	x			x	x	x	x
• Resource and waste guidelines for construction and demolition [66]	x	x	x	x	x		
• Roadmap to a fossil free competitiveness-construction and civil engineering sector [67]	x	x	x	x	x		
• Focus on wood construction [68]	x	x				x	

* 1. A specific section dedicated to construction and demolition waste (CDW); 2. Objectives or targets with respect to the construction sector and/or CDW. ** 1. Reducing the use of resources; 2. Waste prevention; 3. Increasing recycling rates; 4. Use of biobased/renewable materials; 5. Use of recyclable materials.

The assessment of local policies aimed to facilitate the understanding of how national policies are put into practice on a local level. The policies examined were not explicitly CE strategies, but represented the concept of sustainability and CE. The policy documents were benchmarked against the CE criteria presented in Table 1 to confirm their CE focus. CE policies on a local and regional level were examined through 18 policy documents, such as strategies, roadmaps, and networking activities. The list is found in Appendix A.

2.3. Identification of Links to National and Local CE Strategies

A database was created identifying actors of the Nordic construction sector with a CE focus in their business model. The database presents a short description of the business idea of each actor, as well as information on the life cycle phase and CE focus. The database is expandable and updateable. For this assessment, 113 actors from Denmark, Finland, Norway, and Sweden were identified by the authors and represent companies with CE activities in the construction sector, as well as actors actively networking in CE events such as attending conferences and expert group meetings in the construction sector in the Nordics. The database is not exhaustive and can be easily expanded.

The companies of the database have been characterized with respect to life cycle phase and CE criteria to identify where the key actors are focusing their activities. The representation of the five stages of a building's life cycle used by the European Environmental Agency [17] is illustrated in Figure 1, i.e., (i) recycling and product manufacture; (ii) design; (iii) construction; (iv) use and maintenance; and (v) end-of-life and demolition, where one actor can represent more than one stage of a builing's life cycle. The representation of the CE criteria as presented in Table 1, where one actor can focus on more than one CE criteria, is illustrated in Figure 2.

To better understand the links between policies and CE business models, 14 actors from the database representing different stages of the value chain were further assessed to identify links to national and local CE strategies. Actors were chosen from all four Nordic countries to facilitate comparison among the Nordic countries, and selected based upon the relative strength of the business idea focus on CE (as presented in Table 1). Based on these criteria, 14 actors were chosen for further analysis of the links to national and local strategies.

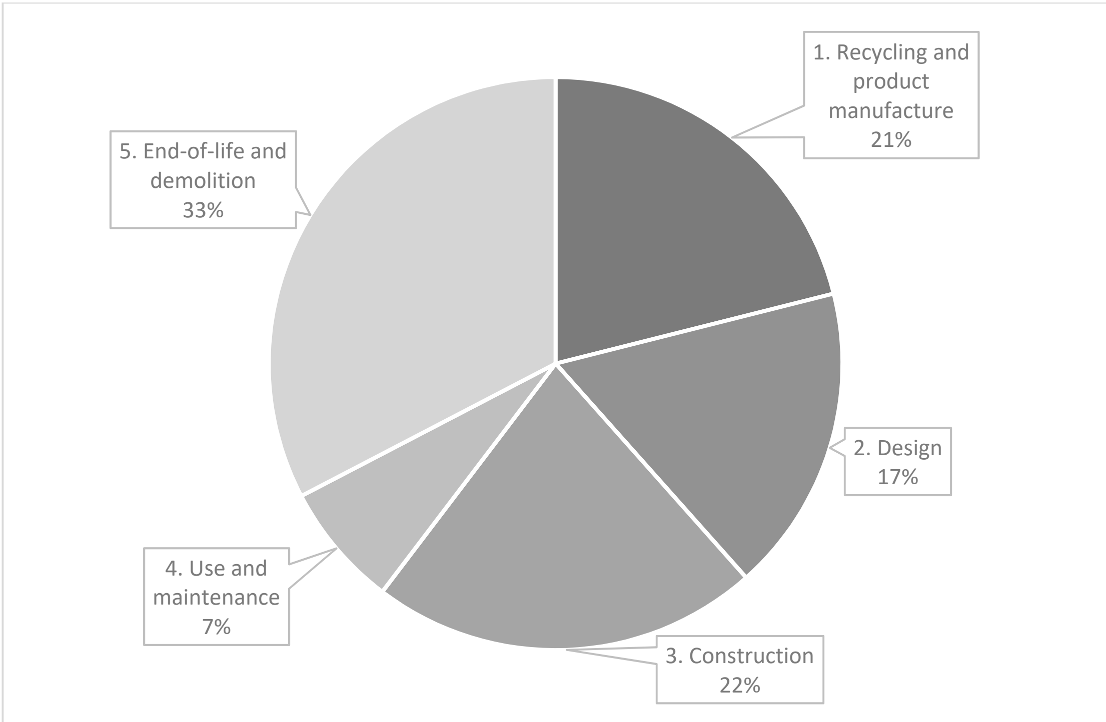

Figure 1. The representation of the companies of the database in respect to the life cycle phase. The database contains 113 companies, and one company can represent more than one stage of a building's life cycle.

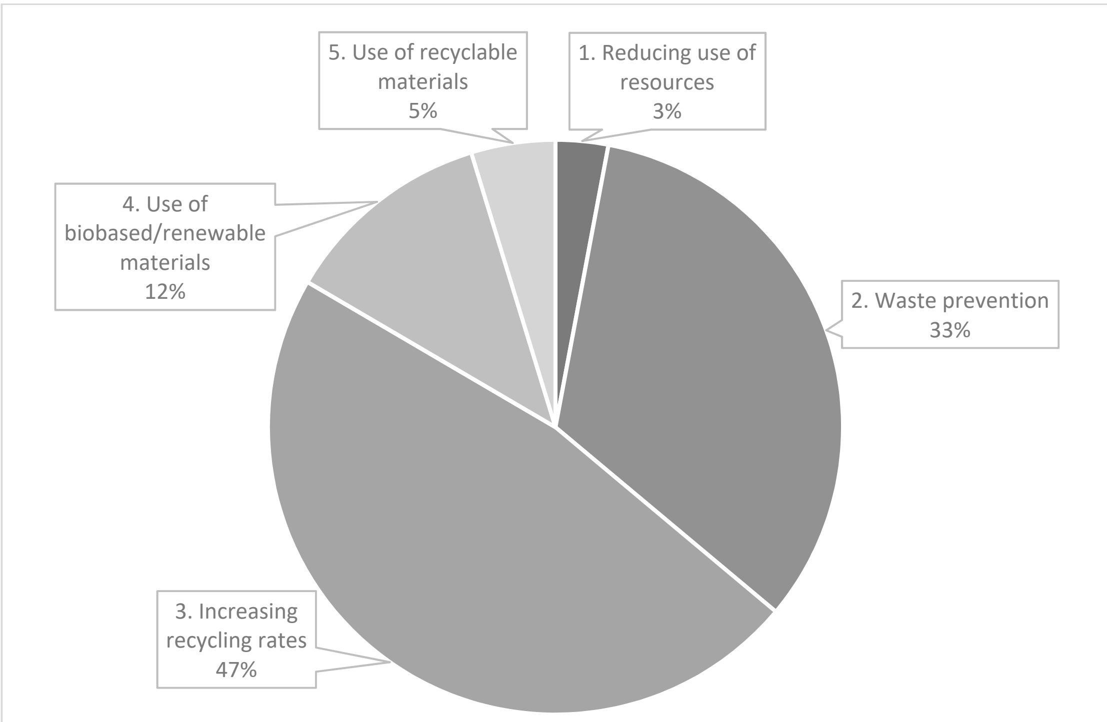

Figure 2. The representation of the companies of the database in respect to the CE criteria. The database contains 113 companies, and one company can address more than one CE criteria.

In order to gain further understanding of the barriers and drivers to the implementation of CE business models in the construction sector, in-depth interviews were conducted with 10 of the companies that had been reviewed. In the interviews, links to national and local strategies were identified, and the key barriers for the business models were also identified. Finally, the interviews aimed at exploring why the selected companies are successful in overcoming these barriers and what the role of different level policies and strategies is for their business models, aiming to evaluate if the policies support the transition to a CE in the construction sector in practice. In all interviews, one or more representatives of the companies were present. The interviews were structured to focus on how national and local policies act as barriers to, and drivers of, the specific company in their business. All interviews followed a similar protocol, although conducted by different members of the team.

3. Results

3.1. Policies

The review of the national CE policy framework in the Nordic countries shows that the construction sector is well represented in CE policies on a national level, both in the mandatory waste management and prevention plans, as well as in other strategies. All countries present objectives or targets for the construction sector in different level policies. Furthermore, the study showed that the national policy scene in all countries was somewhat similar in respect to target setting and objectives. The benchmarking of the national policies is illustrated in Table 2. Finland, Norway, and Sweden have integrated the Waste Prevention Plans into the Waste Management Plans [46–48]. Other strategies with a CE relevance or relevant to the construction sector and CDW can represent several different types of documents, and thus the list is not exhaustive.

The evaluation of local policies found that the transition to a CE is well presented in the local policy framework in the Nordics—mainly incorporated into a general municipal strategy, but also as free-standing strategies for sustainability and CE. The list is found in Appendix A. Local strategies often included more detailed practices and responsibilities for reaching the targets, where national policies were more general. Local strategies and guidelines can also entail a more practical follow-up system for ensuring compliance with the set targets.

It was found that municipalities use mainly three key policies for supporting CE business models and meeting their CE targets, i.e., planning, requirements for sustainable constructions, and requirements for public procurement. As the planning and permitting of construction and demolition activities are under municipal control, local strategies and guidelines give the municipalities a good tool for creating incentives to move towards more circular business models. Some municipalities are actively involved in construction activities, allowing them to highly impact project details in construction via GPP.

The study found that municipalities set requirements on CE solutions in construction with a high focus on end-of-life activities. The requirements of the demolition phase focus on resource mapping prior to demolition, the use of selective demolition, as well as the reuse and recycling of waste. CE solutions in the construction phase focus mainly on the use of materials that are recyclable, dismantlable, and also on the documentation of material content, e.g., in material passports, all with an emphasis on forthcoming end-of-life activities.

Good examples of steering via policies are the City of Helsinki and the City of Copenhagen. Helsinki uses public procurement in construction combined with planning to set requirements supporting the local sustainability strategy. In the "The Carbon-neutral Helsinki 2035 Action Plan", the city sets clear targets for emissions reduction and defines clear measures to reach the set targets [69]. In 2020 the City of Copenhagen decided that Byggeri København, a major developer for Copenhagen, would address CE in all construction projects. The City of Copenhagen has developed guidelines to support and facilitate the implementation of the local CE strategy and setting requirements for sustainable constructions [70].

3.2. Identification of Links to National and Local CE Policies

Based on predefined criteria, 14 actors were chosen for a deeper analysis of the circular value chain of the construction sector. The actors chosen in this report all have a CE focus in their activities and contribute to a rethinking of the traditional value chain. The actors were characterized with respect to the life cycle phase, and it was found that most activities were related to the construction and end-of-life phases. The actors' link to the policies, the position in the value chain of the construction sector, and the CE criteria in focus are presented in Table 3. The business focus of the actors are presented in Appendix B.

Table 3. Assessment of the actors in response to strategies, value chain, and CE criteria.

Actor nr.	Identified Link to Policy Document	Phase of Value Chain *					CE Focus **				
		1.	2.	3.	4.	5.	1.	2.	3.	4.	5.
1.	National CE policy Not linked to local policy level			x		x		x	x		
2.	National waste management/prevention plan National CE policy Not linked to local policy level			x		x		x	x		
3.	National waste management/prevention plan National CE policies Local CE strategies	x	x	x		x		x	x	x	
4.	National waste management/prevention plan Not linked to local policy level	x				x			x		
5.	National waste management/prevention plan Not linked to local policy level	x		x		x			x		
6.	Indirectly linked to national CE policies Local CE strategies		x	x	x	x		x	x		
7.	National waste management/prevention plan Local CE strategies			x		x		x	x		
8.	National waste management/prevention plan National CE policy Not linked to local policy level					x			x		
9.	National waste management/prevention plan National CE policies Not linked to local policy level		x	x	x		x	x		x	
10.	National waste management/prevention plan National CE policy Not linked to local policy level	x		x		x			x		x
11.	Indirectly linked to national CE policies Local CE strategies			x	x	x		x	x		
12.	National waste management/prevention plan Not linked to local policy level			x		x		x			
13.	National waste management/prevention plan National CE policy Local CE strategies			x		x		x	x		
14.	National waste management/prevention plan National CE policy Not linked to local policy level			x		x		x	x		

* 1. recycling and product manufacture; 2. design; 3. construction; 4. use and maintenance; 5. end-of-life and demolition; ** 1. reducing use of resources; 2. waste prevention; 3. increasing recycling rates; 4. use of biobased/renewable materials; 5. Use of recyclable materials.

Most of the reviewed actors had a CE focus on waste prevention and recycling. Only one company had a focus on the reducing use of resources, one had a focus on the use of recyclable materials, and two on the use of biobased/renewable materials. This shows that the CE focus of the reviewed actors is strongly on waste and less on materials and products. Actors 3, 9, and 10 have a product-minded focus: 3 and 9 using wood as raw material; 9 focusing on optimizing material use and reducing the use of resources; and 10 closing the loop using recyclable raw materials.

Waste prevention is on the top of the waste hierarchy [22], and a key CE criterion. Several of the actors focus on the reuse of building materials and the prevention of waste generation. National waste management and prevention plans and CE policies emphasize the importance of waste prevention.

Recycling was represented in all business models except two, being the most common CE criteria for the actors. Recycling represents a well-implemented CE business model and is also well represented in local and national CE policies (see Table 2 and Appendix A).

3.3. Drivers and Barriers for CE Business Activities

Ten focus interviews were conducted to increase the knowledge on how policies have supported the establishment of businesses with a CE focus. The evaluation of local and national policies clearly illustrated how policy instruments can drive CE initiatives. This was also highlighted during in-depth discussions with company representatives, who noted how particular national and local CE policies incentivized CE actions and supported their own business model. The interviews confirmed the results of the assessment presented in Table 3, accenting that the transposing of national recycling targets into local CE strategies with a subsequent implementation through GPP requirements for public construction projects provides a leverage for companies involved in recycling and the utilization of secondary materials.

In the interviews it was highlighted that GPP is a key driver for CE business models. GPP can promote recycling and the use of secondary raw materials and reusable construction products. GPP is needed both in construction and in demolition. Identified barriers related to GPP criteria for secondary raw materials related to the market's readiness; some difficulties were identified related to the supply of high-quality secondary materials, complying with the requirements of both the property developer and the contractor. The lack of information on how to set realistic GPP requirements for recycling and reuse options was highlighted in one interview.

Three interviews disclosed that there is often a lack of information among stakeholders on the availability of recovered and reusable materials and components. There is a need to streamline the reuse processes to make the reusable products and recovered materials easily accessible. This requires, e.g., comprehensive reuse inventories and providing storage solutions. The logistics in dismounting products from buildings must be synchronized with the delivery for reuse. If not, the storage creates extra costs. To enable this, a better coverage of online digital marketplaces for a business-to-business exchange of waste and the production side-streams for this type of CE business models need to evolve.

The material availability is also presented as an important aspect to be considered. In one interview, it was highlighted that mineral waste cannot be transported far from the demolition site without increasing costs and environmental impacts.

The importance of the effective identification, sorting, and collection of building materials to support the security of supply was highlighted in two interviews. Dismantling reusable products, structures, and elements prior to demolition delays the demolition process and increases storage needs and demolition costs.

Doubts about quality (especially fluctuations in the quality of recovered materials) were highlighted in all interviews as one key barrier for recycling. Concerns about the quality of the waste, such as impurities and material degradation, and the potential presence of hazardous materials, such as paint and glues, may cause a safety concern for the recovered waste streams, especially if a tight quality-control system is not applied.

Construction products containing recovered materials need to comply with product requirements, which do not differentiate between virgin and recovered materials. In two interviews, the requirement of the CE-marking of construction products put on the market (as stated in the Construction Product Regulation [37]) was seen as a driver for businesses. Having access to the required data has enabled them to turn this hinder into a driver.

In all interviews there was a consensus that the main obstacle for the reuse and recycling of C&DW is economic, due to the price of secondary raw materials and used products often exceeding the price of virgin raw materials and new products (e.g., aggregate, wood, glass, and gypsum). In Finland, Norway, and Sweden, the abundance of wood and aggregate, in particular, limit the interest in recycling these materials. In two interviews, it was pointed out that landfilling is seen as a more cost-effective solution for the demolition company. In addition, there are extra costs from the sorting of the waste into a fraction that is clean enough to meet the quality demands of the producer of the secondary raw material.

The environmental aspects and reduced costs for waste disposal were recognized as incentives and drivers for increased reuse in all interviews. Still, in one interview, it was emphasized that the financial, social, and organizational barriers of reuse were found to be more difficult to overcome compared to the technical barriers. Awareness and competence in reuse must be increased throughout the value chain for reuse aspects to be considered earlier in the process.

In two interviews, the lack of numerical indicators for all CE criteria was considered a bottleneck. Achieving CE targets is often measured based only on the recycling rate, a numerical indicator used in waste management reporting. There are currently no numerical indicators for waste prevention, even if waste prevention highly supports the CE goals. It is unclear how to address the avoided waste generation, as there is currently no system to report waste prevention in environmental reporting.

One interview highlighted that digitalization is a key driver for circularity. However, digitalization and digital tools cannot stand alone, as they also depend on the stakeholders' acceptance and use of the tools to be effective. Digitalization may play an important role in supporting the flow of information and the traceability of waste, i.e., the origin and treatment of waste, which is crucial for the guarantee of safety and the quality of the waste.

While policies are key to raising awareness, they also need to be followed up by concrete initiatives that ensure implementation in practice. Two interviews highlighted the need for funding programs and initiatives that promote new business start-ups and other entrepreneurial initiatives for bringing ideas to the market.

The drivers and barriers identified in this study all relate to the business models of the companies that were interviewed. It can be concluded that all companies stated that the current policy landscape support, to some extent, their CE activities. The key drivers and barriers related to the successful implementation of CE business models identified in the interviews are summarized in Table 4.

Table 4. Summary of drivers and barriers identified related to the successful implementation of CE business models.

Topic	Driver	Barrier
Green Public Procurement (GPP)	Promotes recycling and the use of secondary raw materials and reusable construction products.	Lack of information on how to set realistic GPP requirements.
Material availability/security of supply		Supply and demand do not meet or the distances are too long. Dismantling delays the demolition process and increases costs.
Lack of information on forthcoming material availability		Dismounting must be synchronized with the delivery for reuse, otherwise storage costs will arise.
Doubts about quality		Concerns about the quality of the waste may cause a safety concern for the recovered waste streams.
Price of secondary raw materials		The price of secondary materials and products often exceed the price of virgin.

Table 4. *Cont.*

Topic	Driver	Barrier
Cost-efficiency of recycling		Landfilling is seen as more cost-efficient than recycling.
Lack of numerical indicators for all CE criteria		Lack of numerical indicators to report waste prevention in environmental reporting.
Digitalization	Supports the flow of information and the traceability of waste.	
Access to waste data and traceability	Full knowledge of material content enables compliance with product requirements.	
Reduced costs for waste disposal through reuse options	Reuse eliminates all costs related to waste disposal.	

4. Discussion

This article had the objective of finding if CE policies support CE business models and the transition to a CE in the construction sector in the Nordics. In previous studies policies have been identified as a key driver for CE in the construction sector by setting the recycling targets for the sector, but little is known about how the policies can support the transition in practice. Local CE strategies or roadmaps toward CE have just recently been published, and experiences from the field have not yet been published in the Nordic countries.

The benchmarking of the national CE policy framework in Denmark, Finland, Norway, and Sweden showed that the construction sector was well represented in CE policy documents and that the national policy scene in all countries was somewhat similar in respect to target-setting and objectives. This can, however, be a mirror effect from EU CE policies for the construction sector, which are well transposed into the Nordic policy framework. The study mainly reviewed the key objectives of the policy documents, excluding enforcement and follow-up mechanisms, which ensure implementation in practice. In order to better understand how policies are put into practice, the enforcement and follow-up mechanisms could be reviewed, possibly in the light of performance indicators, showing the relationship between policy follow-up and CE implementation.The companies reviewed to identify links to the policies, as well as the companies interviewed for the identification of drivers and barriers, showed an inclination towards construction and end-of-life activities in the value chain, as well as waste prevention and recycling activities indicating their CE focus. The uneven distribution throughout the value chain and CE focus is a result of where the CE activities of the construction sector are focused. The question remains as to whether the uneven distribution is a result of a policy landscape failing to support actors of the other phases of the value chain. Still, the uneven representation may be a bias, and forthcoming studies should emphasize either a better distribution, to correct this bias, or investigate the reason behind this bias.

Of the three key policies used by municipalities to facilitate the transition to a CE, i.e., planning, requirements for sustainable constructions, and requirements for public procurement, only GPP was mentioned in the interviews as a policy supporting the CE-focused businesses. This does not exclude the other policies from being efficient in facilitating the transition. Planning and requirements for sustainable construction are elements of an early planning stage, whereas many of the interviewed companies are active later in the value chain and identified policies supporting their activities or phase of the value chain.

In order to fully understand the impacts of policies focusing on activities earlier in the value chain, other types of analyses need to be conducted, such as a comparison of regions with differing approaches to facilitating the transition.

Digitalization was identified as a key driver for CE. Many of the identified barriers address problems that could be solved with the successful implementation of online digital tools. Tools supporting communication on supply and demand combined with digital marketplaces for a business-to-business trade of reusable products and recovered materials could remove barriers related to material availability. Tools supporting traceability would highly support improved access to waste data, removing barriers related to concerns about the quality of the waste.

However, it was stated that the price and availability of recovered and reusable materials and components create major bottlenecks for reuse and recycling. It was expressed that virgin materials are cheaper and more easily accessible than their recovered alternatives. As long as the process for reuse and recycling is not streamlined and these products are not easily accessible, the CE business models will only represent an exotic alternative to the modus operandi.

In the assessment of links between CE business models and policies, it was found that many business opportunities benefit from the national and local policy landscape. Thus, putting theory into practice via CE policies can indeed drive the transition to a CE in the construction sector.

The study showed that, today, CE actors in the construction sector represent construction and end-of-life phases with a strong focus on waste management, such as waste prevention, reuse, and recycling. It was found that these actors benefit from the national and local policy landscape, especially policies that are implemented via GPP requirements. Additionally, this study showed that many of the barriers identified by the actors are such that they can be overcome via the successful implementation of online digital tools for trade and supporting traceability.

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Appendix A

Table A1 shows the reviewed local CE policy documents with a section or targets dedicated to the construction sector.

Table A1. Reviewed local CE policy documents with a section or targets dedicated to the construction sector.

Country	Title and Reference	Key Focus Areas in Respect to Construction Sector	CE Criteria Focus *				
			1.	2.	3.	4.	5.
DK	Climate strategy and climate plan 2016–2020, Aarhus municipality [71]	Energy-efficient renovation of existing building stock, green transition, and sustainability in building projects.			x	x	
DK	Environmental and energy efficient construction in Aarhus municipality [72]	Requirements and recommendations for municipal building work, aiming to make buildings as sustainable as possible.		x	x		x
DK	Copenhagen Resource and waste management plan 2024 [73]	The plan presents initiatives related to the reuse of construction materials from the city's properties and cleaner recycling of C&DW.		x	x		
DK	Circular economy Handbook for the construction sector in Copenhagen [70]	Avoid using virgin non-renewable and non-recyclable raw materials, to become more resource-conscious and to increase the reuse and recycling of waste.	x	x	x	x	x

Table A1. *Cont.*

Country	Title and Reference	Key Focus Areas in Respect to Construction Sector	CE Criteria Focus *				
			1.	2.	3.	4.	5.
DK	Environment in construction and civil engineering 2016, Copenhagen municipality [74]	Environmental requirements to help implement a number of political strategies related to CE.		x	x		x
DK	Bormholm climate strategy [75]	The strategy presents goals for the building and demolition sector, e.g., the goal of renovating buildings sustainably by using sustainably produced materials or reused materials.		x	x		
DK	Bornholm waste strategy [76]	Transposing the Danish waste and CE policies into the national strategy. Including measures for construction waste.		x	x		
DK	Kolding kommune Waste management plan 2019-2024 [77]	The plan presents goals and activities related to the prevention and effective utilization of waste. With respect to C&DW, the municipality will upgrade the effort for increased sorting and removal of contaminated C&DW.		x	x		
NO	Oslo municipality as a leading environmental city [78]	One focus area is circular economy in buildings, aiming for emission-free and waste-free construction sites, increased emphasis on reuse and recycling and improving management of existing building stock.		x	x		x
FI	Carbon neutral Helsinki 2035 [69]	In the strategy, Helsinki presents 58 actions to achieve emissions reduction targets through construction and buildings.		x	x	x	
Fi	Turku Climate Plan 2029 [79]	Sustainable construction is developed and promoted extensively in the entire city area. Using wood as building material is promoted.			x	x	
FI	Vantaa CE plan [80]	Target to become carbon-neutral by 2030. Specific targets for the construction sector	x	x	x	x	
Fi	Kuopio resource efficiency programme [81]	Increase energy efficiency and sustainability in construction.			x		x
Fi	Development and sustainability agenda for Åland [82]	The CE principles of Åland in relation to the construction sector are increasing recycling and using timber grown on Åland in the construction industry			x	x	
SE	Procurement requirements for circular flows in the construction and demolition process. The city of Gothenburg. [83]	The city of Gothenburg has developed procurement requirements for circular flows in the construction and demolition process			x		
SE	Skåne region: guidelines to minimize the waste from construction sites [84]	Guidelines to minimize the waste from construction activities.		x			
SE	Local roadmap for a climate-neutral construction and civil engineering sector in Malmö 2030 [85]	The roadmap includes targets such as resource efficiency and climate-neutral building materials.		x	x	x	
SE	Climate strategic program for Gothenburg [86]	Gothenburg aims to become one of the most progressive cities in the world in the rectification of climate-related problems.		x	x	x	x

* 1 reducing use of resources; 2. waste prevention; 3. increasing recycling rates; 4. use of biobased/renewable materials; 5. use of recyclable materials.

Appendix B

Table A2 shows the business focus of the actors chosen for the assessment of how policies influence the implementation of CE concepts at different levels in the construction sector in the Nordics

Table A2. Business focus of the companies chosen for the assessment of how policies influence the implementation of CE concepts at different levels in the construction sector in the Nordics.

Case nr.	Business Focus
1.	Technology development for a more efficient pre-demolition inventory. The collected information enables a more efficient dismantling of valuable materials and products, and supports selective demolition.
2.	Development of a digital marketplace for the trade of reusable construction products and furniture. Users can register materials and inventory planned for demolition to make them available to others.
3.	Using wood waste from renovation and demolition projects in the production of high-value products. High focus on finding feedstock that can be traced to ensure material quality and safety.
4.	Reuse and closed loop recycling of C&DW. Focus on finding a self-sustaining system for the collection and recycling of flat glass.
5.	Closed loop recycling of C&DW. Focus on the recycling of plasterboards by developing a new business model and streamline the reverse logistics.
6.	Construction of an office building with a high focus on environmental sustainability in the building's design
7.	Dismantling of interior products prior to demolition, focusing on reusable products and materials that have a second-hand value.
8.	Policy and legislation-removal of legislative barriers for recycling. Recyclers actively involved in the revision of legislation, aiming to remove barriers for the use of secondary raw materials in construction.
9.	Modular demountable wooden constructions intended for a temporary and/or unknown length of use. Easy to reconstruct, including possibilities for changes in size and intended use.
10.	Closed loop recycling of C&DW. Certified recycling of concrete waste in new concrete allowing closed loops and full traceability.
11	Municipal construction projects with a CE focus. The developer unit is responsible for the construction of public buildings; the CE efforts have resulted in a number of CE-focused construction projects.
12.	Facilitate the selling of building products for reuse. The company hosts a digital marketplace for the trade of reusable building products and furniture.
13.	Collection of surplus materials and products from construction sites; resell to customers. These products and materials have traditionally ended up as waste at the construction sites.
14.	Development of digital process tools to track the generation of waste at construction sites and optimize the collaboration between partners in planning, procurement, and logistics activities with the aim to achieve waste-free construction sites.

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How Environmental Regulation Affects Industrial Green Total Factor Productivity in China: The Role of Internal and External Channels

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Abstract: Many nations have enacted diverse environmental control regulations to address environmental and climate concerns. Analyzing how environmental regulation affects industrial green total factor productivity can aid in creating appropriate environmental regulation laws and realizing peaceful coexistence between man and nature. Based on the panel data of various provinces in China from 2011 to 2019, this paper used the data envelopment analysis method to measure the industrial green total factor productivity and then used the system generalized method of moments model to empirically study the differential effect of heterogeneous environmental regulation on China's industrial green total factor productivity. In addition, this paper also conducted a test of internal and external mechanisms. The statistics show that environmental regulation can boost the growth of industrial green total factor productivity and pass the robustness test. Innovation ability is the external mechanism variable of environmental regulation acting on industrial green total factor productivity. Regulation can improve industrial productivity and significantly suppress industrial pollution emissions, but market-based environmental regulations do not have an effective impact on carbon emissions. Environmental regulations in economically developed regions can promote the growth of industrial green total factor productivity, but for financially backward areas, market-based environmental regulation inhibits the promotion of industrial green total factor productivity, while command-and-control environmental regulation is not helpful for industrial green total factor productivity.

Keywords: green total factor productivity; environmental regulation; system generalized method of moments; transmission mechanism; carbon emission

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1. Introduction

China's proportion of the world's gross domestic product (GDP) has climbed from 1.74% in 1978 to 18.5% in 2021, representing a period of significant economic development. However, China's industrialization has always been accompanied by high input consumption and pollution emissions. According to the calculation of energy data in 2019, China's industry generated just 32% of the added value, with 68% of carbon dioxide emissions and 65% of energy consumption. China's former growth model has mainly relied on a significant input of production elements. At the same time, it needs to emit many pollutants and greenhouse gases into the environment. It can be seen that the level of green development is relatively low [1]. The extensive development model is becoming increasingly unsustainable as environmental quality deteriorates and marginal returns on production variables decline. Therefore, it is necessary to guide the industry toward greening and big value-added improvement.

Many countries have implemented environmental regulation policies to solve environmental problems [2]. For example, the United States has established organic laws of environmental protection agencies and the pollution rights trading market, France has boosted investment in environmental protection, and the Netherlands has established an environmental protection tax. China has increased its focus on environmental conservation and established laws to prevent environmental degradation in recent years. For example, China has established policies such as dual energy policies, environmental protection taxes, and carbon trading markets [3,4]. However, additional research is required to determine whether these environmental control policies can increase industrial green total factor productivity and how they affect industrial green total factor productivity. Based on this, this paper analyzed the impact of environmental regulation on industrial green total factor productivity and tested the internal and external transmission mechanisms. The framework of this paper is designed as follows. The second part is a literature review on environmental regulation and industrial green total factor productivity. The third part is the data source and methods about the calculation method of industrial green total factor productivity, and the main econometric regression model. The fourth part is the empirical analysis results. The fifth part is the discussion. The sixth part is the conclusions and policy recommendations.

2. Literature Review

Industrial green total factor productivity, often known as industrial GTFP, is the input–output efficiency of the industrial sector that includes undesirable outcomes [5]. It centrally symbolizes the degree of advanced industrial greening. Improving industrial GTFP is crucial to achieving sustainable development in China. There are many methods for calculating industrial GTFP, data envelopment analysis being one of them. The data envelopment analysis approach, also known as the DEA method, evaluates efficiency based on a number of input–output indicators using linear programming. Because the DEA approach can take into account all undesirable output, it has been widely adopted. The DEA method was first given by Charnes et al. [6], and then, Chung et al. proposed the Directional Distance Function (DDF), which made pollution an undesired output to be considered in the production process. As a result, it has become possible to avoid the disadvantages of taking environmental pollution as an input factor in the past, and it can more truly reflect the production process. To solve the slack variable problem, Tone proposed the Slack-Based Measure (SBM) model [7]. To solve the problem of inter-temporal incomparability of productivity indices, Pastor et al. proposed the concept of Global Malmquist (GML) [8], which uses the sum of each period as a reference set to calculate productivity. Until now, the DEA has developed into a reasonably sophisticated GTFP computation methodology. Numerous academics have performed multiple calculations on GTFP using the DEA model. For example, Vivek et al. calculated the GTFP of the Swedish paper industry [9], and Zhang et al. calculated the GTFP of each province in China [10].

As a typical public good, the environment will cause manufacturers to overuse it, cause negative externalities of production, and ultimately lead to social inefficiency and environmental pollution problems [11,12]. Based on this theory, Pigou proposed a scheme of levying taxes to realize the internalization of external problems and solve the problem of environmental pollution. Some scholars also put forward the view of "establishing a market" [13] so that emissions or pollutant discharge permits can be publicly traded in the market to achieve green economic development. Some scholars believe that the government should use laws and regulations to control environmental pollution [14]. These methods of controlling environmental pollution can be collectively referred to as environmental regulation, which are some tools used by the government to reduce environmental pollution [15,16].

When studying how environmental management affects industrial GTFP, the place of innovation capacity in the model should be clarified, which is the test of the "Porter Hypothesis" [17]. It will inevitably involve the "innovation compensation effect" and the "following cost effect", which requires innovation capacity to be put into the model, which is what we often call the transmission mechanism test. To separate it from the internal conduction mechanism later in the paper, we call this conduction mechanism the external conduction mechanism. A number of scholars have studied the effect of environmental control on innovation. For example, when Umar et al. analyzed some non-financial enterprises in Asia, they found that regulation can promote productivity progress and technological innovation [18]. From the perspective of the environmental protection target responsibility system, Hu et al. found that environmental regulation only benefit innovation in China's developed regions [19]. So many scholars have directly described the relationship between them, and few studies have incorporated innovation capability into the framework of environmental management affecting industrial GTFP.

Most scholars took industrial GTFP as a whole when it was the subject of study [20,21]. However, the industrial GTFP describes the degree of industrial intensification and green growth in the region, which reflects not only the changes in industrial output value but also the pollutants and carbon emissions, how to smartly design environmental regulations so the economy can grow steadily while reducing emissions of pollutants and carbon dioxide. This requires a more in-depth study of the interaction of regulation and industrial GTFP. Despite the fact that several studies have decomposed industrial GTFP into scale efficiency and technical efficiency [22], few scholars have examined the internal transmission mechanism from the perspectives of the industrial economy and environment. Clarifying this relationship can help us better design policies. This paper calls it an internal transmission mechanism because environmental regulation does not affect industrial GTFP through external forces such as innovation but changes the internal state of industrial GTFP, which in turn changes industrial GTFP.

To sum up, on the one hand, although previous studies have systematically described how environmental regulation affects innovation, they have not analyzed the external mechanism of environmental regulation affecting industrial GTFP. How exactly does environmental regulation affect industrial GTFP? What is the place of innovation capability in the model? On the other hand, previous studies have analyzed the internal conduction mechanism by which environmental regulation affects industrial GTFP. Incorporating technical innovation capability into the model and assessing how environmental regulation affects industrial GTFP constitutes one of the paper's innovations. The second innovation of this paper is that the industrial GTFP has been decomposed into three parts: industrial output value, pollution emission, and carbon dioxide emission, in order to study the effect of heterogeneous environmental regulation on each decomposed part and then analyze the environmental regulation's impact on the internal conduction mechanisms of industrial GTFP.

3. Methodology

3.1. Industrial GTFP

3.1.1. Measurement of Industrial GTFP

Since the SBM direction distance function can not only reflect the undesired output but also measure the slack part of the production when measuring the production efficiency [23,24], this paper has used the SBM function combined with the GML index to measure. The GML index represents its growth, not an absolute value [25,26]. To better match the research purpose, this article has taken 2010 as the base year and multiplied the industry GML index to obtain the industry GTFP of each year.

$$P^G(x) = \left\{ \left(y^t, b^t\right) : \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t y_{km}^t \geqslant y_{km}^t, \forall m; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t b_{ki}^t = b_{ki}^t, \forall i; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t x_{kn}^t \leqslant x_{kn}^t, \forall n; \sum_{k=1}^{K} z_k^t = 1, z_k^t > 0, \forall k \right\} \quad (1)$$

The above formula reflects the global production possibility set $P^G = P^1 \cup P^2 \cup \ldots \cup P^T$. Assume that the production process requires input unit $X = (x_1, x_2, \ldots, x_N) \in R_N^+$, desirable output units $Y = (y_1, y_2, \ldots, y_M) \in R_M^+$, and undesirable output unit $B = (b_1, b_2, \ldots, b_M) \in R_B^+$. Then, the SBM function form is as follows:

$$\begin{gathered} S_V^G\left(x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b\right) = \max_{s^x, s^y, s^b} \frac{1}{2N} \sum_{n=1}^{N} \frac{s_n^x}{g_n^x} + \frac{\left(\sum_{m=1}^{M} \frac{s_m^y}{g_m^y} + \sum_{i=1}^{I} \frac{s_i^b}{g_i^b}\right)}{2(M+I)} \\ \text{s.t.} \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^t, \forall n; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^t, \forall m; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \forall i \\ \sum_{k=1}^{K} z_k^t = 1, z_k^t \geqslant 0, \forall k; s_n^x \geqslant 0, \forall n; s_m^y \geqslant 0, \forall m; s_i^b \geqslant 0, \forall i \end{gathered} \quad (2)$$

The above formula is the SBM directional distance function constructed in this paper, where g represents the direction vector of each element, and s represents the relaxation vector. Based on the research of other scholars [27], this paper constructs the following GML index.

$$GML_t^{t+1} = \frac{1 + S_V^G(x^t, y^t, b^t; g)}{1 + S_V^G(x^{t+1}, y^{t+1}, b^{t+1}; g)} \quad (3)$$

3.1.2. Indicators Selection for Industrial GTFP

On the basis of learning from previous research, the input indicators of this paper have included industrial energy consumption, net industrial fixed assets and labor force [28]. Industrial value added is not suitable as an expected output variable as inputs contain intermediate products of energy, the industrial output value data in the statistical yearbook were only counted up to 2011, and the sales output value was counted up to 2017. Therefore, this paper has used the output value of industries above the designated size (operating income of industries above the designated size in 2018 and 2019) as the expected output indicator.

Undesirable outputs include industrial pollution emissions and industrial carbon dioxide. Industrial pollution emissions consist of wastewater, waste gas, and solid waste. Industrial wastewater has been represented by chemical oxygen demand and ammonia nitrogen emissions using the entropy technique. Using the research of Qiu et al. as a reference [29], this paper uses sulfur dioxide emissions to represent industrial waste gas. Industrial solid waste has utilized statistical yearbook data directly. The weight of the three industrial wastes has been determined using the entropy method. This article has calculated industrial carbon dioxide emissions based on each province's energy balance sheets. Since carbon dioxide is only produced when energy is burned, the net industrial energy consumption was employed for this study. Formula (4) is the specific technique of calculation.

$$CO_2 = \sum_{i=1} CO_2 = \sum_{i=1} E_{\text{i}} \times NCV_{\text{i}} \times COF_i \times CEF_i \times \frac{44}{12} \quad (4)$$

Among them, NCV is the average low calorific value of fossil fuels, COF is the carbon oxidation rate, CEF is the carbon content per unit calorific value, and E represents the consumption of various fossil fuels. The statistics have come from the data of Chinese provinces from 2010 to 2019 (since the data of some provinces are not available, the research scope of this paper only includes 30 provinces in China). The relevant data are obtained from the China Industrial Statistical Yearbook, China Energy Statistical Yearbook, IPCC National Greenhouse Gas Emission Inventory Guidelines and provincial statistical yearbooks, and some missing data have been processed by linear interpolation.

3.2. Regression Models and Variable Selection

Since the productivity measured by the GML method has a serial correlation [30], to better explore the impact of GTFP in previous years, this paper has introduced the system generalized method of moments model, which is also known as the GMM model. Compared with the differential GMM, the system GMM can better reduce the endogenous impact. Therefore, this paper has chosen the system GMM as the regression model of this paper. The specific regression model is as follows:

$$GTFP_{it} = \alpha + \chi GTFP_{it-1} + \beta er_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (5)$$

where GTFP represents industrial GTFP; $GTFP_{it\text{-}1}$ represents industrial GTFP with a lag of one order; *er* represents environmental regulation, which can be divided into command-and-control environmental regulation and market-based environmental regulation; X, μ, γ and ε represent control variables, individual effects, time effects, and random disturbance terms, respectively.

In order to analyze how environmental regulation causes changes in industrial GTFP through innovation capability, this paper has introduced the innovation capability (*tech*) of industrial enterprises as an external mechanism variable into the model, as follows:

$$tech_{it} = \alpha + \chi tech_{it-1} + \beta er_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (6)$$

$$GTFP_{it} = \alpha + \chi GTFP_{it-1} + \beta er_{it} + \delta tech_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (7)$$

So as to verify and explore the internal principles of heterogeneous regulation for industrial GTFP, this paper has introduced industrial production efficiency (*effi*), industrial pollutant emission level (*poll*) and industrial carbon emission level (*carb*) as internal mechanism variables into the model. Different from the external conduction mechanism, the internal conduction mechanism variables are the components of industrial GTFP. Greater industrial productivity correlates to greater industrial GTFP, whereas increased pollution and carbon emissions correlate to decreased industrial GTFP, so there is no need to use the classical three-step method to analyze the internal conduction mechanism. It is enough to analyze whether environmental regulation is helpful to each internal transmission mechanism variable. For details, please refer to the following model:

$$\begin{aligned} effi_{it} &= \alpha + \chi effi_{it-1} + \beta er_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \\ poll_{it} &= \alpha + \chi poll_{it-1} + \beta er_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \\ carb_{it} &= \alpha + \chi carb_{it-1} + \beta er_{it} + \sum \lambda_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \quad (8)$$

This paper has taken the industrial GTFP of each province as the dependent variable of the model. The key independent variables of this paper have included command-and-control environmental regulation and market-based environmental regulation. Although China started a pilot carbon trading market in some regions in 2011, a nationwide carbon trading market was not established until 2021. There is only one year of data for nationwide carbon trading. Therefore, this paper does not study carbon-related environmental regulations, so the market-based environmental regulation in this paper has been only expressed by the logarithm of the ratio of the pollutant discharge fee (environmental protection tax in 2018 and later) to the total discharge of the three industrial wastes (*lnmar*). The higher the value, the higher the unit pollutant charge and the stricter the environmental control. In previous studies, the number of environmental laws was mostly used to represent command-and-control environmental regulations, but in recent years, the lack of environmental laws data has become more serious. In this paper, the logarithm of the ratio of environmental administrative penalty to pollutant (*lncom*) discharge is used to represent the command-and-control environmental regulation. Higher values indicate stricter environmental regulations.

This paper has used industrial technology innovation capability (*tech*) instead of R&D as the external mechanism variable, because R&D only reflects the investment in research and development and cannot directly reflect the real technical ability. Therefore, this paper calculated the technological innovation ability of each province using the SBM function, with the capital stock of industrial R&D, the equivalent of industrial R&D workers, and the number of industrial R&D projects serving as input indicators. The output indicator is the total number of inventive patents with industrial validity. This paper has used the perpetual inventory method to estimate the R&D capital stock [31]. Industrial production efficiency (*effi*), industrial pollutant discharge (*poll*) and industrial carbon emission (*carb*) have been selected as internal transmission mechanism variables. Industrial production efficiency has been calculated using the SBM method, the input index was the same as that of GTFP, and the output index has only included the industrial sales output value. The discharge of industrial pollutants has been expressed by the ratio of three industrial wastes and the number of enterprises above the designated size, and the weight has been calculated by the entropy method. The ratio of industrial carbon dioxide emissions to the number of regulated businesses has been used to quantify industrial carbon emissions.

The following control variables have been selected to control the disturbance of other variables based on previous research: the degree of economic development (*lnpgdp*) has been measured by the logarithm of per capita GDP, foreign capital dependence (*fdi*) has been expressed as the proportion of foreign direct investment in GDP, road traffic (*infra*) has measured in kilometers of expressways owned per square kilometer, the level of capital deepening (*lncappeo*) has been expressed as the logarithm of the net fixed assets owned by a single labor force, the ownership structure (*own*) has been represented by the proportion of the operating income of industrial state-owned holding enterprises above the designated size, the industry concentration (*big*) has been expressed by the proportion of the operating income of large enterprises, and the R&D investment (*rd*) has been expressed as the flow of internal expenditures of industrial R&D funds above the designated size. All nominal variables have price effects removed to eliminate price effects. In addition to the yearbooks mentioned above, the data sources also include the Wind database and the National Bureau of Statistics database. Table 1 shows the details of each variable.

Table 1. The details of each variable.

Variables	Max	Mean	Sd	Min
GTFP	1.494	1.079	0.107	0.840
mar	150.1	8.657	13.60	0.411
com	35.43	1.092	3.435	0.00565
tech	1	0.315	0.198	0.0436
pgdp	148,002	49,581	25,845	14,866
fdi	0.121	0.0213	0.0191	0.000096
infra	0.126	0.0311	0.026	0.000901
cappeo	922.8	51.58	60.97	11.86
own	0.836	0.357	0.176	0.0959
big	0.769	0.435	0.124	0.142
rd	0.0186	0.00809	0.00346	0.00276
effi	1	0.474	0.168	0.194
carb	17.09	4.072	3.591	0.378
poll	0.768	0.104	0.133	0.00143

4. Results

4.1. Benchmark Regression

The basic statistical results are represented in Table 2 by the outcomes of mixed regression, fixed effect regression, and systematic GMM regression. It shows that the AR (2) and the probability *p* values of Sargan are not statistically significant, indicating that the model does not have second-order autocorrelation, the instrumental variables are effective, and the system GMM model is suitable. It also shows that the first-order lag term of industrial GTFP promotes current GTFP, and it passes the 1% significance test, indicating that industrial GTFP possesses autocorrelation characteristics, and the effect is positive: the current value will promote the growth of the value for the next period.

Table 2. Benchmark regression.

Variables	Mixed Regression (GTFP)		Fixed Regression (GTFP)		Dynamic Panel Regression (GTFP)	
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
L.GTFP					0.949 ***	0.955 ***
					(11.571)	(14.751)
lnmar	0.019 *		0.044 ***		0.051 **	
	(1.945)		(3.698)		(2.133)	
lncom		0.025 **		0.057 ***		0.061 **
		(2.095)		(3.089)		(2.335)
Control variables	YES	YES	YES	YES	YES	YES
Province FE			YES	YES	YES	YES
Year FE			YES	YES	YES	YES
Observations	270	270	270	270	240	240
Number of id			30	30	30	30
R-squared	0.402	0.403	0.379	0.368		
Sargan					2.871	18.72
					(0.720)	(0.711)
AR (1)					−4.990	−5.414
					(0.000)	(0.000)
AR (2)					0.567	0.641
					(0.571)	(0.522)

Note: Sargan, AR (1), AR (2) are *p*-values in parentheses, mixed regression and fixed regression are t-statistics in parentheses, and the rest are z-statistics; ***, **, * represent the significance levels of 1%, 5%, and 10%, respectively.

Whether using mixed regression or fixed effect regression, it is discovered that command-and-control environmental regulation aids in the promotion of industrial GTFP. However, in the mixed regression, the 5% significance test failed in the market-based environmental regulation to upgrade the development of industrial GTFP, but the mixed regression results are often not robust. From the more robust fixed regression and dynamic panel regression, we found that the promoting effect of market-based environmental regulation on industrial GTFP has passed the 5% significance test. Therefore, it can be concluded that environmental regulation is helpful for the advancement of industrial GTFP. First of all, the cost of non-compliance with environmental regulations is very high, and environmental regulations can contribute to industrial GTFP growth by prompting industrial enterprises to eliminate outdated production capacity. Secondly, environmental regulation can send a clear signal to the outside world: environmental control and production costs in high-pollution industries are being strengthened, which in turn leads to a decrease in investment in high-pollution industries, allowing social capital to enter other green and high-value-added industries. As a result, the industrial structure will be modified, and pollutant emissions will inevitably be decreased, which will ultimately promote the progress of industrial GTFP. In conclusion, environmental control facilitates industrial intensification and green transformation, hence enhancing industrial GTFP.

4.2. Robustness Test

Two robustness tests have been carried out to verify the robustness of previous research results in this paper. The first was the model replacement, where the regression model was replaced with a differential GMM. The second was the replacement of key independent variables. There are many ways to express environmental regulation. In this paper, the market-based environmental regulation has been replaced by the ratio of industrial pollution control investment to the total discharge of three industrial wastes, and the command-and-control environmental regulation has been replaced by the ratio of the number of environmental proposals made by the National People's Congress and the Chinese People's Political Consultative Conference to the total amount of industrial waste; the relevant data come from the yearbooks of the provinces. The regression data are shown in Table 3. It shows that whether changing the estimation method or the representation method of the key independent variables, the signs of the coefficients of the market-based environmental regulation and the command-and-control environmental regulation are all positive, and at least 5% of the coefficients have passed. Therefore, it can be said that both types of environmental regulation can contribute to the progress of industrial GTFP, and the model results are robust.

Table 3. Robustness test.

Variables	Difference Equations (GTFP)		Replacement Metrics (GTFP)	
L.GTFP	0.755 ***	0.787 ***	1.040 ***	0.867 ***
	(8.185)	(7.064)	(12.832)	(25.738)
lnmar	0.121 ***		0.020 **	
	(9.991)		(2.232)	
lncom		0.101 **		0.349 ***
		(2.187)		(2.935)
Control variables	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	210	210	240	240
Number of id	30	30	30	30
Sargan	6.626	1.916	2.938	1.483
	(0.357)	(0.384)	(0.817)	(0.476)
AR (1)	−1.427	−5.407	−5.752	−1.531
	(0.154)	(0.000)	(0.000)	(0.126)
AR (2)	0.326	1.199	0.437	0.160
	(0.745)	(0.230)	(0.662)	(0.873)

Note: Sargan, AR (1), and AR (2) are *p*-values in parentheses, and z-statistics in other brackets; ***, **, represent the significance levels of 1%, 5%, respectively.

4.3. Inspection of External Mechanisms

Models 7 and 9 in Table 4 represent the relationship between innovation capability and heterogeneous environmental regulation. We found that both types of environmental regulation contribute to the advancement of innovation capability. When the government implements regulations, first, the cost of high-emission enterprises will suddenly increase, which will lead to the withdrawal of some high-energy-consuming and low-value-added industries, which will increase the social investment in high-tech industries, and high-tech industries often represent higher technological innovation ability, so environmental regulation improves technological innovation ability. Second, environmental regulation improves the cost of high-emission enterprises. It will not cause all high-emission enterprises to withdraw. Some enterprises with strong financial strength and strong market voice will survive, but enterprises believe that environmental regulation is not a short-term policy. In order to obtain long-term stable profits, enterprises must enhance their innovation capabilities and reduce pollutant emissions. Enterprises are driven by this motivation to improve their technological innovation capabilities. It shows that the "Porter Hypothesis" exists in China, and environmental regulation helps to enhance innovation ability. Models 8 and 10 indicate that environmental regulation and innovation capability are jointly incorporated into the framework of industrial GTFP, and it is found that both environmental regulation and innovation capability can contribute to the progress of industrial GTFP. This proves that environmental regulation contributes to the advancement of technological innovation capabilities, which in turn contributes to the improvement of industrial GTFP. When enterprises try to avoid the rising costs associated with environmental regulation, they will conduct innovation activities, which will eventually lead to the improvement of innovation capability, and the benefits brought by the improvement of innovation capability outweigh the cost of environmental regulation. While increasing the industrial output value, it also reduces the emission of pollutants and carbon dioxide and finally promotes the progress of industrial GTFP, which is consistent with the study by Fan [32].

Table 4. External Mechanism Inspection.

Variables	Market-Based		Command-and-Control	
	tech (Model 7)	**GTFP (Model 8)**	**tech (Model 9)**	**GTFP (Model 10)**
L.GTFP		0.929 ***		0.921 ***
		(12.686)		(23.723)
tech		0.055 **		0.050 **
		(2.283)		(2.084)
L.tech	0.893 ***		0.923 ***	
	(18.267)		(28.105)	
lnmar	0.076 ***	0.048 ***		
	(3.078)	(2.632)		
lncom			0.026 **	0.018 ***
			(2.380)	(2.590)
Control variables	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	240	240	240	240
Number of id	30	30	30	30
Sargan	0.448	5.124	1.068	9.236
	(0.799)	(0.925)	(0.785)	(0.416)
AR (1)	−5.413	−4.819	−1.805	−1.562
	(0.000)	(0.000)	(0.071)	(0.118)
AR (2)	−1.280	0.464	−1.455	0.138
	(0.201)	(0.643)	(0.146)	(0.890)

Note: Sargan, AR (1), AR (2) are *p*-values in parentheses, and z-statistics in other brackets; ***, **, represent the significance levels of 1%, 5%, respectively.

4.4. Analysis of Internal Mechanism

Table 5 shows the statistical results of the internal mechanism test. Through models 11, 12, 14 and 15, we found that environmental regulation contributes to increased production efficiency and reduced pollution emissions. Environmental regulations will force enterprises to eliminate outdated production capacity, which is conducive to improving the overall competitiveness of the industrial industry. Finally, the production efficiency of industrial enterprises is improved. At the same time, most environmental administrative penalties and all environmental protection taxes are designed to reduce pollutant emissions. In addition, statistical results also confirm that regulation policies help reduce pollution emissions, which proves the desirability of China's environmental policy. The regression results of Model 13 show that market-based environmental regulation cannot reduce carbon dioxide emissions. The market-based environmental regulation studied in this paper has only included environmental protection tax, and the environmental protection tax does not include the carbon tax. Therefore, China's current environmental protection tax system "reduces pollution without lowering carbon". It shows that market-based environmental regulation based solely on environmental protection taxes will not reduce carbon emissions. Although the carbon trading market has been expanded to the entire nation, it only includes the power industry and not all industrial sectors. Therefore, the carbon trading market must be expanded to include the entire economy. Through Model 16, the result shows that it fails the 5% significance test in that command-and-control environmental regulation can hindrance carbon dioxide emissions, indicating that the primary role of China's command-and-control environmental regulation within the research time range is still to reduce pollution, and the effect of carbon reduction is not very obvious.

Table 5. Internal mechanism inspection.

Variables	Market-Based			Command-and-Control		
	effi (Model 11)	**poll (Model 12)**	**carb (Model 13)**	**effi (Model 14)**	**poll (Model 15)**	**carb (Model 16)**
L.effi	0.703 ***			0.744 ***		
	(10.662)			(11.912)		
L.poll		0.844 ***			0.826 ***	
		(33.444)			(33.950)	
L.carb			1.288 ***			1.225 ***
			(16.809)			(16.901)
lnmar	0.050 ***	−0.008 ***	0.042			
	(3.077)	(−2.771)	(0.252)			
lncom				0.044 **	−0.010 ***	−0.520 *
				(2.258)	(−2.576)	(−1.706)
Control variables	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	240	240	240	240	240	240
Number of id	30	30	30	30	30	30
Sargan	1.955	0.814	4.682	25.80	4.285	3.128
	(0.744)	(0.937)	(0.197)	(0.173)	(0.369)	(0.372)
AR (1)	−4.522	−6.215	−4.082	−5.027	−6.208	−4.446
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
AR (2)	0.203	0.236	−0.227	0.603	0.189	−0.0257
	(0.840)	(0.813)	(0.821)	(0.547)	(0.850)	(0.979)

Note: Sargan, AR (1), AR (2) are *p*-values in parentheses, and z-statistics in other brackets; ***, **, * represent the significance levels of 1%, 5%, and 10%, respectively.

4.5. Regional Heterogeneity Analysis

For regional heterogeneity studies, researchers in the past frequently divided the country into three parts: east, middle, and west. Although this method is straightforward, it can be kept the same as the national administrative division. However, this method also has drawbacks: the western, middle, and eastern regions represent differences in economic development in China, but this does not mean that every province in the middle or western region belongs to a backward region. It is unreasonable to include the more developed provinces in the middle or western regions into the backward regions for analysis. Therefore, this paper has divided the country into developed regions and backward regions according to the per capita GDP in 2019. The developed regions consist of the top 15 provincial administrative regions, whereas the backward regions consist of the last 15 provincial administrative regions. Table 6 shows the regression results of regional heterogeneity. We found that in economically developed regions, both environmental regulations contribute to the advancement of industrial GTFP. Because the current industrial situation and innovation capabilities of economically developed regions have reached a high level, environmental regulation contributes to the profound adjustment of the industrial structure, eliminates low-end and backward industries, and realizes the green and intensive development level of the industry. However, for the economically backward regions, the market-based environmental regulation significantly impeded the advancement of industrial GTFP, but the command-and-control environmental regulation cannot contribute to the advancement of industrial GTFP because the economically backward regions have not crossed "Porter's turning point", the ability of technological innovation is weak, the ability of industrial agglomeration is poor, and some regions even regard high-energy-consuming industries as the pillar industries of the region. This all results in the poor ability of industrial industries in the region to resist risks; in addition, the government is taxing pollutants or enforcing administrative control. As a result, the profit of the company that is not rich is further compressed, and it can even make the company on the verge of bankruptcy. Thus, it is impossible for the company to achieve transformation and upgrading in a short time, and they are thus ultimately unable to achieve the progress of industrial GTFP.

Table 6. Regional heterogeneity analysis.

Variables	Economic Developed Area		Economically Backward Areas	
	GTFP	GTFP	GTFP	GTFP
L.GTFP	0.818 ***	0.851 ***	0.758 ***	0.752 ***
	(8.447)	(9.308)	(7.794)	(7.898)
lnmar	0.052 **		−0.025 ***	
	(2.131)		(−3.085)	
lncom		0.078 **		−0.002
		(2.464)		(−0.117)
Control variables	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	120	120	120	120
Number of id	15	15	15	15
Sargan	10.66	26.07	16.45	16.66
	(0.639)	(0.249)	(0.422)	(0.547)
AR (1)	−3.507	−3.976	−3.048	−2.857
	(0.000)	(0.000)	(0.002)	(0.004)
AR (2)	0.777	1.063	0.974	0.702
	(0.437)	(0.288)	(0.330)	(0.483)

Note: Sargan, AR (1), AR (2) are *p*-values in parentheses, and z-statistics in other brackets; ***, **, represent the significance levels of 1%, 5%, respectively.

5. Discussion

Market-based environmental regulation is the government's environmental control by means of taxation, emissions trading and other market instruments [33]. These environmental regulation policies will transfer the cost of the enterprise due to the consumption of the environment from society to the production enterprise, shrink the production boundary of enterprises to a position equal to the optimal production boundary of society, internalize the external problems, and finally realize pollution reduction. It fully reflects the "polluter pays principle". Similarly, command-and-control environmental regulation means that the government directly intervenes in the production and business activities of enterprises through relevant documents, laws and regulations to reduce the pollution discharge of enterprises. Since the cost of enterprises not complying with such environmental regulations is very high, such environmental regulation policies often have the characteristics of a short implementation period and immediate effect. Ultimately, reducing pollution emissions reduces the undesired output in the economic system and realizes the growth of industrial GTFP.

When the "innovation compensation effect" is smaller than the "following cost effect", it means that the cost and revenue loss of the enterprise are greater than the benefit brought by innovation. In the meantime, the enterprise will not choose to innovate, so environmental regulation does not help the advancement of innovation capability [34]. When the "following cost effect" is smaller than the "innovation compensation effect", it means that although the revenue loss and cost of the enterprise increase, the increased benefits through innovation activities are greater. In turn, the increased losses and costs can be compensated by the benefits brought by innovation activities. At this time, enterprises will choose to innovate [35], so environmental regulation can increase innovation. The industrial GTFP represents the intensive development of the industry, and the improvement of innovation means that the industry develops in the direction of intensification, thereby improving the industrial GTFP. For China, the situation faced by enterprises is not only the two situations mentioned above. When the cost of a company in response to environmental regulations increases, the innovation effect will be greater than the cost-effectiveness on the leading enterprises due to their substantial capital and technical strength, and they will improve themselves through R&D investment. However, for enterprises with relatively backward technology, environmental regulation will increase their costs. Suppose they do not have strong financial and technical strength. In that case, their cost effect will be greater than the innovation effect, and they will inevitably withdraw from the market in the face of competition from large enterprises and environmental regulation by the government. At the same time, environmental regulation will cause social capital to reduce investment in high-energy-consuming and high-emission industrial projects and instead invest in high-tech enterprises, which will also promote the improvement of innovation capabilities. To sum up, environmental regulation allows enterprises without innovation ability to withdraw from the market, while it allows enterprises with innovation ability to innovate and attract social capital to enter high-tech enterprises, thereby enhancing technological innovation ability and industrial GTFP.

The industrial GTFP describes the development of the industry systematically. In terms of output, it not only reflects industrial economic development but also encompasses emissions of pollutants and carbon dioxide. The high-quality development of industry also involves all aspects of the economy and the environment. In this paper, industrial GTFP has been decomposed into three parts: industrial production efficiency, pollution emission, and carbon dioxide emission according to its source. In addition, the influence of heterogeneous environmental regulation on each decomposed part has been analyzed, and then, the internal transmission mechanism of environmental regulation affecting industrial GTFP has been discussed. Environmental regulation will compel enterprises to eliminate backward production methods, transform and upgrade, and transition from extensive to intensive development mode, all of which will contribute to an overall increase in production efficiency [36]. At the same time, environmental regulation is a government management method aimed at environmental pollution, and the cost of companies not complying with environmental regulations is very high. Therefore, when companies face the government's environmental regulations, they will inevitably reduce the discharge of pollutants. Since the current market-based environmental regulation policy focuses primarily on taxing pollutants and does not include a carbon tax, market-based environmental regulations cannot be used to reduce carbon emissions.

6. Conclusions and Policy Recommendations

6.1. Conclusions

This paper used the industrial panel data of various provinces in China from 2011 to 2019. On the basis of calculating the industrial GTFP through the SBM-GML index, the system GMM estimation method has been used to empirically analyze the effect of market-based environmental regulation and command-and-control environmental regulation on industrial GTFP. In addition, the internal and external mechanism routes by which heterogeneous environmental regulation influences industrial GTFP have been investigated. Statistics show that all environmental regulations are helpful for the progress of industrial GTFP and pass the robustness test. The external mechanism test found that environmental regulation contributes to the advancement of technological innovation capabilities, which in turn contributes to the improvement of industrial GTFP. In addition, this paper has decomposed industrial GTFP into three parts: production efficiency, pollution emissions and carbon emissions. Then, we have studied the internal transmission effect of heterogeneous environmental regulation on industrial GTFP and found that both market-based environmental regulation and command-and-control environmental regulation can promote the progress of industrial production efficiency and significantly inhibit industrial pollution emissions, but the market-based environmental regulation does not have an effective impact on carbon emissions. Finally, this paper divided the country into developed regions and backward regions based on per capita GDP in 2019, and it conducted regional heterogeneity analysis. The statistical results found that environmental regulation in economically developed regions can promote the growth of industrial GTFP, but for economically backward regions, the market-based environmental regulation significantly inhibits the progress of industrial GTFP, while the command-and-control environmental regulation cannot contribute to the advancement of industrial GTFP.

6.2. Policy Recommendations

According to the research content and results, this paper has proposed the following policy suggestions: (1) Establish and improve the market-based environmental regulation policy system. Through the analysis of the decomposition part of industrial GTFP, as can be seen, the current market-based environmental regulation has the effect of "reducing pollution without reducing carbon", and the market-based environmental regulation mainly based on environmental protection tax does not restrict carbon dioxide emissions. China's current market-based environmental regulations urgently need to be updated in terms of carbon tax and carbon trading market. Although China's carbon trading market has begun to operate, the included trading groups only include power companies and have not expanded to the entire industry. Therefore, it is necessary to incorporate the entire industry into the carbon trading market system as soon as possible and pay attention to the use of market-based regulation. (2) Improve the ability of technological innovation. We found that in addition to acting as a mechanism variable for environmental regulation to affect industrial GTFP, the technological innovation capability itself also promotes the improvement of industrial GTFP. So, we should increase investment in technology, lead the industrial industry to develop in the direction of high added value and high technology, better adjust the industrial structure, and reduce dependence on high energy-consuming industries. (3) Economically backward areas should adhere to the policy of paying equal attention to economic development and pollution control. Environmental regulation policies in economically backward areas will not promote the progress of industrial GTFP, because the industrial structure is relatively simple, and the industrial chain has a poor ability to resist risks. This area should increase investment promotion, actively adjust the industrial structure, improve the industrial chain in the region, remove the industrial structure dominated by high energy consumption, and strengthen environmental governance.

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Article

Research on the Impact of Environmental Regulations on Industrial Green Total Factor Productivity: Perspectives on the Changes in the Allocation Ratio of Factors among Different Industries

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Abstract: This paper constructs a two-sector manufacturer model of endogenous technological progress. We analyze the impact of environmental regulations on the factor input and output of different industries. Then, we reveal the intermediary role of inter-industry factor allocation in the impact of environmental regulations on industrial green total factor productivity (GTFP). Finally, the paper uses panel data from 30 provinces in China's industry from 2000 to 2017 to conduct empirical tests. We can draw the following conclusions: (1) The relative magnitude of the output compensation of the production department and the innovation compensation of the R&D department could change the impact of environmental regulations on the input and output of inter-industry factors, and the comprehensive effects of both input and output will affect the level of GTFP. (2) The curve of the direct impact of environmental regulations on GTFP is in an inverted "U" shape. However, the production factor allocation ratio can "reverse" the inhibitory effect of high-intensity regulations on GTFP. (3) The capital factor has a greater impact on the regulatory effect, but the labor factor has a more lasting impact on the regulatory effect. High-strength environmental regulations can enhance manufacturers' preference for human capital. Therefore, formulating environmental regulatory policies oriented to improve the ratio of factor allocation, mixing different types of regulatory policies, and increasing investment in human capital are all conducive to accelerating the transformation and upgrading of China's industrial structure and achieving high-quality development of the industrial economy.

Keywords: environmental regulation; green total factor productivity; inter-industry factor allocation; EBM-ML model; instrumental variable method

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1. Introduction

Since the reform and opening up, China's economy has achieved rapid development. From 1978 to 2017, the average annual growth rate of China's gross domestic product (GDP) was 9.61%. In 2016, China developed into the second largest economy in the world, and the economic gap with the United States was narrowing. Although the rapid economic growth for more than 40 years has caused China's GDP to grow rapidly, it has also brought about serious environmental problems and hindered further economic growth. The report of the 19th National Congress of the Communist Party of China proposed that we should focus on high-quality economic development. Therefore, how to coordinate the relationship between economy and ecology and improve the quality of economic growth, while ensuring economic growth, is the primary task facing China's development at this stage. The essence of improving the quality of economic growth is to improve energy use efficiency and reduce environmental pollution during economic development, so as to realize the coexistence of gold and silver mountains and green mountains, that is, to improve green total factor productivity (GTFP). In order to control environmental pollution, governments have promulgated and implemented various environmental regulations to reduce environmental pollution to a certain extent. However, some environmental governance measures are at the expense of development or the transfer of high-polluting industries, which deviates from the original intention of improving the quality of economic growth. Therefore, it is worth exploring the use of environmental regulations to reduce pollution while increasing GTFP.

The impact of environmental regulations on GTFP has always been the focus of the academic community. At present, there are mainly the following three views. The first view is that environmental regulations will increase the cost of environmental compliance for companies, reduce energy efficiency and corporate performance, and reduce GTFP, which is called the "cost effect" of environmental regulations [1]. The second view is that reasonable environmental regulations will force innovation by offsetting the increased costs of regulations to promote technological progress, improve energy efficiency, and improve GTFP, which is called the "compensation effect" of environmental regulations. [2–5]. The third view is that cost effect and compensation effect exist at the same time, and the impact of environmental regulation on GTFP depends on which effect is dominant under different intensity environmental regulations. On the one hand, the "cost effect" in the short term will crowd out the investment in innovation and reduce the productivity of enterprises. In the long run, rational manufacturers will use the "compensation effect" of technological innovation to offset the increase in costs caused by the "cost effect" and increase the productivity of enterprises, such as improving production and pollution control technologies. Therefore, a certain intensity of environmental regulations can stimulate technological innovation and improve GTFP [6,7]. Environmental regulations and GTFP have a "U"-shaped nonlinear relationship. On the other hand, high-strength environmental regulations will affect production activities. There is an inverted "U"-shaped change trend between environmental regulations and GTFP [8]. The authors in [9] concluded that environmental regulations should be within a suitable range, and that too high or too low levels of regulation are not conducive to the improvement of GTFP. In summary, the existing literature mainly focuses on the factor input and changes in input technology and research and development (R&D) factors caused by environmental regulations. However, GTFP is an efficiency indicator, which is affected by both factor input and output. Only by considering the changes in input and output can the impact of environmental regulations on GTFP be more accurately described.

Increasing factor input can promote economic growth [10]. With the advancement of supply-side reforms, the contribution rate of factor input to economic growth has maintained a downward trend for a long period of time [11]. The core driving force of economic growth needs to transform to increase productivity gradually. Studies have shown that the increase in productivity of an economy comes from the increase in productivity in various sectors of the economy and the increase in allocation efficiency caused by the flow of production factors among various sectors. The "mushroom effect" of the allocation of production factors from low-efficiency industries to high-efficiency industries can promote economic growth [12], because the factor replacement effect can reduce the misallocation of resources and improve the average quality of input factors [13]. Therefore, structural adjustment between industries is as important as technological innovation within the industry. Promoting the effective allocation of production factors, such as capital and labor among industries, is an effective means to improve the efficiency of the entire economic allocation [14]. As a type of industrial policy, the purpose of environmental regulations is to improve the environmental quality while not reducing the level of economic development. Its essence is to promote the transformation of industrial structure through technological progress. Therefore, in the process of environmental regulations to promote industrial GTFP, the role of factor allocation cannot be ignored. The existing research on the impact of environmental regulations on industrial GTFP mostly focuses on the impact on technological innovation, ignoring that the preference of innovative activities for elements will promote the allocation of capital and labor among different industries. Due to the difference in pollution levels between pollution-intensive industries and clean industries, the actual effects of environmental regulations are also different. When the intensity of environmental regulations changes, factor input to different types of industries will change the factor allocation ratio because of the "prosperity to avoid disadvantages", which will change the GTFP of each industry and gradually change the GTFP level of the entire industry. Then, changes in the ratio of factor allocation between industries will also change the size of the impact of environmental regulations on industrial GTFP. The conclusion that the effect of environmental regulation on industrial GTFP is mainly achieved through technological innovation holds for the industry as a whole. However, due to the differences in the level of emissions in each industry, there are also differences in the level of technology used to combat pollution, which leads to the fact that the effect of environmental regulation on industrial GTFP through influencing technological innovation differs between clean and pollution-intensive industries. Technological innovation is affected by factor inputs, leading to an increase in the level of technology with the increase of factor inputs within a certain range. It is assumed that the total factor inputs remain constant over a certain period of time. Therefore, the change in the proportion of factor inputs between industries is equivalent to the change in the amount of factor inputs in different industries. When the ratio of factor inputs among different industries differs, the level of technological innovation in the two types of industries changes, thus changing the impact of environmental regulation on industrial GTFP. This paper focus on the factor allocation between industries and comprehensively studies the GTFP effect of environmental regulation from the two aspects of input and output to the industry level. This research helps to intuitively reflect the impact of environmental policies on the transformation of industrial structure and provides references for the formulation of government environmental policies. The research method diagram is shown in Figure 1.

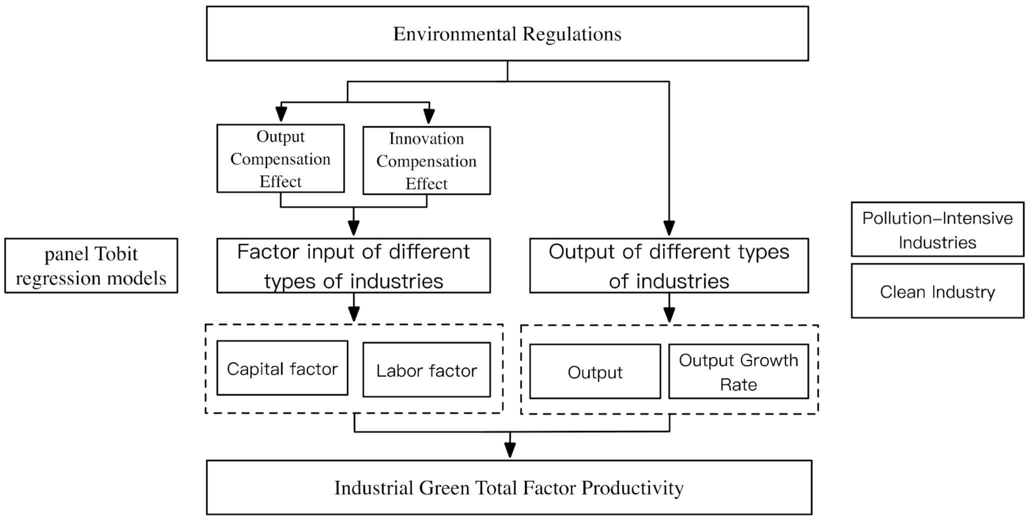

Figure 1. The research method diagram.

This study takes energy conservation, emission reduction, and economic development mode transformation as the entry points and provides an in-depth analysis of the impact of environmental policies on the production decision behavior of enterprises from the perspective of factor allocation among industries. By constructing a vendor model of endogenous technological progress, the paper reveals the micro mechanism of environmental regulation affecting industrial green total factor productivity and expands and improves the theory that environmental policy promotes economic growth quality improvement and economic transformation. At the same time, this study takes enterprises as decision makers and studies the behavioral choices of enterprises under government intervention from the perspective of factor allocation among industries, which points out the direction for industrial enterprises in economic transition. The findings of this study are beneficial for policy makers to fully understand the role pathways in the process of policy implementation and provide references for future environmental policy formulation.

The contributions of this article mainly include the following three points. First, comparing factor input and industry output between industries, it is found that there is a difference between the direct impact and the indirect impact by affecting the ratio of factor allocation among different industries of environmental regulations on GTFP. The improvement of the distribution ratio of factors in different industries can "reverse" the inhibitory effect of high-strength environmental regulations on industrial GTFP. Second, this paper makes technological progress endogenous to the production function of the enterprise and establishes a two-sector model of the enterprise. It is found that the relative magnitude of the "output compensation effect" and "innovation compensation effect" affects the effect of environmental regulation on industrial GTFP. This study reveals the micro-mechanism of the impact of environmental regulations on industrial GTFP. The existing studies generally believe that environmental regulations can squeeze out the cost of innovation in a short period of time, ignoring the behavior of enterprises as an "economic man" who will try to reduce the cost of regulations. This article expands related research and improves the explanatory power of existing theories. Third, this paper uses Python to map wind speed and atmospheric altitude data to 30 provinces in China with the help of meteorological latitude and longitude data released by the European Center for Medium-Term Weather Forecast (ECMWF) and constructs the air flow coefficient as an instrumental variable for environmental regulations. It alleviates the endogenous problems in existing studies.

2. Theoretical Model

2.1. Benchmark Model

This paper establishes a two-sector manufacturer model to analyze the impact of environmental regulations on GTFP by affecting the allocation ratio of influencing factors among different industries. The premises of the research are as follows. First, the initial capital and labor input ratios of manufacturers belonging to different sub-sectors in the same industry are different, and the characteristics of different companies in the same sub-sector are the same. Second, each manufacturer has an R&D sector and a production sector. There is skill improved and the marginal product of factors is increased in the R&D sector. The technology produced by the R&D department continues to be invested in the production sector as an intermediate product. The marginal output of factors in the production sector is diminishing. Third, manufacturers will take the lead in changing labor input, because labor is more mobile than capital. Fourth, both product and factor markets are perfectly competitive, and manufacturers are price takers in the market.

According to the level of pollution emissions, this paper divides the sub-industries of industry into pollution-intensive industries and clean industries. Both types of industries have production sectors and R&D sectors. It is necessary to set the form of the production function of the two sectors. The Cobb–Douglas production function and the CES production function are more commonly used. Within the two sectors, the input factors are substitutable for each other, and in fact, the CES function is more realistic. However, the elasticity of substitution in the CES function is an uncertain parameter, which will increase the complexity of the analysis. Therefore, to simplify the analysis, this paper uses the C–D production function to set the elasticity of substitution to one.

The R&D sector uses capital K_{12} and labor L_{12} as inputs, and it uses technology as the output. There is technological progress. Pollution control technology is a function of environmental regulation $A_1(R)$. The production function of the R&D sector of a manufacturer in a pollution-intensive industry is as follows:

$$T_1 = A_1(R){K_{12}}^{\alpha_{12}}{L_{12}}^{\beta_{12}}, \quad (1)$$

where α_{12} and β_{12} are the output elasticity of the invested capital and labor of the R&D sector. The production sector invests capital K_{11}, labor L_{11}, technology T_1, and energy resources E_1 to produce the final product, and technology is the output of the R&D sector. The production sector will discharge pollution W_1 during production, which will affect production activities as a negative output. In this paper, pollution is introduced into the production function as a negative impact on output, expressed as $[1 - d(W_1)]$, referring to the research of Fan Qingquan [15] and Tong Jian et al. [16].

The production function of the production sector of a manufacturer in a pollution-intensive industry is as follows:

$$Y_1 = [1 - d(W_1)]T_1 {K_{11}}^{\alpha_{11}} {L_{11}}^{\beta_{11}} {E_1}^{\gamma_1}, \tag{2}$$

$$W_1 = W_1(E_1, R, A_1(R)) = \frac{\rho_1 E_1}{A_1(R)R} \tag{3}$$

where α_{11}, β_{11}, and γ_1 are output elasticity of capital, labor, and energy, respectively. Y_1 and R are output and environmental regulations, respectively. $d(W_1)$ represents the negative impact of pollution on output and increases with the increase of pollution. W_1 represents the amount of pollution emissions, which is inversely proportional to the level of pollution control technology and directly proportional to the amount of energy input, and ρ_1 is the proportional coefficient.

Similar to pollution-intensive industries, the production functions of manufacturers' R&D sectors and production sectors of clean industries are as follows:

$$T_2 = A_2(R) {K_{22}}^{\alpha_{22}} {L_{22}}^{\beta_{22}}, \tag{4}$$

$$Y_2 = [1 - d(W_2)]T_2 {K_{21}}^{\alpha_{21}} {L_{21}}^{\beta_{21}} {E_2}^{\gamma_2} \tag{5}$$

$$W_2 = W_2(E_2, R, A_2(R)) = \frac{\rho_2 E_2}{A_2(R)R} \tag{6}$$

where the interpretation of variables is similar to that of pollution-intensive industries. Both pollution-intensive industries and clean industries have positive technical levels, but clean industries discharge less pollution due to higher levels of pollution control technology and the productivity of R&D sectors. It is constrained to $0 < A_1(R) < A_2(R)$, $T_1 < T_2$, $W_1 > W_2$. With the improvement of the intensity of environmental regulations, manufacturers in the clean industry will continuously adjust their pollution control technology level according to the changes in the level of regulation, so as to maintain the emission of pollution at a low level. The pollution control technology of manufacturers in pollution-intensive industries will not change with changes in environmental regulations. It will maintain the original technical level for production. The pollution control technology level of the two industries is shown as $0 = A'_1(R) < A'_2(R)$. When pollution emissions increase, clean industries can treat more pollution and have less negative impact on output due to their higher level of pollution control technology. Pollution-intensive industries have a lower level of pollution control to deal with less pollution, so they have a greater negative impact on output. It is shown as $d(W_1) > d(W_2)$, and $d'_1(W_1) > 0$, $d'_2(W_2) > 0$.

2.2. The Impact of Environmental Regulations on the Allocation Ratio of Factors among Industries

According to the firm theory, analyzing the choice of the firm requires the first-order conditions for maximizing profit. The profit of a manufacturer is shown in the following equation:

$$\Pi = PY_1 - C(K, L, R), \tag{7}$$

where Π represents the profit of a manufacturer and K and L are all capital and labor invested by the manufacturer, respectively. P represents product price. The cost function $C(K,\ L,\ R)$ is constrained to $C'_{K_1}(K,\ L,\ R) > 0$ and $C'_{K_2}(K, L, R) > 0$, where K_1 and K_2 represent total capital investment in pollution-intensive and clean industries, respectively. A rational manufacturer will use input elements to maximize its profits. Use K_1 and K_2 to find the partial derivatives of Equation (7), and substitute Equations (1) and (2) into it.

The first-order conditions for maximizing profit are shown in the following equations:

$$\frac{\partial \Pi}{\partial K_1} = P[1-d(W)]A(R){K_2}^{\alpha_2}{L_2}^{\beta_2}\alpha_1{K_1}^{\alpha_1-1}{L_1}^{\beta_1}E^{\gamma} - C'_{K_1}(K,L,\mathrm{R}) = 0, \tag{8}$$

$$\frac{\partial \Pi}{\partial K_2} = P[1-d(W)]A(R)\alpha_2{K_2}^{\alpha_2-1}{L_2}^{\beta_2}{K_1}^{\alpha_1}{L_1}^{\beta_1}E^{\gamma} - C'_{K_2}(K,L,\mathrm{R}) = 0 \tag{9}$$

Divide Equation (9) by Equation (8) to obtain the following equation:

$$\frac{\alpha_2 K_1}{\alpha_1 K_2} = \frac{C'_{K_2}(K,L,\mathrm{R})}{C'_{K_1}(K,L,\mathrm{R})}, \tag{10}$$

By incorporating the relevant variables of pollution-intensive industries and clean industries into Equation (10), we can obtain the following equations for pollution-intensive industries and clean industries:

$$\frac{\alpha_{12} K_{11}}{\alpha_{11} K_{12}} = \frac{C'_{K_{12}}(K_1,L_1,\mathrm{R})}{C'_{K_{11}}(K_1,L_1,\mathrm{R})}, \tag{11}$$

$$\frac{\alpha_{22} K_{21}}{\alpha_{21} K_{22}} = \frac{C'_{K_{22}}(K_2,L_2,\mathrm{R})}{C'_{K_{21}}(K_2,L_2,\mathrm{R})}, \tag{12}$$

Assume that the marginal product of capital and labor of the two types of industries are the same, respectively, and satisfy $K_1 = K_{11} + K_{12}$, $L_1 = L_{11} + L_{12}$, $K_2 = K_{21} + K_{22}$, $L_2 = L_{21} + L_{22}$. Divide Equation (11) by Equation (12) and substitute K_{11} and K_{21} into it, and the equation is as follows:

$$\frac{K_{11}(K_2 - K_{21})}{K_{21}(K_1 - K_{11})} = \frac{C'_{K_{12}} \cdot C'_{K_{11}}}{C'_{K_{22}} \cdot C'_{K_{21}}}, \tag{13}$$

Decompose the left side of Equation (13) to obtain the following formula:

$$\frac{K_{11}(K_2 - K_{21})}{K_{21}(K_1 - K_{11})} = \frac{K_{11}\cdot K_2 - K_{11}\cdot K_{21}}{K_{21}\cdot K_1 - K_{21}\cdot K_{11}} > 1 - \frac{K_{11}\cdot K_2}{K_{21}\cdot K_1}, \tag{14}$$

Substituting Equation (13) into formula (14) gives the following formula:

$$\frac{K_1}{K_2} < \frac{K_{11}}{K_{21}}\left[1 - \frac{C'_{K_{22}} \cdot C'_{K_{21}}}{C'_{K_{12}} \cdot C'_{K_{11}}}\right], \tag{15}$$

Set $V = \frac{K_1}{K_2}$ to obtain the following formula:

$$\frac{\partial V}{\partial R} < \frac{K_{11}}{K_{21}}\left[1 - \frac{C''_{K_{12},R}\cdot C'_{K_{21}} + C''_{K_{21},R}\cdot C'_{K_{12}}}{C'_{K_{12}}\cdot C'_{K_{21}}} - \frac{C''_{K_{22},R}\cdot C'_{K_{11}} + C''_{K_{11},R}\cdot C'_{K_{22}}}{C'_{K_{22}}\cdot C'_{K_{11}}}\right] < \frac{K_{11}}{K_{21}}\left[1 - \left(\frac{C''_{K_{12},R}}{C'_{K_{12}}} + \frac{C''_{K_{11},R}}{C'_{K_{11}}} + \frac{C''_{K_{21},R}}{C'_{K_{21}}} + \frac{C''_{K_{22},R}}{C'_{K_{22}}}\right)\right] \tag{16}$$

where the items in the parentheses on the right represent the ratio of the marginal cost of capital of the production department and the R&D department, which invest in the production sectors and R&D sectors of pollution-intensive industries and clean industries when regulations are strengthened and unchanged, respectively. When environmental regulations are strengthened, the marginal cost of factors increases because manufacturers will spend part of the money to control pollution. Therefore, the numerators in the parentheses on the right side of formula (16) are greater than the denominator, resulting in $\partial V/\partial R < 0$. That is, stronger environmental regulations enable more production factors to be allocated to clean industries. This leads to Hypothesis 1.

Hypothesis 1. *With the enhancement of environmental regulations, the allocation of capital elements to clean industries has led to a decline in the proportion of capital allocation in pollution-intensive industries and clean industries.*

2.3. The Impact of Environmental Regulations on the Output of Different Types of Industries

Using R to find the partial derivatives of Equation (2), the impact of environmental regulations on output is shown in the following equation:

$$\frac{\partial Y_1}{\partial R} = \left\{ d'(W_1)\rho_1 E_1 \cdot \left[\frac{A'_1(R)}{A_1(R)R} + \frac{1}{R^2} \right] + A'_1(R)[1 - d(W_1)] \right\} K_{11}{}^{\alpha_{11}} L_{11}{}^{\beta_{11}} K_{12}{}^{\alpha_{12}} L_{12}{}^{\beta_{12}} E_1{}^{\gamma_1} \quad (17)$$

Since $A'_1(R) = 0$, we obtain the following formula:

$$\frac{\partial Y_1}{\partial R} = \frac{d'(W_1)\rho_1 E_1}{R^2} K_{11}{}^{\alpha_{11}} L_{11}{}^{\beta_{11}} K_{22}{}^{\alpha_{22}} L_{22}{}^{\beta_{22}} E_1{}^{\gamma_1} > 0, \quad (18)$$

Using R to find the partial derivatives of $\partial Y_1 / \partial R$, the impact of the growth rate of environmental regulations on output is shown as follows:

$$\frac{\partial^2 Y_1}{\partial R^2} = -\frac{\rho_1 E_1}{R^3} d'(W_1) K_{11}{}^{\alpha_{11}} L_{11}{}^{\beta_{11}} K_{22}{}^{\alpha_{22}} L_{22}{}^{\beta_{22}} E_1{}^{\gamma_1} < 0, \quad (19)$$

Equations (18) and (19) show that, as the intensity of environmental regulations increases, the output of pollution-intensive industries gradually increases, but the output growth rate gradually decreases until it drops to zero. Therefore, when the intensity of environmental policy and regulation reaches a certain level, the output of pollution-intensive industries increases to the maximum. Figure 2 shows the relationship between the intensity of environmental regulations and the output of pollution-intensive industries.

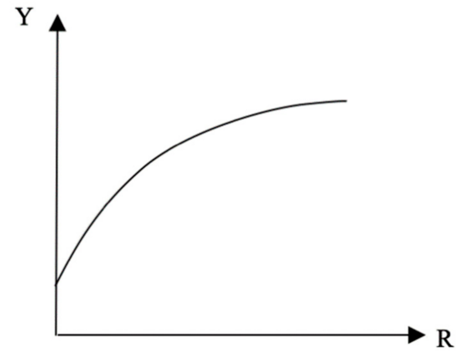

Figure 2. The relationship between the intensity of environmental regulations and output in pollution-intensive industries.

Similarly, the use of R to find first-order and second-order partial derivatives on the output of clean industries will result in the following formulas:

$$\frac{\partial Y_2}{\partial R} = \left\{ d'(W_2)\rho_2 E_2 \cdot \left[\frac{A'_2(R)}{A_2(R)R} + \frac{1}{R^2} \right] + A'_2(R)[1 - d(W_2)] \right\} K_{21}{}^{\alpha_{21}} L_{21}{}^{\beta_{21}} K_{22}{}^{\alpha_{22}} L_{22}{}^{\beta_{22}} E_2{}^{\gamma_2} > 0 \quad (20)$$

$$\frac{\partial^2 Y_2}{\partial R^2} = \left\{ \rho_2 E_2 d'(W_2) \left[\frac{A''_2(R)A_2(R)R - A'^2_2(R)R - A'_2(R)A_2(R)}{A^2_2(R)R^2} - \frac{2}{R^2} \right] + A''_2(R)[1 - d(W_1)] \right\} \cdot K_{21}{}^{\alpha_{21}} L_{21}{}^{\beta_{21}} K_{22}{}^{\alpha_{22}} L_{22}{}^{\beta_{22}} E_2{}^{\gamma_2} \quad (21)$$

When the intensity of regulation is weak, the pollution discharge pressure of clean industries is smaller, so the driving force for technological progress is also weaker, and the growth of $A'_2(R)$ is slower. With the gradual increase in the intensity of regulations, the pressure on the clean industry to discharge pollution also increases. At this time, the driving force for technological progress and the growth rate of $A'_2(R)$ are also gradually increasing, showing as $A''_2(R) > 0$. It can be converted to $A'_2(R) = A''_2(R) \cdot dR < A''_2(R) \cdot R$. As the same, $A_2(R) < A'_2(R) \cdot R$. The right side of Equation (21) can be rewritten as the Equation (23):

$$\frac{A''_2(R)A_2(R)R - A'^2_2(R)R - A'_2(R)A_2(R)}{A^2_2(R)R^2} - \frac{2}{R^2} > -3\left[\frac{A'_2(R)}{A_2(R)R}\right]^2 > -3\left[\frac{A''_2(R)}{A_2(R)}\right]^2, \tag{22}$$

$$\frac{\partial^2 Y_2}{\partial R^2} > A''_2(R)\left\{[1 - d(W_1)] - 3\rho_2 E_2 d'(W_2)\left[\frac{A''_2(R)}{A_2(R)}\right]\right\} \tag{23}$$

In the second term of Equation (23), $A_2(R)$ increases with the increase of R, and $A''_2(R)$ and $d'(W_2)$ are constants, so the term decreases as R increases. As R increases further, the second term will gradually decrease to less than $[1 - d(W_1)]$, so that $\partial^2 Y_2 / \partial R^2$ will change from negative to positive. Therefore, when the intensity of regulation gradually increases, the output of clean industries will gradually increase, but its growth rate will first decline and then rise. Figure 3 shows the relationship between the intensity of environmental regulations and the output of clean industries.

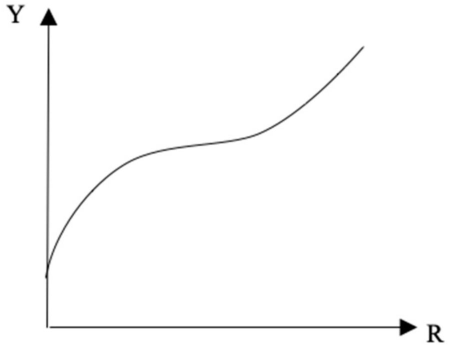

Figure 3. The relationship between the intensity of environmental regulations and output in clean industries.

There are both output compensation effects and innovation compensation effects in pollution-intensive industries and clean industries. The two effects make the output of the two types of industries gradually increase with the increase in the intensity of environmental regulations, but there are differences in the relative magnitude of the two effects in the two types of industries. Due to the low level of pollution control technology and innovation compensation in pollution-intensive industries, pollution control technology will remain unchanged at the original level when regulations are strengthened. The lower technical level is difficult to compensate for the increase in regulatory costs. Manufacturers will increase output by increasing the factor input of the production department, which is called an output compensation effect. Therefore, the output compensation effect of pollution-intensive industries is greater than the innovation compensation effect. The level of pollution control technology and innovation compensation for clean industries are relatively high. When regulations are strengthened, pollution control technologies will be upgraded to maintain a low level of pollution, which will bring about technological progress in the industry. Therefore, the innovation compensation effect of clean industries is greater than the output compensation effect.

When the output compensation effect is dominant, the cost of pollution discharge increases with the enhancement of environmental regulations, and it is becoming more and more difficult to use the increase in output to compensate for the cost of compliance. The output growth rate of pollution-intensive industries is getting slower and slower, and the output gradually increases to a certain level.

The compensation effect of innovation increases output by promoting technological progress. With the improvement of the intensity of regulation, the innovation compensation effect is in a dominant position, which has continuously improved the level of pollution control technology. Because the output growth brought about by the improvement of the technological level is persistent, the output of the clean industry will continue to increase. This leads to Hypotheses 2 and 3.

Hypothesis 2. *With the enhancement of environmental regulations, the output of pollution-intensive industries has gradually increased, but its growth rate has decreased.*

Hypothesis 3. *With the enhancement of environmental regulations, the output of clean industries has gradually increased, and its growth rate first declined and then increased.*

2.4. The Impact of Environmental Regulations on Industrial Green Productivity

Comparing the impact of factor allocation and output of different industries on GTFP in different industries, the change trend of industrial GTFP can be obtained by adding the GTFP of the two types of industries. Hypothesis 1 shows that with the enhancement of environmental regulations, the capital investment in pollution-intensive industries and the capital investment in clean industries have increased, but the increase in capital investment in clean industries has been even greater. Assume that the increment of capital investment among different industries all grow linearly.

For the pollution-intensive industries, we focus on the extreme situation of Hypothesis 2: as the intensity of environmental regulations increases, the capital input of the industry increases linearly while the increment of output decreases to zero. It indicates that the input–output efficiency of pollution-intensive industries, namely GTFP, decreases with the increase of capital input. Therefore, the GTFP of pollution-intensive industries gradually declines with the increase of environmental regulation intensity. For clean industries, it is known from Hypothesis 3 that their output shows a non-linear growth trend. The level of environmental regulation at the output growth rate of zero is taken as the cut-off point. On the left side of the cut-off point, similar to the pollution-intensive industry, the capital input of the industry increases linearly with the increase of environmental regulation intensity, while the increment of output decreases gradually until it reaches zero. The input–output efficiency of the clean industry, namely GTFP, gradually decreases with the increase of capital input. On the right side of the cut-off point, with the increase of the intensity of environmental regulation, the capital input of the industry still increases linearly, but the output increases non-linearly. The input–output efficiency of the clean industry, namely GTFP, gradually increases with the increase of capital input. Thus, the GTFP of clean industry decreases and then increases with the increase of environmental regulation intensity, showing a "U"-shaped trend. Considering the trends of GTFP in pollution-intensive industries and clean industries, the industrial GTFP shows a "U"-shaped trend of decreasing and then increasing in general. This leads to Hypothesis 4.

Hypothesis 4. *With the enhancement of environmental regulations, the allocation of capital between pollution-intensive industries and clean industries has declined, leading to a "U"-shaped trend in industrial GTFP.*

3. Model and Variables

3.1. Regression Model

Equations (24) and (25) are ordinary panel regression models to verify the relationship between environmental regulations and industry output as well as output growth rate.

$$lnY_{it} = \theta_0 + \theta_1 Enr_{it} + \theta_2 Z_{it} + \varphi_{it}, \tag{24}$$

$$ln\dot{Y}_{it} = \theta'_0 + \theta'_1 Enr_{it} + \theta'_2 Enr^2{}_{it} + \theta'_3 Z_{it} + \varphi_{it} \tag{25}$$

where lnY_{it} and $ln\dot{Y}_{it}$ denote the industry output and output growth rate in year t of region i, respectively; Enr_{it} denotes the level of environmental regulation in year t of region i, and Z_{it} is all control variables. The maximum likelihood estimate (MLE) was used to estimate the model to ensure the consistency of the estimation results. Equations (24) and (25) are used to test Hypotheses 1 and 2, respectively.

A three-stage model is used to test the indirect effect of environmental regulation on GTFP by changing the ratio of factor allocation among different industries. Considering the explanatory variable industrial GTFP as a restricted variable, the last two models were replaced with panel Tobit regression models.

$$K\_outflow_{it} = \alpha_0 + \alpha_1 Enr_{it} + \alpha_2 Z_{it} + \varepsilon'_{it}, \tag{26}$$

$$GTFP^*_{it} = \beta_0 + \beta_1 Enr^2_{it} + \beta_2 Enr_{it} + \beta_3 Z_{it} + \vartheta'_{it} \tag{27}$$

$$GTFP^*_{it} = \gamma_0 + \gamma_1 Enr^2_{it} + \gamma_2 Enr_{it} + \gamma_3 K\_outflow_{it} + \gamma_4 K\_outflow_{it}{}^2 + \gamma_5 Z_{it} + \varphi'_{it} \tag{28}$$

$$GTFP_{it} = \begin{cases} 1 & if\ GTFP^*_{it} > 1 \\ GTFP^*_{it} & if\ 0 < GTFP^*_{it} \le 1 \\ 0 & if\ GTFP^*_{it} \le 0 \end{cases} \tag{29}$$

where $K\_outflow_{it}$ denotes the inter-industry capital factor allocation ratio in year t of region i ($K\_outflow_{it}$ is replaced by $L\_outflow_{it}$ to study the inter-industry labor factor allocation ratio), $GTFP_{it}$ denotes the actual industrial GTFP in year t of region i, $GTFP^*_{it}$ is the latent variable, and other variables have the same meaning as above. Considering the consistency of the estimation results, the regression model is estimated by the method of MLE. Equation (26) is used to test Hypothesis 3, where the coefficient α_1 measures the effect of environmental regulation on the factor allocation ratio. Equation (27) verifies the overall effect of environmental regulation on industrial GTFP. The coefficients γ_1 and γ_2 of Equation (28) measure the direct impact of environmental regulation on industrial GTFP. Equations (26) and (28) are used to test Hypothesis 4, whose coefficients α_1, γ_3, and γ_4 together measure the indirect effect of environmental regulation on industrial GTFP by affecting the factor allocation ratio.

3.2. Measurement of GTFP

In this paper, we adopt a non-oriented EBM-ML model with non-consensual outputs to measure industrial GTFP, which can maximize profits by considering both input reduction and output increase and can effectively avoid the productivity overestimation of the oriented model. The industrial GTFP measured in this paper uses capital, labor, and energy as inputs and produces finished products while discharging pollution. Each input–output indicator is selected as follows.

3.2.1. Capital

Most of the existing studies set the depreciation rate to a constant value when calculating capital investment. However, depreciation rates can vary depending on the equipment purchased, the region in which it is located, and the particular year. Therefore, this paper returns to the concept of the basic perpetual inventory method and calculates the depreciation rate using the ratio of the current year's depreciation to the previous year's original cost of fixed assets. Moreover, the initial capital stock will have an impact on the capital stock in subsequent years. In this paper, drawing on Tu Zhengge [17] and Pang Ruizhi and Li, Peng [18], the capital stock is approximated using the annual average balance of the net fixed asset investment of industrial enterprises above the size of each province, and the net fixed asset investment calculated in previous years is adjusted to comparable price data, with the year 2000 as the base period using the fixed asset investment index. The data are obtained from the *China Industrial Economic Statistical Yearbook*.

3.2.2. Labor

The number of employees at the end of the year in industrial enterprises above the size of each province is used to measure labor. The data were obtained from the *China Industrial Economy Statistical Yearbook*, where the year-end number of employees in 2004 was obtained from the 2004 *China Economic Census Yearbook*.

3.2.3. Energy

The energy consumption of industrial enterprises above the size of each province was used to measure energy. The data are obtained from the energy consumption of each region in the *China Energy Statistical Yearbook*. In this paper, the unit of energy consumption is converted to million tons of standard coal using the conversion coefficient, which is obtained from the *China Energy Statistical Yearbook* of previous years.

3.2.4. Expected Output

The expected output is generally measured using industrial GDP [3,19] or industrial value added [20,21] in existing studies. Since the energy in the input indexes has the nature of intermediate inputs when calculating industrial GTFP in this paper, it is appropriate to use the industrial GDP that includes the cost of intermediate inputs for the expected output [19]. At the same time, considering the availability of data and the consistency across years, the total industrial output value of each province is used as the expected output indicator in this paper. In order to eliminate the price factor, the industrial GDP of each province is deflated by using the ex-factory industrial producer price index of each province separately, using the year 2000 as the base period. The data are obtained from the *China Industrial Economic Statistical Yearbook*.

3.2.5. Non-Expected Output

The EBM-ML is a relative efficiency accounting method. This means that when the measurement indicators of each variable remain relatively consistent, the results will not have large deviations [22]. Considering the availability of data, in this paper, the industrial wastewater emissions, industrial sulfur dioxide emissions, and industrial smoke (dust) emissions of each province are combined into one pollution index to measure the industrial non-desired output of each province. As for the methods of comprehensive evaluation, there are principal component analysis, factor analysis, expert scoring method, and entropy value method. The entropy value method determines the indicator weights based on the relative changes of the impact of the indicators on the overall system, which can reflect the effect and value of the indicators. It is similar to the effect of the role of each indicator in the pollution index, in which the main factors affecting the pollution index are also those with a large degree of variation. Therefore, this paper adopts the entropy value method to estimate the weights of each indicator in the pollution index and then the weighted average of three kinds of pollution emissions to obtain the comprehensive pollution index, which is used to measure the industrial pollution emission level of each province in China. The pollutant emission data are obtained from the *China Environmental Statistical Yearbook* and the *China Environmental Yearbook*. This paper uses MaxDEA 8 Ultra software to measure the industrial GTFP of 30 provinces of China in calendar years except Tibet.

3.3. Variable Selection

3.3.1. Environmental Policies and Regulation

The intensity of environmental regulations represents the severity of environmental regulations in various regions. In empirical research, scholars at home and abroad mainly use six methods to measure the intensity of environmental regulations, such as the promulgation and implementation of environmental policies in various regions, the amount of pollution emitted per unit of production, the costs or expenses incurred during the operation of pollution control facilities in various regions, per capita pollution control expenses, the proportion of the company's total cost or total output value of the company's pollution control costs, per capita income, and a comprehensive index constructed based on the emissions of three main pollutants (exhaust gas, wastewater, and solid waste). However, all these methods have certain shortcomings. The number of policies only reflects the importance of environmental protection at all levels of government, but not the level of implementation of the relevant policies. In addition, data on the implementation efforts are difficult to obtain. The amount of pollution emitted per unit of product is greatly influenced by product heterogeneity. The operating cost of pollution control in each region is influenced by the size of local enterprises and the industry they belong to, and the data are not comparable between regions. The proportion of pollution control costs of enterprises is affected by the heterogeneity of enterprises, for example, the proportion of pollution control costs of enterprises in low-pollution industries is lower, while the proportion of pollution control costs of enterprises in high-pollution industries tends to be higher. The relationship between per capita income and the intensity of environmental regulations is not simply linear; as per capita income increases, people become less tolerant of the environment. The composite index constructed using pollutant emissions only reflects the absolute quantity of pollution emissions, ignoring the heterogeneity of regions and industries.

Based on the above analysis, the ideal proxy variable for environmental regulation should both characterize the absolute level of pollution emissions of enterprises within the region and reflect the difference between the emissions of the region and other regions. Considering the data availability and data quality, this paper constructs the following composite indicators as the proxy variables of environmental regulation.

$$Enr_{it} = \frac{1}{3}\sum_{j=1}^{3}\left(v_{ij}/\frac{1}{30}\sum_{i=1}^{30}v_{ij}\right), \tag{30}$$

where v_{ij} is the industrial value added for the region i by emitting one unit of the pollutant j, which indicates the relative level of the output value per unit of pollution emission of a region in the country. The higher the industrial value added and the lower the pollution emission, the higher the intensity of environmental regulation in the region. Meanwhile, the unit pollution control investment is used as a robustness test. The unit pollution control investment is calculated by dividing the regional pollution control investment by the pollution composite index. The higher pollution control cost a region invests in pollution control, the higher the intensity of environmental regulation.

3.3.2. Output of Different Industries

The division of pollution-intensive industries and clean industries was carried out by drawing on the study of Ling Li and Feng Tao [23]. First, the pollution emissions per unit of output value of wastewater, exhaust gas, and solid waste were calculated for each segment of industry. Then, the pollution emission values per unit output value of the three pollutants for each industry were linearly normalized according to a range of values from 0 to 1. Finally, the above three pollution emission scores are arithmetically averaged to obtain the total pollution emission intensity factor γ for the industry. The median of the pollution emission intensity coefficient (γ_m) is used as the standard. If $\gamma < \gamma_m$, then it is a clean industry; if $\gamma > \gamma_m$, then it is a pollution-intensive industry. With the development of the economy and the adjustment of industrial structure, the ranking of pollution emissions of various industries in different places has changed in the past years. Therefore, in this paper, the sub-sectors of pollution-intensive and clean industries are obtained for 30 provinces across the country from 2000 to 2017, respectively, by pollution emission intensity for different years. Therefore, this paper divides each industry by pollution emission intensity within different years to obtain the breakdown of pollution-intensive and clean industries in 30 provinces across China from 2000–2017. Limited to the availability of pollutant emissions by industry by province, provincial differences are not considered in this paper.

Referring to the above classification criteria, the sales value of each industrial subsector belonging to pollution-intensive industries is summed up as the output of pollution-intensive industries. The growth rate of output is calculated by using (current year's sales output − previous year's sales output)/previous year's sales output. Similarly, the output and output growth rate of clean industries can be obtained.

3.3.3. Allocation Ratio of Elements among Industries

For the capital factor ($K\_outflow_{it}$), the fixed asset investments belonging to pollution-intensive and clean industries are summed up separately and converted to capital stock using the perpetual inventory method (the same method as before). Then, the capital stock K_{1it} of pollution-intensive industries is divided by the capital stock K_{2it} of clean industries as the allocation ratio of capital factors among industries. An increasing ratio indicates that capital is invested more in pollution-intensive industries, and vice versa indicates that it is invested more in clean industries.

For the capital element ($L\_outflow_{it}$), the year-end number of employees in the corresponding industries is summed up separately according to the industry classification. Then, the year-end number of employees L_{1it} of pollution-intensive industries is divided by the year-end number of employees L_{2it} of clean industries as the allocation ratio of labor factors among industries. An increasing ratio indicates that labor is invested more in pollution-intensive industries, and vice versa indicates that it is invested more in clean industries.

3.3.4. Control Variables

Referring to existing studies, this paper selects technological progress [24], property rights structure [25], industrial agglomeration [26], energy consumption structure, economic development level, wage level [27], and foreign direct investment [28] as the control variables of the model. The measurement of each variable is shown in Table 1.

Table 1. Description of control variables.

Variable Name	Proxy Variables	Measurement Method
Technological Progress (TEC_{it})	Effective invention patents for enterprises.	Number of valid invention patents for industrial enterprises in each region.
Property Rights Structure (PRO_{it})	The proportion of output value of state-owned enterprises.	The output value of state-owned and state-controlled industrial enterprises divided by the output value of industrial enterprises above the scale.
Industrial Agglomeration (LQ_{it})	Zone entropy index.	$LQ_{it} = \frac{x_{it}/\sum_i x_{it}}{\sum_n x_{it}/\sum_i \sum_n x_{it}}$
Energy Consumption Structure (EST_{it})	Percentage of coal energy consumption.	Coal consumption divided by total energy consumption.
Economic Development ($GDPP_{it}$)	GDP per capita.	Standardized regional GDP per capita.
Wage (WAG_{it})	Average wage.	Standardized regional average wage of industrial enterprises.
Foreign Direct Investment (FDI_{it})	Percentage of actual foreign investment utilized.	Actual utilization of foreign investment by industrial enterprises divided by industrial value added.

3.4. Data Source and Processing

The research object of this paper is industry. Data from 2000 to 2017 are selected for 30 provinces across China, excluding Tibet, where there are serious data deficiencies. The time span is selected mainly for the following three reasons. First, the inflection point in the regional allocation of economic resources by the state in 2000, e.g., from 2000, the state allocated more construction land targets and transfer payments to the central and western regions [29]. Using only the data after this inflection point prevents policy shocks from biasing the estimation of the econometric model. Second, to ensure the completeness of all the data available in this paper, the cut-off year of the data is 2017, because the data related to industrial wastewater, industrial sulfur dioxide, and industrial solid waste emissions are not available in the *China Environmental Statistics Yearbook 2019* and subsequent yearbooks. Third, the longer the time span the more likely to be disturbed by policy changes, and the greater the possibility of bias in the regression analysis, because China is in an era of change.

The data related to environmental regulation, inter-industry factor allocation ratio, and control variables are obtained from the *China Statistical Yearbook*, *China Industrial Economic Statistical Yearbook*, *China Energy Statistical Yearbook*, *China Science and Technology Statistical Yearbook*, *Labor Statistical Yearbook*, and *Fixed Asset Investment Yearbook* of each province from 2001 to 2018. For the data of industrial enterprises above the scale, the ratios of industrial enterprises above the scale to all industrial enterprises in the *China Economic Census Yearbook* in 2004, 2008, and 2013 were collected, and the data of other years were completed by using Python fitting. The resulting data are then used to adjust each indicator to all industrial enterprises. In order to eliminate the influence of prices, this paper takes the year 2000 as the base period and uses price indices to convert the relevant indicators into the actual amounts calculated according to constant prices. Total assets were adjusted using the perpetual inventory method by drawing on the practice of Jun Zhang et al. [30].

4. Results and Discussion

4.1. The Impact of Environmental Regulations on the Allocation Ratio of Factors among Industries

Model (4) and model (5) in Table 2 show the effect of environmental regulations on the proportion of factors allocated among industries. The results show that as the intensity of environmental regulation increases, capital and labor factors are allocated more toward clean industries. Hypothesis 1 is tested. Production and R&D sectors exist within both pollution-intensive and clean industries. When the intensity of regulation starts to increase, the output compensation is greater than the innovation compensation, causing more allocation of factors to the production sector. Pollution-intensive industries discharge relatively more pollution, and their output compensation is smaller than that of technology-intensive industries, which implies that the marginal cost of factors in pollution-intensive industries is higher when the amount of factor inputs is the same in both industries. Therefore, rational manufacturers will allocate more capital and labor to clean industries, causing the allocation ratio of factors between industries to decrease. Therefore, rational manufacturers will allocate more capital and labor to clean industries, causing the allocation ratio of factors between industries to decrease. When the intensity of regulation increases further, factors are allocated more to the R&D sector because the innovation compensation is greater than the output compensation. The higher level of pollution control technology is in the clean sector, and its innovation compensation is smaller than that in the pollution-intensive sector, indicating that the marginal cost of factors in the clean sector is lower when the amount of factor inputs is the same in both sectors. Therefore, rational manufacturers will still allocate more capital and labor to clean industries, causing a further decrease in the factor allocation ratio between industries.

4.2. The Impact of Environmental Regulations on the Output of Different Types of Industries

A time-fixed effects panel model was used for estimation. The results of model (1) and model (3) in Table 3 show that as the intensity of environmental regulation increases, the output of pollution-intensive industries increases significantly, but the output growth rate decreases significantly. Hypothesis 2 is tested. The results of model (2) and model (4) show that as the intensity of environmental regulation increases, the output of clean industries increases significantly, and the output growth rate decreases and then increases in a "U"-shaped trend. Hypothesis 3 is tested. Since the output compensation effect of pollution-intensive industries is greater than the innovation compensation effect, the increase in regulation raises the cost of pollution emissions and makes it more and more difficult to compensate for the cost by increasing output. Therefore, the growth rate of output in pollution-intensive industries gradually decreases, and the output tends to a specific level in the process of gradual increase. The innovation compensation effect of clean industries is greater than the output compensation effect, and the innovation compensation effect enhances output through technological progress. With the increase of regulation intensity, the innovation compensation effect is in the dominant position to make the technology level of pollution control continuously improve. The output of clean industry will continue to increase because of the durability of the output growth brought by technological advancement. However, the initial stage of technological innovation requires a large amount of investment, which squeezes out some production inputs in the short term, thus causing a decrease in the output growth rate. At a later stage, production inputs are supplemented while innovations bring about technological advances, causing output growth rates to increase.

Table 2. Description of control variables.

Variables	GTFP			$K\_outflow_{it}$	$L\_outflow_{it}$
	(1)	(2)	(3)	(4)	(5)
ENR_{it}	0.1999 ***(3.06)	0.1825 ***(2.80)	0.1987 ***(3.06)	−0.0013 *(−1.67)	−0.0299 *(−1.81)
ENR_{it}^2	−0.1325 **(−2.07)	−0.1164 *(−1.82)	−0.1300 **(−2.04)	-	-
$K\_outflow_{it}$	-	0.0283 **(2.05)	-	-	-
$K\_outflow_{it}^2$	-	−0.0041 **(−2.49)	-	-	-
$L\_outflow_{it}$	-	-	0.0118 **(2.20)	-	-
$L\_outflow_{it}^2$	-	-	−0.0007 **(−2.21)	-	-
TEC_{it}	0.0007 *(1.92)	0.0005 *(1.81)	0.0005 *(1.73)	−0.1152 **(−2.37)	−0.4122 ***(−2.85)
PRO_{it}	−0.0616 *(−1.79)	−0.0514 **(−2.19)	−0.0521 **(−1.98)	0.2013 *(1.71)	0.0049 *(1.92)
LQ_{it}	0.2132 ***(7.11)	0.2063 ***(6.87)	0.2063 ***(6.86)	0.5375 **(2.33)	2.0510 ***(2.99)
EST_{it}	−0.1252 ***(−3.71)	−0.1169 ***(−3.46)	−0.1300 ***(−3.86)	0.6411 **(2.28)	0.1321 *(1.77)
$GDPP_{it}$	0.0001 ***(4.57)	0.0001 ***(4.55)	0.0001 ***(4.65)	−0.0001(−4.14)	−0.0001 **(−2.36)
FDI_{it}	−0.0020 *(−1.69)	−0.0022 *(−1.88)	−0.0019 *(−1.73)	0.0118 *(1.86)	0.1015 *(1.80)
WAG_{it}	−0.0001 *(−1.81)	−0.0001 *(−1.69)	−0.0001 *(−1.88)	0.0004 ***(4.92)	0.0005 **(2.13)
_Cons	0.5494 ***(5.29)	0.5107 ***(4.82)	0.5364 ***(5.12)	−2.8058 ***(−3.04)	−2.2331 (−0.81)
Regulatory Inflection Point	Direct Impact	Indirect impact		-	-
	0.75	0.78	0.76	-	-
Maximum or minimum value	0.62(Max)	0.58(Min)	0.61(Min)	-	-
N	540	540	540	540	540
F Test	-	-	-	5.43 ***	3.07 ***
Wald Test	216.56 ***	226.64 ***	224.41 ***	-	-
LR Test	360.18 ***	344.13 ***	361.46 ***	-	-

Remarks: t statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3. Regression results of the impact of environmental regulations on output of different types of industries.

Variables	Outputs		Output Growth Rate	
	Pollution-Intensive Industries	Clean Industries	Pollution-Intensive Industries	Clean Industries
	(1)	(2)	(3)	(4)
ENR_{it}	396.7292 ***(7.10)	493.2701 ***(7.74)	−0.0246 **(−2.46)	−2.0107 *(−1.66)
ENR_{it}^2	-	-	-	0.6948 *(1.70)
TEC_{it}	0.0301 ***(6.16)	0.0933 ***(16.73)	0.0718 ***(13.48)	0.1267 ***(19.33)
PRO_{it}	−7698.965 ***(−14.80)	−8481.071 ***(−14.28)	0.0143 ***(8.27)	0.0638 ***(6.39)
LQ_{it}	1538.719 **(2.47)	1587.726 **(2.23)	0.1049 ***(5.66)	0.1515 ***(4.58)
EST_{it}	182.3217 (0.59)	17.4476 (0.05)	0.0156 *(1.82)	0.0530 *(1.79)
$GDPP_{it}$	0.0176 *(1.95)	0.0246 **(2.38)	0.0718 **(2.48)	0.0626 **(2.05)
FDI_{it}	−158.7626 ***(−4.56)	−160.6637 ***(−4.05)	−0.0028 ***(−4.62)	−0.0030 ***(−5.71)
WAG_{it}	−0.0341 (−0.64)	−0.0286 (−0.47)	−0.0618 (−0.92)	−0.0816 (−1.35)
_Cons	3794.05 ***(4.42)	4009.825 ***(4.09)	0.0484 (0.30)	1.6831 *(1.86)
Time Fixed	YES	YES	YES	YES
N	540	540	510	510
F Test	73.81 ***	144.83 ***	25.46 ***	14.88 ***

Remarks: *t* statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.3. The Impact of Environmental Regulation on GTFP

4.3.1. The Overall Impact of Environmental Regulation on GTFP

Model (1) in Table 2 shows the regression results of the overall effect of environmental regulation on GTFP. The regression equation is valid overall, due to the Wald value being significant at the 1% level. The results of the LR test of the equation reject the original hypothesis of fixed effects at the 1% level of significance, indicating that it is reasonable to use a panel Tobit model with random effects. The coefficients of both the primary and secondary terms of environmental regulation in model (1) are significant, indicating that there is a significant nonlinear relationship between environmental regulation and industrial GTFP. Specifically, the coefficients of the primary term of environmental regulation are significantly negative and the coefficients of the secondary term are significantly positive, indicating that as the intensity of environmental regulation increases, industrial GTFP increases and then decreases, showing an inverted "U"-shaped relationship.

4.3.2. Indirect Effects of Environmental Regulations on Industrial GTFP-Mediating Role of Inter-Industry Factor Allocation

In models (2) and (3) of Table 2, the coefficients of the primary term and the quadratic term of the allocation of capital and labor among industries are significantly positive and negative, indicating that the industrial GTFP decreases and then increases with the allocation of factors to clean industries (as shown by the decrease in the value), showing a "U"-shaped trend. Combining the results of model (4) and model (5) in Table 2, it is clear that the effect of environmental regulation on industrial GTFP stems from the relative changes in GTFP of pollution-intensive industries and GTFP of clean industries. As the intensity of environmental regulation increases, the allocation ratio of factors in pollution-intensive industries and clean industries decreases, resulting in a "U"-shaped trend of industrial GTFP. Hypothesis 4 is verified.

Models (2) and (3) show that the direct effect of environmental regulation on industrial GTFP has an inverted "U" shape. Comparing the direct and indirect effects of environmental regulation on industrial GTFP, we find that increasing the intensity of environmental regulation oriented to changing the allocation ratio of factors among industries can "reverse" the effect of high-intensity regulation to suppress industrial GTFP and achieve the effectiveness of government environmental management instruments. Comparing the magnitude of the inflection points in models (1), (2), and (3), we find that the inflection points in models (2) and (3) are larger than those in model (1), indicating that ignoring the mediating role of the inter-industry factor allocation ratio overestimates the inflection point of environmental regulation. The change of factor allocation ratio among industries can improve the decline of industrial GTFP due to the high intensity of regulation, to a certain extent.

4.4. Robustness Tests

In order to ensure the reliability and scientific validity of the regression results, this paper uses three methods to test the robustness of the results. First, different proxy variables for the core variables will cause differences in the results, so this paper replaces the proxy variables for environmental regulation with unit pollution control investment to re-regress. Second, outliers can cause errors in the estimation results, and the truncated and shrunken tails of each variable can precisely solve the bias caused by outliers effectively. In this paper, a 1% two-way truncation and a 1% two-way tail reduction are applied to all variables. Third, the ordinary least squares (OLS) method was used to regress the original equations. The results of the robustness test show that the relationship and significance between environmental regulation, inter-industry factor input structure, and industrial GTFP are consistent with the results of the benchmark regression after replacing the core explanatory variables, applying tailoring and truncation to all variables and changing the regression method. Therefore, the existing results in this paper have strong robustness. Due to space limitations, the results of the robustness test are shown in Appendix A.

4.5. Endogenous Issues

The endogenous factors between variables are not taken into account in the above analysis. For example, areas with low industrial GTFP are relatively more polluted and tend to use higher intensity environmental regulations in order to reduce pollution, which leads to an inverse causal relationship between environmental regulations and industrial GTFP. The existence of endogenous factors can bias the estimation results. In this paper, the endogenous factors are treated by using the air flow coefficient as an instrumental variable for environmental regulations.

On the one hand, the more air mobility a region has, the less pollution it has, and the larger the composite index of the proxy variable for environmental regulation the less pollution it has. Therefore, the air mobility coefficient is correlated with environmental regulation and satisfies the hypothesis of correlation of instrumental variables [31]. On the other hand, the air flow coefficient is used to measure the geographical characteristics of a region, satisfying the endogenous assumption of the instrumental variable, while the industrial GTFP is used to measure its economic characteristics [32]. Drawing on the study of Shiyi Chen and Dengke Chen [33], this paper uses the air flow coefficient to measure environmental regulation. The construction method is as follows:

$$VC_{it} = WS_{it} \times BLH_{it}, \tag{31}$$

where VC_{it} is the air flow coefficient, WS_{it} is the wind speed, and BLH_{it} is the atmospheric boundary layer height. The raw data of WS_{it} and BLH_{it} are obtained from the monthly average data of ERA-Interim released by the European Centre for Medium-Range Weather Forecasts (ECMWF). Considering that the data are global data under each latitude and longitude, in order to obtain the data for 30 Chinese provinces from 2000–2017, this paper uses Python to correspond them on the map of China and averages the data under the latitude and longitude in each province.

Table 4 shows the results of the two-step estimation of the system two-stage least squares (2SLS). The F-values of the first-stage regressions are all greater than 10 and significant at the 1% level, indicating that the selected air mobility coefficients do not have weak instrumental variable problems. The results of the second stage indicate that the direct effect of environmental regulation on industrial GTFP is an inverted "U" shape, but the greater allocation of capital and labor factors to clean industries makes industrial GTFP "U"-shaped. Therefore, the shift in the allocation of factors among industries can "reverse" the suppression of industrial GTFP by high-intensity environmental regulations.

Table 4. The 2SLS regression results for the effect of environmental regulation on GTFP.

Variables	First Stage		Second Stage	First Stage		Second Stage
	Allocation of Capital among Industries			Allocation of Labor among Industries		
	ENR_{it}	ENR_{it}^2	$GTFP_{it}$	ENR_{it}	ENR_{it}^2	$GTFP_{it}$
	(1)	(2)	(3)	(4)	(5)	(6)
ENR_iv_{it}	0.0192 *** (2.84)	0.1111 *** (3.20)	-	0.0204 *** (2.95)	0.0754 * (1.91)	-
$ENR\_iv_{it}^2$	−0.0001 *** (−3.14)	−0.0005 *** (−3.40)	-	−0.0001 *** (−3.25)	−0.0003 ** (−2.30)	-
$K\_outflow_{it}$	0.5651 ** (2.32)	3.9412 ** (2.31)	0.0285 * (1.79)	-	-	-
$K\_outflow_{it}^2$	−0.1227 ** (−1.99)	−0.8618 ** (−2.17)	−0.0034 * (−1.88)	-	-	-
$L\_outflow_{it}$	-	-	-	0.7677 * (1.81)	9.4834 *** (2.60)	0.2132 * (1.85)
$L\_outflow_{it}^2$	-	-	-	−0.2310 * (−1.70)	−2.9166 ** (−2.29)	−0.0634 * (−1.92)

Table 4. *Cont.*

Variables	First Stage		Second Stage	First Stage		Second Stage
	Allocation of Capital among Industries			Allocation of Labor among Industries		
	ENR_{it}	$ENR_{it}{}^2$	$GTFP_{it}$	ENR_{it}	$ENR_{it}{}^2$	$GTFP_{it}$
	(1)	(2)	(3)	(4)	(5)	(6)
ENR_{it}	-	-	0.3944 *** (2.67)	-	-	0.3948 ** (2.47)
$ENR_{it}{}^2$	-	-	−0.0575 * (−1.83)	-	-	−0.0538 * (−1.73)
_Cons	YES	YES	YES	YES	YES	YES
Control variables	YES	YES	YES	YES	YES	YES
N	540	540	540	540	540	540
Wald Test	-	-	113.39 ***	-	-	129.09 ***
Adjust R^2	0.2387	0.1778	-	0.2360	0.1816	-
F-value of First stage	8.66 ***	4.69 ***	-	9.02 ***	4.61 ***	-

Remarks: *t* statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5. The Influence of Heterogeneous Factors

5.1. Changes in the Ratio of Capital to Labor within Each Industry at the Time of Factor Input

It is known from the results in Chapter 4 that an increase in the intensity of environmental regulation causes more capital and labor to be invested in clean industries, but are the capital and labor factor inputs synchronized? Do factor inputs cause a change in the ratio of capital and labor factor inputs within pollution-intensive and clean industries? If the factor input ratio changes, how does this change affect the GTFP of the industry as a whole? The following section investigates the impact of factor input ratios using the capital and labor ratios within pollution-intensive and clean industries, respectively, replacing the factor allocation ratios across industries in the original model. Table 5 shows that the increase in the intensity of regulation causes the ratio of capital to labor input within the two industries to increase and then decrease. Therefore, the inputs of capital and labor are likewise not synchronized between industries. When the intensity of regulation is weak, manufacturers tend to add more capital elements. As the intensity of regulation gradually increases, manufacturers' preference for labor factors gradually emerges, and the capital–labor ratio within the two industries changes in the process of additional factor inputs by manufacturers. The increase of capital input relative to labor input significantly reduces industrial GTFP within both pollution-intensive and clean industries, indicating that human capital has a stronger role in enhancing GTFP compared to fixed assets. Comparing the rate of change in the ratio of capital and labor inputs between the two industries, the rate of impact of the capital–labor ratio on industrial GTFP within clean industries is greater than that in pollution-intensive industries ($|-0.0009|>|-0.0003|$). This is related to the fact that clean industries tend to have a higher level of pollution control.

Table 5. Regression results of the effects of environmental regulations, capital, and labor ratios within each industry on industrial GTFP.

Variables	K/L_pol_{it}	K/L_cle_{it}	GTFP	
	(1)	(2)	(3)	(4)
ENR_{it}	15.3773 ***(3.57)	1.9821 *(1.69)	0.1949 ***(2.95)	0.2002 ***(3.06)
$ENR_{it}{}^2$	−14.5208 ***(−3.44)	−1.2.4782 *(−1.88)	−0.1279 **(−1.97)	−0.1331 **(−2.07)
K/L_pol_{it}	-	-	−0.0003 *(−1.78)	-
K/L_cle_{it}	-	-	-	−0.0009 *(−1.91)
Control Variables	YES	YES	YES	YES
_Cons	YES	YES	YES	YES
Time Fixed	YES	YES	-	-
N	540	540	540	540
F Test	9.99 ***	19.63 ***	-	-
Wald Test	-	-	217.13 ***	216.58 ***
LR Test	-	-	343.47 ***	314.85 ***

Remarks: *t* statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.2. Differences in the Effects of Capital and Labor Allocation between Industries

Table 6 shows the differences in the impact of environmental regulation on GTFP when capital and labor factors are allocated between industries. The minimum values of factor allocation coefficients, regulatory inflection points, and GTFP are illustrated here for comparison. First, the absolute values of both the primary and quadratic term coefficients of the inter-industry allocation of capital factors are larger than those of the inter-industry allocation of labor factors, indicating that the inter-industry allocation of capital factors has a stronger impact on GTFP. This is because China's current industrial enterprises are mainly capital-intensive, and such enterprises are more sensitive to changes in capital. Second, comparing the regulatory inflection points of the indirect effects of environmental regulation on GTFP mediated by the inter-industry allocation of capital and labor factors, it can be found that the regulatory inflection point of the inter-industry allocation of labor is located to the right of capital, and the corresponding minimum value of GTFP is larger than that of capital, which shows that the interval of regulation to enhance GTFP is longer and the starting point is higher. That is, the effect of labor inter-industry allocation on the effect of regulation is more persistent. This suggests that, compared to physical capital, human capital is the core driver of high-quality economic development.

Table 6. Differences between capital and labor allocation in the indirect effects of environmental regulation on GTFP.

		Capital	Labor
Coefficients of factor allocation	Primary term coefficients	0.0283 **	0.0118 **
	Quadratic term coefficients	−0.0041 **	−0.0007 **
Regulatory Inflection Point		0.78	0.76
Minimum value of GTFP		0.58	0.61

Remarks: *t* statistics in parentheses: ** $p < 0.05$.

6. Conclusions

In this paper, we divided industries into pollution-intensive and clean industries to construct a two-sector vendor production function with endogenous technological progress. This paper analyzed the effects of environmental regulations on factor inputs and outputs in different industries and derived the mediating role of inter-industry allocation of factors in the impact on industrial GTFP. Then, we used industrial panel data of 30 Chinese provinces from 2000–2017 and an EBM-ML model to measure the whole industrial GTFP and used Tobit panel regression and instrumental variables to test the effect of environmental regulation on industrial GTFP and the role of inter-industry factor allocation ratio on the effect of regulation. The air flow coefficient was then used as an instrumental variable of environmental regulation to solve the problem of endogenous factors in the original model. Finally, the results were discussed with respect to the heterogeneity of factors. The paper draws the following conclusions:

1. The relative magnitude of output compensation and innovation compensation in the production and R&D sectors changes the impact of environmental regulation on factor inputs and outputs across industries, and the combined effect of both inputs and outputs affects the level of GTFP. From the perspective of factor inputs, as the intensity of regulation increases, factors are allocated more toward clean industries. From the perspective of output, the pollution-intensive industry decreases the output growth rate with the increase of regulation intensity because the output compensation is greater than the innovation compensation, and the clean industry increases the output growth rate with the increase of regulation intensity because the innovation compensation is greater than the output compensation. Therefore, the government should further improve the innovation incentive policy for enterprises and reduce or waive part of the taxes or implement innovation subsidies for industrial enterprises to help them reduce innovation costs and smoothly pass through the technology development period.
2. The change in the factor allocation ratio among industries can "reverse" the inhibitory effect of high-intensity environmental regulations on industrial GTFP and effectively increase industrial GTFP. In terms of direct effects, the impact of regulation on industrial GTFP is an inverted "U" shape. In terms of indirect effects, the increase of environmental regulations will lead to a greater allocation of capital and labor factors to clean industries, and the industrial GTFP will be in a "U" shape. Therefore, environmental regulation policies should be formulated to promote the change of the factor allocation ratio among industries, so as to promote the reasonable allocation of factor resources among industries, thus effectively alleviating the production pressure brought by high regulation intensity and improving industrial GTFP.
3. Manufacturers' preference for capital and labor factors varies with the intensity of regulation. When regulation is weak, firms tend to add more capital factors, and as the intensity of regulation increases, firms tend to add more capital factors. It suggests that human capital is stickier to the intensity of regulation. Although the inter-industry allocation of capital factors has a greater intensity on GTFP, the inter-industry allocation of labor has a more lasting effect on the effect of regulation, and human capital is the core driver of high-quality economic development. Therefore, to achieve high-quality development of the industrial economy, the investment in human capital should be increased and the level of technological innovation should be enhanced.

The conclusions of this manuscript argue for the implementation of existing environmental regulation policies and point the way to the development of environmental policies and regulations for the Chinese government. It also shows what kind of environmental regulations can be formulated to promote economic growth while reducing pollution. This manuscript is devoted to the study of environmental regulations that decouple environmental pollution from economic development. On the one hand, it monitors the effects of policy implementation. On the other hand, it provides feasible suggestions for policy formulation.

There are two limitations of this paper: (1) The findings suggest that the relative size of output compensation and innovation compensation affects the ratio of environmental regulation to factor allocation among industries, and the specific values of output compensation and innovation compensation are not calculated here. Future research can use feasible methods to calculate the size of output compensation and innovation compensation and further analyze the impact of the difference between the two types of compensation on the ratio of factor allocation among industries. (2) Restricted by data availability, the research interval of this paper is 2000–2017. If the data can be updated to 2020, the relevance of the study will be more significant.

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Appendix A

The appendix is the result of the robustness test.

Table A1. Regression results of the impact of unit pollution control investment on industrial GTFP.

Variables	GTFP			$K\_outflow_{it}$	$L\_outflow_{it}$
	(1)	(2)	(3)	(4)	(5)
ENR_{it}	0.0777 ***(4.80)	−0.0353 **(−2.12)	0.0002 ***(−2.56)	−0.0013 *(−1.67)	−0.0299 *(−1.81)
ENR_{it}^2	−0.0784 ***(−2.75)	−0.0054 ***(3.28)	1.03×10^{-6} ***(4.37)	-	-
$K\_outflow_{it}$	-	0.0025 *(1.89)	-	-	-
$K\_outflow_{it}^2$	-	−0.0001 *(−1.78)	-	-	-
$L\_outflow_{it}$	-	-	0.0020 **(2.41)	-	-
$L\_outflow_{it}^2$	-	-	−0.0001 **(−2.02)	-	-
TEC_{it}	0.0059 ***(5.85)	2.39×10^{-6} ***(5.89)	2.28×10^{-6} ***(5.67)	−0.1152 **(−2.37)	−0.4122 ***(−2.85)
PRO_{it}	−0.5549 ***(−17.91)	−0.5504 ***(−17.39)	−0.5493 ***(−17.80)	0.2013 *(1.71)	0.0049 *(1.92)
LQ_{it}	0.0959 **(2.55)	0.0946 **(2.52)	0.0999 ***(2.68)	0.5375 **(2.33)	2.0510 ***(2.99)
EST_{it}	−0.0456 **(−2.10)	−0.0450 **(−2.07)	−0.0377 *(−1.73)	0.6411 **(2.28)	0.1321 *(1.77)
$GDPP_{it}$	0.0129 ***(9.20)	5.13×10^{-6} ***(8.99)	5.04×10^{-6} ***(8.97)	−0.0001 (−4.14)	−0.0001 **(−2.36)
FDI_{it}	−0.0001 ***(−3.79)	−0.0001 ***(−3.75)	−0.0001 ***(−3.70)	0.0118 *(1.86)	0.1015 *(1.80)
WAG_{it}	−0.0076 ***(−3.65)	−0.0074 ***(−3.52)	−0.0069 ***(−3.33)	0.0004 ***(4.92)	0.0005 **(2.13)
_Cons	0.7415 ***(12.55)	0.7460 ***(12.57)	0.7582 ***(12.73)	−2.8058 ***(−3.04)	−2.2331 (−0.81)
N	540	540	540	540	540
F Test	-	-	-	5.43 ***	3.07 ***
Wald Test	192.41 ***	201.91 ***	207.63 ***	-	-
LR Test	342.67 ***	345.15 ***	353.44 ***	-	-

Remarks: *t* statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A2. Regression results after shrinking and censoring.

Variables	GTFP			$K\_outflow_{it}$	$L\_outflow_{it}$
	(1)	(2)	(3)	(4)	(5)
1% two-way tail reduction of all variables					
ENR_{it}	0.2034 ***(3.08)	0.0447 ***(4.22)	0.0463 ***(4.42)	−0.2184 **(−2.12)	−0.1263 *(−1.79)
ENR_{it}^2	−0.1316 **(−2.03)	−0.0102 ***(−2.58)	−0.0186 ***(−2.76)	-	-
$K\_outflow_{it}$	-	0.2261 *(3.43)	-	-	-
$K\_outflow_{it}^2$	-	−0.1592 **(−2.45)	-	-	-
$L\_outflow_{it}$	-	-	0.2205 ***(3.38)	-	-
$L\_outflow_{it}^2$	-	-	−0.1444 **(−2.26)	-	-
_Cons	YES	YES	YES	YES	YES
Control Variables	YES	YES	YES	YES	YES
N	540	540	540	540	540
F Test	-	-	-	2.95 ***	3.15 ***
Wald Test	201.41 ***	213.21 ***	221.54 ***	-	-
LR Test	349.14 ***	355.05 ***	363.21 ***	-	-

Table A2. *Cont.*

Variables	GTFP			$K\_outflow_{it}$	$L\_outflow_{it}$
	(1)	(2)	(3)	(4)	(5)
1% two-way truncation of all variables					
ENR_{it}	0.1067 ***(4.39)	0.0337 ***(3.23)	0.0353 ***(3.46)	−0.2323 **(−2.19)	−0.1349 *(−1.87)
ENR_{it}^2	−0.0569 *(1.83)	−0.0024 *(−1.71)	−0.0026 *(−1.91)	-	-
$K\_outflow_{it}$	-	0.1261 **(1.97)	-	-	-
$K\_outflow_{it}^2$	-	-	-	-	-
$L\_outflow_{it}$	-	-	0.1155 *(1.83)	-	-
$L\_outflow_{it}^2$	-	-	−0.0609 *(−1.88)	-	-
_Cons	YES	YES	YES	YES	YES
Control Variables	YES	YES	YES	YES	YES
N	528	528	528	528	528
F Test	-	-	-	2.98 ***	3.25 ***
Wald Test	176.32 ***	184.78 ***	204.39 ***	-	-
LR Test	365.75 ***	370.42 ***	385.33 ***	-	-

Remarks: t statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3. OLS regression results of the fixed effects of environmental regulations on industrial GTFP.

Variables	GTFP			$K\_outflow_{it}$	$L\_outflow_{it}$
	(1)	(2)	(3)	(4)	(5)
ENR_{it}	0.2071 ***(3.22)	0.0379 **(2.32)	0.0399 ***(4.33)	−0.0013 *(−1.67)	−0.0299 *(−1.81)
ENR_{it}^2	−0.1416 **(−2.25)	−0.0054 **(−2.30)	−0.0029 **(−2.54)	-	-
$K\_outflow_{it}$	-	0.2320 ***(−3.60)	-	-	-
$K\_outflow_{it}^2$	-	−0.1717 ***(−2.71)	-	-	-
$L\_outflow_{it}$	-	-	0.2198 ***(3.46)	-	-
$L\_outflow_{it}^2$	-	-	−0.1497 **(−2.41)	-	-
TEC_{it}	1.22×10^{-6} ***(4.18)	1.23×10^{-6} ***(4.20)	1.17×10^{-6} ***(4.02)	−0.1152 **(−2.37)	−0.4122 ***(−2.85)
PRO_{it}	−0.5495 ***(−18.29)	−0.5467 ***(−17.82)	−0.5415 ***(−18.15)	0.2013 *(1.71)	0.0049 *(1.92)
LQ_{it}	0.0964 ***(2.68)	0.0955 ***(2.65)	0.1003 ***(2.82)	0.5375 **(2.33)	2.0510 ***(2.99)
EST_{it}	−0.0860 ***(−4.80)	−0.0855 ***(−4.75)	−0.0709 ***(−3.87)	0.6411 **(2.28)	0.1321 *(1.77)
$GDPP_{it}$	6×10^{-6} ***(11.28)	5.96×10^{-6} ***(11.06)	5.7×10^{-6} ***(10.67)	−0.0001(−4.14)	−0.0001 **(−2.36)
WAG_{it}	−0.0001 ***(−6.01)	−0.0001 ***(−5.95)	−0.0001 ***(−5.81)	0.0118 *(1.86)	0.1015 *(1.80)
FDI_{it}	−0.0086 ***(−4.30)	−0.0085 ***(−4.20)	−0.0077 ***(−3.82)	0.0004 ***(4.92)	0.0005 **(2.13)
_Cons	0.7855 ***(15.88)	0.7882 ***(15.81)	0.8048 ***(16.32)	−2.8058 ***(−3.04)	−2.2331 (−0.81)
N	540	540	540	540	540
F Test	27.1 ***	27.60 ***	28.40 ***	5.43 ***	3.07 ***

Remarks: t statistics in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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Article

Does Regional Integration Improve Carbon Emission Performance?—A Quasi-Natural Experiment on Regional Integration in the Yangtze River Economic Belt

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Abstract: Carbon emission performance (CEP) comprehensively considers the four-dimensional factors of "carbon reduction, pollution reduction, green expansion, and growth" and constitutes a key indicator for low-carbon and high-quality development. Although some studies have previously explored the relationship between regional integration and carbon emissions from different perspectives, it remains unclear how regional integration affects carbon emission performance. This article regards the regional integration construction of the Yangtze River Economic Belt as a quasi-natural experiment and uses the difference-in-difference (DID) model to empirically examine the mechanisms behind regional integration and their impact on carbon emission performance. The results show that regional integration significantly promotes improvements in carbon emission performance, primarily through three transmission mechanisms: resource factor allocation, economies of scale, and green innovation. It can also promote improvements in carbon emission performance in high-level carbon emission performance cities, middle- and downstream cities, non-natural-resource-oriented cities, and non-riverside cities. This article provides theoretical and empirical evidence that can be utilized to promote China's high-quality, low-carbon transformation through regional integration construction in the Yangtze River Economic Belt.

Keywords: regional integration; carbon emission performance; DID model; Yangtze River Economic Belt

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1. Introduction

As global climate change intensifies, low-carbon sustainable development has become a focus of governments and academia worldwide. As a major carbon emitter globally, China's strategies and actions in the low-carbon transition will be crucial in global climate governance. To achieve high-quality, low-carbon sustainable development in China, the full report of the 20th National Congress of the Communist Party of China explicitly proposes to "coordinate efforts to reduce carbon, reduce pollution, expand greenery, and promote growth, prioritizing ecology, conserving resources, and pursuing green low-carbon development". Carbon emission performance comprehensively considers the four dimensions of "carbon reduction, pollution reduction, green expansion, and growth", serving as a key indicator for measuring the green low-carbon development of Chinese-style modernization. However, the market segmentation that persists due to local government protectionism hinders progress in achieving regional environmental collaborative governance and green and low-carbon transformation [1], which is not conducive to improving the carbon emission performance level. With regional integration gradually becoming a national strategy for China's economic development [2], a series of regional integration construction documents, based on urban agglomerations, has been continuously promulgated and implemented [3]. This has provided new ideas for solving the problem of environmental collaborative governance in regional integration construction and promoting green and low-carbon economic transformation.

Within the context of regional climate governance, the advancement of integration offers jurisdictions a unified platform for collaborative action against the challenges posed by climate change. Such synergistic governance not only facilitates the attainment of carbon emission objectives but also promotes the efficient allocation of resources and the dissemination of technological innovation. Moreover, regional integration affords the opportunity to collaboratively devise and enforce more stringent environmental standards and policies. The quintessential role of regional climate governance lies in its capacity to transcend administrative boundaries, fostering extensive collaboration and synergy. This governance paradigm encourages regions to tailor adaptive strategies in accordance with their unique environmental and economic contexts, thereby addressing climate change challenges more effectively. It is imperative to note that regional climate governance is not solely an intergovernmental endeavor. It instead encompasses the broad participation of corporations, non-governmental organizations, and civil society, all of whom can play pivotal roles in the formulation and execution of climate strategies. This multifaceted involvement ensures a more holistic and efficacious implementation of strategies, simultaneously bolstering public enthusiasm for and engagement in climate policies. Nonetheless, regional climate governance faces several challenges, such as ensuring consistency in commitments and actions across regions, resolving potential conflicts of interest, and guaranteeing the long-term sustainability and adaptability of strategies. Yet, given the escalating complexity and urgency of global climate governance, regional climate governance undoubtedly presents a promising solution. So, can regional integration construction empower carbon emission performance? If so, what is the specific transmission mechanism at work? Is there heterogeneity in its operation? Exploring this series of issues has important theoretical and practical significance for achieving green and low-carbon development in China. Therefore, this study treats the construction of the Yangtze River Economic Belt regional integration as a quasi-natural experiment, utilizing panel data from 283 Chinese cities from 2006 to 2019 to investigate the impact and mechanisms of regional integration on carbon emission performance and explain their differential impacts. The aim is to provide theoretical and empirical evidence from the Yangtze River Economic Belt in order to advance regional integration and promote a high-quality, low-carbon transition in China and globally.

The literature closely related to this study focuses, firstly, on the evaluation of carbon emission performance. Some studies use single-indicator methods such as carbon emission intensity [4,5] and carbon productivity [6,7] to measure carbon emission performance, but these methods ignore the comprehensive effects of other factors [8]. Additionally, the research on this topic adopts the input–output technique and measures carbon emission performance from the perspective of carbon emission efficiency, using methods such as the SBM model [9,10]. Another major aspect of this field of research examines the basic connotation, driving mechanism, implementation path, and measurement of regional integration. Regional integration refers to the process and state of the rational allocation of production factors in accordance with market dynamics, institutional arrangements, and functions, in order to achieve factor-scale agglomeration and cooperation across the division of labor [11]. This concept is not only applicable to cross-regional cooperation organizations, but also to urban agglomerations. Since the rise of regional integration theory and new regionalism theory [12,13], some scholars have conducted qualitative analyses of the basic connotations, driving mechanisms, and implementation paths of regional integration [14], using production methods [15], price methods [16], and comprehensive indicators [17] to quantitatively measure economic integration, market integration, and overall regional integration.

The environmental, social, and economic effects of regional integration have also received considerable attention from the academic community. Based on the use of price methods to measure regional integration in China, research has empirically determined that regional integration promotes carbon emission performance [18] and regional green total factor productivity [19]. Additionally, market integration can reduce carbon emissions [20]. However, some studies have found that the positive and negative impacts of the integration level of the Chengdu Chongqing urban agglomeration in China on the urban ecological environment depend on factors such as economic development level, development stage, and location [21]. There are also studies that have found the regional economic integration in Chinese urban agglomerations to be able to promote optimal resource allocation and improve urban land use efficiency in the process of socio-economic transformation [22]. Since the development of the DID model, the PSM–DID (propensity score matching DID) model, and synthetic control methods, most studies have examined the green and low-carbon development effects of regional integration policies.

Research into environmental pollution suggests that regional unification efforts, as seen in the EU integration [23] and the expansion of China's Yangtze River Delta integration [24], can mitigate such pollution. Conversely, other findings indicate that while the Yangtze River Economic Belt's integration in China curtails transboundary pollution through enhanced governmental oversight, joint governance, industrial restructuring, green tech advancements, and competitive markets, it intensifies this pollution by broadening market dimensions and fostering population concentration [25]. In terms of carbon emissions, evidence from China's administrative reform—transitioning from counties to districts—reveals that intra-city regional amalgamation curtails emissions by relocating energy-intensive, high-pollution businesses elsewhere [26]. The confluence of industrial and urban sectors in China's Yellow River Basin has caused a decline in carbon emissions [27]. Furthermore, the broadening scope of regional amalgamation in China's Yangtze River Delta has markedly diminished urban carbon outputs. Deepening collaborative governance, refining industrial frameworks, and advancing green innovations stand as pivotal drivers in this reduction [28]. However, certain studies, centered on the Yangtze River Delta's integration, argue that while regional unification endeavors have streamlined urban carbon emission intensities by elevating industrial structures and technological prowess, they have inadvertently amplified emissions due to intensified inter-city economic interactions [29]. Research also found that regional trade integration has failed to affect CO_2 emissions in Cambodia, Malaysia, Indonesia, and Thailand [30]. Additionally, it has been determined that de facto conditions, in terms of trade integration, and de jure conditions in financial integration have mitigating effects on CO_2 emissions in Venezuela [31]. Economically and socially, research indicates that the strategic development of China's Yangtze River Economic Belt has the potential to address overproduction [32] and bolster employment opportunities [33].

In summary, this study believes that there remains room for further exploration in the research on regional integration construction. Firstly, the single-indicator method for measuring carbon emission performance overlooks the comprehensive effects of other factors, and the input–output method based on the SBM model from the perspective of carbon emission efficiency fails to incorporate "green expansion and pollution reduction" into the indicator system. Secondly, regarding the relationship between regional integration and carbon emissions, discussions have not reached a consensus due to varying research subjects, methodologies, and perspectives. (3) In terms of model endogeneity, while some studies have attempted to evaluate the green and low-carbon effects of regional integration, the endogeneity issue still requires further resolution using natural geographic tool variables.

This study expands and enriches these considerations from the following perspectives: (1) this study incorporates "green expansion and pollution reduction" into the connotation theory of carbon emission performance, comprehensively and systematically constructing a carbon emission performance indicator system and thereby making up for the shortcomings of previous single-indicator methods and input–output methods. (2) This study focuses on the urban scale and uses the DID model to accurately evaluate the impact of the integration strategy of the Yangtze River Economic Belt on carbon emission performance. Additionally, this research examines the multidimensional implementation mechanisms used to enact the strategy. It systematically analyzes the transmission mechanisms between strategy and performance, including resource factor allocation, economies of scale, and green innovation. (3) This study uses river density and river length as instrumental variables for regional integration, in order to further alleviate the endogeneity problem of the model. (4) This research investigates the differential effects of urban carbon emission performance levels, different river basins where cities are located, urban-scale characteristics, urban resource endowments, and whether cities are located along the Yangtze River.

2. Theoretical Analysis and Hypothesis

Carbon emission performance can be defined as the economic, social, and ecological benefits produced in human social production and living activities by consuming the carbon ecological capacity of nature. The core goal of assessing such a metric is to optimize and intensively manage resource elements, hoping for minimal resource input and reduced carbon emissions among other unintended outputs, in order to achieve the best possible economic, social, and ecological effects. This study suggests that regional integration construction can generate a low-carbon dividend of "emission reduction efficiency enhancement" through resource factor allocation effects, economy-of-scale effects, and green innovation effects, thereby affecting carbon emission performance.

Under the boundary effect of market segmentation, the cross-regional flow of resource elements and collaboration in production links are hindered [34], which is the main reason for the inefficient utilization of urban energy and the high-level carbon emission intensity [1]. According to the connotations of economic integration proposed by Tinbergen, coordinated development within the geographical scope of economic cooperation can weaken boundary barriers, meaning that regional integration has the direct effect of breaking market segmentation. As one of the developmental forms of regional integration, factor market integration provides basic conditions for eliminating and weakening obstacles to the free flow of resources and factors [35]. Specifically, regional integration promotes market integration and openness, with more free distribution of resource elements such as capital, labor, and information [36]. On the one hand, it plays a market selection effect, driving resource elements to flow towards enterprises with higher marginal output, accelerating the elimination of backward and inefficient production [37] and forcing enterprises to improve processes, resource utilization efficiency, and production efficiency. On the other hand, regional integration has strengthened the cooperation mechanisms of the market. For example, cities with stricter environmental standards can obtain intermediate products through purchasing instead of production, thereby reducing carbon emissions in the production process. This process demonstrates the trade creation and substitution effects of regional integration, reducing urban carbon emissions by improving factor returns and "transaction efficiency" [16].

The new trade theory emphasizes the importance of market size and economies of scale in international trade. Regional integration, by expanding market size, offers firms greater production and sales scale, theoretically providing support for the economy-of-scale effects of regional integration. Regional integrated infrastructure planning, coordination, and cooperative construction can effectively improve transportation accessibility and provide cost advantages between provinces and cities through the "spatiotemporal compression" mechanism, promoting industrial production activities to become "standardized" and "scaled" within a region. The resulting cost advantages promote improvements in energy consumption and resource utilization efficiency, achieving the goal of improving production efficiency and reducing carbon emission intensity. In addition, the economy-of-scale effects caused by regional integration will also extend the industrial chain and production links, forming favorable spillovers. For example, advanced demonstration enterprises and enterprises in low-carbon, underdeveloped areas will continue to cooperate. This has the effect of spreading and promoting production experience, advanced production models, and clean production technologies, thereby creating favorable incentives for improving production efficiency and reducing carbon emissions upstream and downstream for enterprises in the industrial chain and surrounding cities.

The technology diffusion theory suggests that the spread of technology is influenced by geographical and spatial factors. For instance, new technologies are more likely to disseminate between regions that are geographically adjacent or culturally similar. Against a backdrop of regional integration, technology diffusion and knowledge sharing become more frequent, offering richer resources and opportunities for green innovation. Green innovation is an important driving force for improving production efficiency and carbon reduction intensity [38]. On the one hand, the endogenous growth theory argues that innovation is endogenous in the production process and is an effective means of improving the utilization efficiency of production factor resources and reducing natural resource depletion [39]. Conversely, existing research and empirical evidence also indicate that progress in green technologies (such as carbon reduction technologies) is the key to reducing carbon emission intensity and improving carbon emission reduction efficiency [16]. Against the background of regional integration, innovation entities can provide new momentum for the spillover of innovative elements by expanding the scope of cooperation and weakening boundary barriers [40], thereby forming an important mechanism for promoting urban carbon emission reduction and carbon efficiency improvement. On the one hand, according to the classical growth convergence model, integrated cities, due to their comparative advantage in innovation benefits, can provide excellent opportunities for gathering innovation factors. The integrated market guidance function helps to fully leverage the allocation role of price signals among innovation entities, leading to a "demand innovation" mechanism and promoting the application and derivation of advanced and clean production technologies within the economic belt. Conversely, regional integration provides the possibility for innovative division of labor and collaboration. In building a regional collaborative innovation platform, integration enhances the driving force of innovation belts such as entrepreneurial behavior, R&D funding investment, and new product project development within the region, thereby improving the regional coordination of green innovation development and promoting a low-carbon transformation within the region.

Hypothesis 1. *Regional integration can improve carbon emission performance, which is done primarily through three transmission mechanisms: resource factor allocation, economies of scale, and green innovation.*

3. Research Methods

3.1. Econometric Model

The difference-in-differences (DID) model is a statistical technique in econometrics and empirical economics, used to measure the impact of specific interventions or treatments (such as policy changes) on outcome variables. The fundamental idea of DID is to compare the changes in outcomes between a group subjected to the intervention and a control group not subjected to it, with data taken before and after the intervention. This includes both the single-period DID model and the multi-period DID model, wherein the single-period DID model primarily focuses on the changes in outcome variables over one period before and after the intervention. Its advantage lies in its simplicity in calculation and capacity to examine the effects of intervention, using data from just two periods. A drawback of this method is its assumption that, without any intervention, the difference between the two groups remains constant before and after the intervention, which might not always hold true. The multi-period DID model considers multiple periods before and after the intervention, allowing researchers to capture the effects of the intervention more accurately, especially when these effects vary over time. The multi-period DID model can capture the changes in intervention effects over time and better control for unobserved time-varying confounders. However, the multi-period DID model is prone to biases in multi-time-point difference-in-differences estimates under bidirectional fixed effects. In 2014, the

Chinese government incorporated Shanghai and 10 other provinces (cities) into the Yangtze River Economic Belt regional integration strategy, with 2014 being the sole year of policy implementation. Therefore, the single-period DID model is suitable for evaluating the impact of the Yangtze River Economic Belt's regional integration construction on CEP. The specific formula for the single-period DID model is as follows:

$$CEP_{it} = \alpha_0 + \alpha_1 POLICY_{it} + \varphi X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{1}$$

where *CEP* is carbon emission performance, *POLICY* is the policy variable for regional integration construction, X_{it} is the control variable, α_0 is a constant term, α_1 is the influence coefficient of *POLICY*, μ_i is an individual fixed effect, v_t is a time fixed effect, and ε_{it} represents a random interference term.

To verify Hypothesis 1, this article constructed a panel-mediated effect model based on Formula (1), which includes Formulas (2) and (3):

$$MED_{it} = \beta_0 + \beta_1 POLICY_{it} + \varphi X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{2}$$

$$CEP_{it} = \gamma_0 + \gamma_1 MED_{it} + \gamma_2 Policy_{it} + \varphi X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{3}$$

where *MED* is the mediating variable, β_1 is the coefficient of influence on *MED*, and γ_1 is the coefficient of influence of the mediating variable on *CEP*. If the α_1 coefficient in the model (1) is significantly positive and the β_1 and γ_1 coefficients are both significantly positive, regional integration can improve carbon emission performance via variable mediation.

3.2. Variables

3.2.1. Dependent Variable

The carbon emission performance indicator system of this study is shown in Table 1. The system involves three categories: input indicators, expected output indicators, and non-expected output indicators. Among these, input indicators include four categories: land, labor, capital, and energy; expected output indicators include three categories: economic benefit output, ecological benefit output, and social benefit output; and non-expected output indicators include pollution emissions and carbon dioxide emissions. Previous studies have mostly used the SBM model to measure carbon emission performance. This study used an EBM model that includes radial and SBM distance functions to measure carbon emission performance [41], overcoming the bias in carbon emission performance measurement based on the SBM model alone.

Table 1. Index system for carbon emission performance.

Indicators	Variables	Description of Variables
Input indicator	Land input	Urban construction land area (unit: km^2)
	Labor input	Urban employment at the end of the year (unit: ten thousand)
	Capital input	Urban capital stock (unit: CNY 10,000)
	Energy input	Total consumption of three types of energy (unit: 10,000 metric tons of standard coal)
Expected output indicator	Economic benefit output	Urban GDP (unit: CNY 10,000)
	Ecological benefit output	The green coverage rate of urban built-up area (%)
	Social benefit output	The average salary of urban employees (yuan)

Table 1. *Cont.*

Indicators	Variables	Description of Variables
Unexpected output indicator	Carbon emissions	Carbon emissions from natural gas consumption in urban society (10,000 tons)
		Carbon emissions from liquefied petroleum gas consumption in urban areas (10,000 tons)
		Carbon emissions from electricity consumption in urban areas (10,000 tons)
		Carbon emissions from heat energy consumption in urban areas (10,000 tons)
	Pollutant emissions	Total industrial wastewater discharge in urban areas (10,000 tons)
		Total industrial SO_2 emissions in urban areas (10,000 tons)
		Total industrial dust and smoke emissions in urban areas (10,000 tons)

3.2.2. Core Independent Variable

In 2014, the Chinese government officially issued the "Guiding Opinions on Promoting the Development of the Yangtze River Economic Belt through the Golden Waterway". This incorporated 11 provinces (cities) such as Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan into the regional integration strategy of the Yangtze River Economic Belt, marking its official implementation. This study selected 283 cities in China as the overall research sample, assigning a value of one to the cities included in the Yangtze River Economic Belt regional integration strategy as the experimental group and zero for the cities not included within this region as the control group. We assigned the time dummy variables included from the 2014 regional integration strategy of the Yangtze River Economic Belt to zero and one, respectively. The policy variable (*POLICY*) for regional integration is measured by the interaction term between the regional dummy variable and the time dummy variable of the implementation of the Yangtze River Economic Belt regional integration strategy. Working from the research sample, 108 cities in the Yangtze River Economic Belt were selected as the experimental group, and the remaining 175 non-Yangtze River Economic Belt cities were selected as the control group.

3.2.3. Mediating Variables

This study measured resource factor allocation (AE), green innovation (INNOV), and economies of scale (SCALE) using the metrics of urban total factor productivity [42], green invention patent applications per 10,000 people [43], and non-agricultural added value per unit of administrative land area [44].

3.2.4. Control Variables

In this study, we selected the following control variables based on the previous research [45]:

(1) Temperature variation (TV): Elevated temperatures might lead to increased energy consumption, which is detrimental to CEP. This study measured TV using the average daily temperature of cities.
(2) Transport infrastructure (INFRA): Efficient transportation infrastructure can reduce traffic congestion, ensuring smoother vehicle flow and thereby decreasing carbon emissions caused by idling and frequent stops and starts. This study measured INFRA using the per capita road area of cities.

(3) Environmental regulation (ER): Environmental regulations can compel enterprises to adopt low- or zero-carbon technologies, thereby promoting technological innovation and R&D, and steering industries towards a more environmentally friendly and low-carbon direction. This study employed the entropy method to measure ER using an integrated index based on three indicators: the removal rate of sulfur dioxide, the removal rate of industrial smoke (dust), and the comprehensive utilization rate of industrial solid waste.
(4) Openness to foreign investment (OPEN): Opening up to foreign investments can introduce advanced clean technologies domestically, which is beneficial for CEP. This study measured OPEN using the proportion of foreign direct investment (FDI) in GDP.
(5) Industrial agglomeration (AGG): Excessive industrial agglomeration can lead to congestion effects, thus increasing a city's carbon emissions, which is unfavorable for CEP. This study measures AGG using the locational entropy of manufacturing employees.
(6) Industrial structure (INDUSTR): The presence of a higher proportion of secondary industry's added value in GDP indicates a larger share of high-emission, low-efficiency heavy industries, which is detrimental to CEP. This study measured INDUSTR using the proportion of secondary industry's added value in relation to overall GDP.
(7) Government intervention (GOV): Local governments, in pursuit of GDP, might offer various incentives to heavy industries with high pollution and a large tax base. Hence, government intervention might be unfavorable for CEP. This study measured GOV using the proportion of government expenditure, excluding investment in science and education.
(8) Population density (POP): A higher population density might lead to urban traffic congestion, increasing carbon emissions. This study measured POP using the population per administrative region.
(9) Energy utilization efficiency (ENER): Enhancing energy efficiency can reduce the demand for fossil fuels like coal, oil, and natural gas, thereby decreasing the carbon emissions associated with their combustion. This study measured ENER using the total energy consumption per unit of GDP.
(10) Human capital (HUMAN): Human capital can provide talent support for low-carbon technologies, which is beneficial for CEP. This study measured HUMAN using the number of undergraduate students per 10,000 population.

3.3. Data Source and Statistical Analysis

Table 2 shows the statistical description results of each variable. The data for this study were sourced from the "China Urban Statistical Yearbook" from 2007 to 2020 and the EPS data platform (https://www.epsnet.com.cn/, accessed on 10 October 2023), and missing data were supplemented using interpolation methods. This study excluded samples with missing data from cities such as Chaohu, Bijie, Tongren, Sansha, Lhasa, Hegang, and Sanya, and ultimately, panel data from 283 Chinese cities from 2006 to 2019 were selected for analysis.

Table 2. Statistical description of variables.

Variables			Mean	SD	Min	Max
Variable Label	**Attribute of Variable**	**Explanation of Variables**				
Dependent variable	Carbon emission performance (CEP)	See dependent variable in Section 3.2.1	0.650	0.180	0	1.200
Core independent variable	Policy on regional integration construction of the Yangtze River Economic Belt (POLICY)	See core independent variable in Section 3.2.2	0.160	0.370	0	1.000
Mediator variable	Resource factor allocation (AE)	Urban total factor productivity	1.710	0.800	0.180	17.460
	Economies of scale (SCALE)	Non-agricultural added value per unit of administrative land area	6.790	1.400	1.970	11.810
	Green innovation (INNOV)	Green invention patent applications per 10,000 people	0.510	1.460	0	26.820
Control variable	Temperature variation (TV)	Average daily temperature of cities	14.600	5.100	−1.090	25.680
	Transport infrastructure (INFRA)	Per capita road area in cities	4.520	5.890	0	73.040
	Environmental regulation (ER)	Integrated index based on three indicators: the removal rate of sulfur dioxide, the removal rate of industrial smoke (dust), and the comprehensive utilization rate of industrial solid waste, employing the entropy method	0.610	0.200	0.060	0.990
	Openness to foreign investment (OPEN)	The proportion of foreign direct investment (FDI) in GDP	1.900	1.980	0	15.320
	Industrial agglomeration (AGG)	The locational entropy of manufacturing employees	0.860	0.480	0.020	3.050
	Industrial structure (INDUSTR)	The proportion of the secondary industry's added value in GDP	47.790	10.870	10.680	90.970
	Government intervention (GOV)	The proportion of government expenditure excluding science and education	0.800	0.040	0.610	0.980
	Population density (POP)	The population per administrative region	5.740	0.910	1.610	7.880
	Energy utilization efficiency	The total energy consumption per unit GDP	22.11	19.82	0.070	244.500
	Human capital (HUMAN)	The number of undergraduate students per 10,000 population	8.560	15.510	0.020	105.700

4. Empirical Results and Analysis

4.1. Benchmark Analysis

Table 3 contains the benchmark test results of the impact of regional integration construction on carbon emission performance. From columns (1) to (3) of Table 3, it can be seen that, irrespective of whether a model controls for time effects or urban effects, regional integration construction can significantly promote improvements in carbon emission performance. From column (3) in Table 3, it can be seen that, compared to non-Yangtze River Economic Belt cities, the carbon emission performance of cities in the Yangtze River Economic Belt has increased by an average of 0.0355. On the one hand, the regional integration strategy of the Yangtze River Economic Belt guides the convergence of environmental regulation measures and provision among cities, thereby weakening the policy incentives and distortions caused by administrative and geographical divisions. These changes are conducive to achieving improvements in carbon emission performance across the entire basin at lower regulatory costs. On the other hand, this strategy indirectly promotes carbon emission performance by stimulating green innovation, guiding resource factor allocation, and generating economies of scale.

Table 3. Benchmark inspection results.

Variables	(1)	(2)	(3)
POLICY	0.1067 ***	0.0503 ***	0.0355 ***
	(19.268)	(10.044)	(6.101)
Controls	YES	YES	YES
_cons	0.6357 ***	−1.0121 ***	−0.3921
	(343.942)	(−3.930)	(−1.550)
City fixed effect	NO	YES	YES
Time fixed effect	NO	NO	YES
N	3962	3962	3962
R^2	0.6601	0.7570	0.7962
Adj-R^2	0.6339	0.7375	0.7792
F	371.2635	148.0073	61.9743

Note: The regression coefficients in parentheses represent *t* values, while *** represents significant values at the 1% level.

4.2. Robustness Analysis

4.2.1. Parallel Trend Testing

Figure 1 shows the results of the common trend test of the impact of regional integration construction on carbon emission performance. It can be concluded that in 2014, there was no significant difference in the coefficient of policy variables between each period and zero, indicating that there was no significant difference in carbon emission performance between cities in the Yangtze River Economic Belt and non-Yangtze River Economic Belt cities in 2014. In 2014 and later years, there was a significant difference in carbon emission performance between cities in the Yangtze River Economic Belt and non-Yangtze River Economic Belt cities, and the coefficient of policy variables in each period was significantly greater than 0, indicating that the regional integration construction of the Yangtze River Economic Belt had a significant positive impact on carbon emission performance.

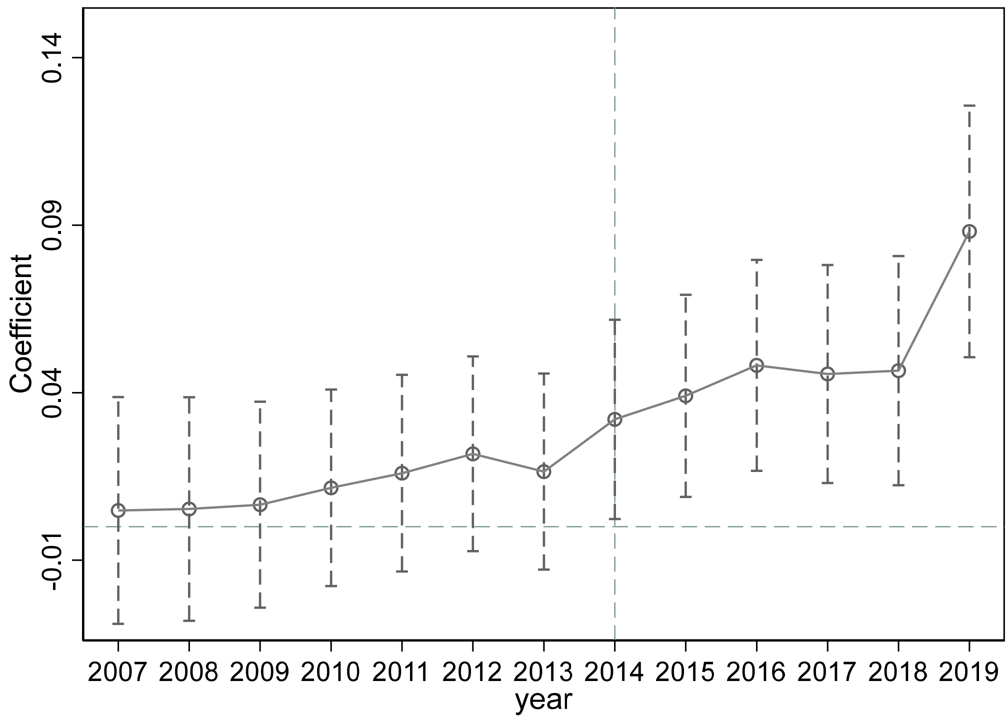

Figure 1. The parallel trend test of the Yangtze River Economic Belt integration strategy. Note: The *x* axis represents the year, and the *y* axis represents the estimated coefficients of policy.

4.2.2. Placebo Test

To further rule out the possibility of the effect of regional integration on carbon emission performance being influenced by other policies or random factors, this study drew on an existing study [42] and randomly selected the same number of cities as contained within the experimental group of the earlier research. A "virtual" policy variable was constructed according to the randomly generated time, and the baseline model was regressed 500 times for each city. The estimated coefficients of *POLICY* from the 500 regressions were plotted into a kernel density distribution (Figure 2). The mean of the simulated regression coefficients is 0.0000072, which is closer to zero compared than the regression coefficient of 0.0355 shown in column (3) of Table 3. This indicates that the baseline regression coefficient is larger than most of the simulated values and can be regarded as an extreme value. In other words, obtaining a baseline regression coefficient of 0.0355 is a high-probability event. Therefore, the effect of regional integration construction on carbon emission performance is not affected by other policies or random factors.

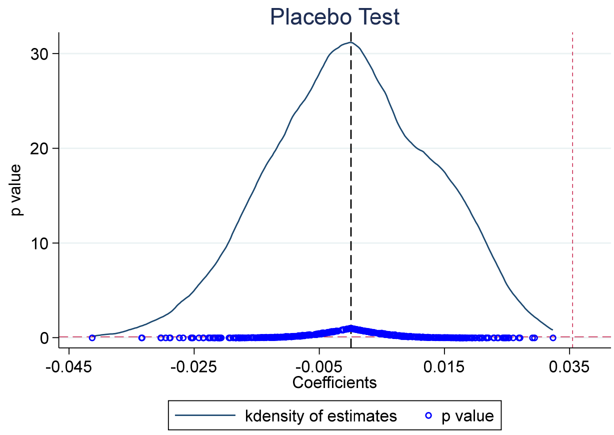

Figure 2. Placebo test.

4.2.3. Other Robustness Analysis

This study conducted other robustness analyses by excluding other pilot policies, changing the regression model, and using the instrumental variable approach. Firstly, other pilot policies that may have affected carbon emission performance were excluded, such as civilized city, low-carbon city, smart city, energy-saving, and emission-reduction fiscal pilot policies. The regression results of the model are shown in column (1) of Table 4. Secondly, the regression model was changed. Unlike the traditional DID model, the PSM–DID model can reduce sample self-selection bias caused by urban heterogeneity. The regression results of the PSM–DID model are shown in column (2) of Table 4. Columns (1) and (2) show that regional integration construction still significantly promotes improvements in carbon emission performance.

Secondly, a two-stage instrumental variable approach was used to reconduct the model regression. On the one hand, natural geographical features are a key factor in determining the level of regional integration. Highly developed water systems can engender close connections between regions, satisfying the instrumental variable correlation assumption. On the other hand, carbon emission performance cannot affect the natural formation of river length and river density in the region, satisfying the instrumental variable exogeneity assumption. Since the river length and density of the Yangtze River are variables that do not change over time, this study constructs two instrumental variables for regional integration construction: the interaction term between river length and time dummy variables, and the interaction term between river density and time dummy variables. The model regression results are presented in columns (3) and (4) of Table 4. It can be concluded that both river length and river density as instrumental variables do not have a weak instrumental variable problem. At the same time, the regression coefficient of POLICY is still significantly positive, indicating that regional integration construction still significantly promotes improvements in carbon emission performance.

Table 4. Other robustness test results.

Variables	(1) Excluding Other Policy Effects	(2) PSM–DID	(3) IV-2SLS (River Length)	(4) IV-2SLS (River Density)	(5) Sensitivity Analysis
POLICY	0.0234 **	0.0283 ***	0.1856 ***	0.0666 **	0.0344 ***
	(2.298)	(4.830)	(8.424)	(2.245)	(5.351)
Controls	YES	YES	YES	YES	
City fixed effect	YES	YES	YES	YES	
Year fixed effect	YES	YES	YES	YES	
Constant	0.5761	−0.4874 **	-	-	0.0204
	(1.405)	(−2.037)	-	-	(0.076)
Kleibergen–Paap rk LM statistic	-	-	316.086	149.914	
	-	-	[0.000]	[0.000]	
Kleibergen–Paap rk Wald F statistic	-	-	26.347	11.905	
	-	-	{11.520}	{11.520}	
N	1456	3794	3948	3948	3472
R^2	0.7847	0.8088	0.3604	0.4502	0.7836
Adj-R^2	0.7642	0.7923	0.3604	0.4502	0.7653
F	17.2374	93.3286	109.46	124.13	63.6645

Note: The regression coefficients in the () represent *t* values, while ** and *** represent significant values at the 5%, and 1% levels, respectively. The values in the [ ] are *p* values, and the values in the { } are critical values of the Stock–Yogo weak identification test at the 10% level.

Finally, compared to prefecture-level cities in China, sub-provincial cities and municipalities directly under the central government have advantages in terms of administrative level, which may have an impact on the above conclusions. Therefore, this research excluded this part of the data from the sensitivity analysis. The regression results of the model excluding some samples are shown in column (6) of Table 4. It can be concluded that the regression coefficient of POLICY is still significantly positive.

4.3. Action Mechanisms Analysis

Table 5 shows the test results of the transmission mechanism of regional integration construction on carbon emission performance. From column (1) of Table 5, it can be seen that regional integration construction significantly promoted the allocation of resource elements and that, in turn, resource element allocation significantly improved carbon emission performance. After adding resource factor allocation variables, the promotion coefficient of regional integration construction on carbon emission performance decreased from 0.0355 in column (3) of Table 3 to 0.0244 and was significant at the 1% level.

According to column (2) of Table 5, regional integration construction promoted improvements in carbon emission performance by generating economies of scale. After adding economy-of-scale variables, the promotion coefficient of regional integration construction on carbon emission performance decreased from 0.0355 in column (3) of Table 4 to 0.0132 and was significant at the 5% level.

Column (3) of Table 5 shows that regional integration construction promoted improvements in carbon emission performance by enhancing green innovation. After adding the green innovation variable, the promotion coefficient of regional integration construction on carbon emission performance decreased from 0.0355 in column (3) of Table 3 to 0.0304, being significant at the 1% level.

Table 5. Transmission mechanism tests.

Variable	(1)		(2)		(3)	
	Resource Allocation		Economies of Scale		Green Innovation	
Policy	0.1395 ***	0.0244 ***	0.1353 ***	0.0132 **	0.2662 ***	0.0304 ***
	(4.260)	(4.348)	(17.848)	(2.105)	(4.247)	(5.260)
Resource allocation		0.0799 ***				
		(2.864)				
Economies of scale				0.1652 ***		
				(8.868)		
Green innovation						0.0193 ***
						(7.687)
Controls	YES	YES	YES	YES	YES	YES
_cons	−3.3503 **	−0.1243	0.0625	−0.4024	−22.9528 ***	0.0505
	(−2.372)	(−0.524)	(0.149)	(−1.550)	(−3.500)	(0.197)
N	3962	3962	3962	3962	3962	3962
R^2	0.7230	0.8323	0.9946	0.8053	0.7287	0.8030
Adj-R^2	0.6998	0.8183	0.9942	0.7890	0.7060	0.7865
F	31.8440	74.7842	250.2784	74.3994	25.7529	66.2506
Sobel test	4.372 [0.0000]		10.510 [0.0000]		4.331 [0.0000]	

Note: The number in parentheses is the *t* value; ** and *** indicate significance at the 5% and 1% levels, respectively. The values in the [ ] are *p* values.

The results for the Sobel test of mediating effects, shown in Table 5, support the existence of these three transmission mechanisms. This indicates that regional integration construction can promote improvements in carbon emission performance through resource factor allocation, economies of scale, and green innovation, thereby verifying Hypothesis 1. After the implementation of the regional integration strategy, the allocation of factors within the Yangtze River Economic Belt was continuously optimized and the allocation efficiency significantly improved. By allocating production factors to clean and transitional industries, the cooperation between cities and enterprises in the industrial chain was significantly strengthened, creating conditions for regional low-carbon development. At the same time, by leveraging economies of scale, cities promoted carbon emission efficiency by saving on unit energy consumption, strengthening specialized division of labor, and disseminating the concept of green development. Hence, it is possible to promote green technology innovation and spillover, drive breakthroughs, and generate improvements in production and pollution control technologies related to energy conservation and emission reduction, thereby promoting common emission reduction among enterprises and guiding industrial structure adjustment towards low energy consumption and low emissions. Administrators can gradually achieve green upgrading within a region, injecting vitality into the process of improving carbon emission performance.

4.4. Heterogeneity Analysis

The provinces and cities in the Yangtze River Economic Belt show significant differences in economic development, geographic location, and other regards. In order to explore the heterogeneity of the impact of regional integration on carbon emission performance in the Yangtze River Economic Belt, this study groups together the samples based on the levels of carbon emission performance, urban location characteristics, and natural resource endowments, conducting in-depth discussions from these perspectives.

4.4.1. Heterogeneity in Carbon Emission Performance

Table 6 shows the regression results of the heterogeneity of carbon emission performance levels. It can be concluded that the estimated coefficients of regional integration construction exhibit significant structural differences at different quantiles. At the 25%, 50%, 75%, and 95% quantiles, the promotion coefficients of regional integration construction on carbon emission performance are 0.0362, 0.0486, 0.0637, and 0.0842, respectively. The reason for this is that high-level carbon emission performance cities are usually areas with high levels of green innovation and reasonable allocations of resource elements. Such conditions are conducive to the functioning of regional integration, emission reduction, and efficiency enhancement.

Table 6. Heterogeneity in carbon emission performance levels.

Variable	25%	50%	75%	95%
POLICY	0.0362 ***	0.0486 ***	0.0637 ***	0.0842 ***
	(5.730)	(9.414)	(8.266)	(6.077)
Controls	YES	YES	YES	YES
City fixed effect	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES
N	3962	3962	3962	3962

Note: The number in parentheses is the *t* value; *** indicate significance at the 1% level.

4.4.2. Urban Location Heterogeneity

Column (1) of Table 7 shows the results of the impact of regional integration construction on the carbon emission performance of cities in different river basins. It can be concluded that regional integration construction can better promote improvements in carbon emission performance levels in the middle- and downstream regions. The reason for this is that the economic development level of middle- and downstream cities is relatively high, with a relatively complete industrial chain and rich technological know-how facilitating the optimization and upgrading of industrial structure and technological innovation, improving resource utilization efficiency and ecological efficiency. Upstream cities have advantageous natural endowments, including water and solar resources, and production systems that rely on clean energy during the urban development process. However, in the process of promoting the integration strategy, upstream cities, as relatively backward development areas, participate to some degree in high-pollution and high value-added production links and industrial chains from middle- and downstream cities, while also providing important ecological support for middle- and downstream cities. The result is that there are not significant changes in carbon emission performance in the upstream region during the integration strategy promotion process. The conclusion of this research is also consistent with the research conclusion on the heterogeneity of carbon emission performance levels shown in Table 6.

Table 7. Test results of urban location heterogeneity.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Downstream	Midstream	Upstream	Non-Natural-Resource-Dependent Cities	Natural Resource-Dependent Cities	Along the Yangtze River	Not along the Yangtze River
Policy	0.0679 ***	0.0264 ***	−0.0116	0.0391 ***	−0.0058	0.0272 ***	0.0631 ***
	(8.744)	(3.478)	(−1.154)	(6.231)	(−0.516)	(3.967)	(6.612)
Controls	YES	YES	YES	YES	YES	YES	YES
Constant	−0.3894	−0.2419	−0.1377	−0.2302	−0.5329	−0.3787	−0.0764
	(−1.462)	(−0.801)	(−0.444)	(−0.865)	(−1.193)	(−1.260)	(−0.271)
City fixed effect	YES	YES	YES	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES	YES	YES	YES
N	3024	2954	2884	3962	1596	3542	2870
R^2	0.7861	0.7941	0.7615	0.7645	0.7063	0.7584	0.7621
$Adj\text{-}R^2$	0.7677	0.7764	0.7410	0.7449	0.6790	0.7381	0.7416
F	48.1197	41.8706	28.2965	37.8063	7.0886	30.8884	27.5685

Note: The number in parentheses is the *t* value; *** indicate significance at the 1%,level.

Column (2) of Table 7 shows the results of the impact of regional integration construction on the carbon emission performance of different natural resource endowments. It can be concluded that compared to natural resource-based cities, regional integration construction can better promote improvements in carbon emission performance levels in non-natural-resource-based cities. The reason for this is that, compared to natural r-source-reliant cities, non-natural-resource-based cities usually depend on the development of other industries and service industries, resulting in their carbon emissions being relatively low. The promotion of regional integration has brought broader markets and cooperation opportunities to non-natural-resource-based cities, enabling them to develop green and high-tech industries and reduce the proportion of traditional high-carbon industries, thus improving carbon emission performance.

Column (3) of Table 7 shows the impact of regional integration construction on the carbon emission performance of cities along and outside the Yangtze River. It can be concluded that, compared to cities along the river, regional integration construction can better promote improvements in carbon emission performance in non-river cities. The reason for this is that cities along the river have higher levels of economic development and industrialization due to their long-term dependence on rivers as important transportation and economic power sources, but this is also accompanied by high carbon emissions. However, the promotion of regional integration provides more development opportunities and resource integration for non-riverside cities, enabling them to better transform, upgrade, and promote green development, while also reducing carbon emissions.

5. Conclusions, Policy Implications, and Limitations

5.1. Conclusions

Based on theoretical analysis, this article regarded the regional integration construction of the Yangtze River Economic Belt as a quasi-natural experiment and used the DID model to explore the impact of regional integration construction on carbon emission performance and the mechanisms behind this process. The results show that regional integration construction can significantly promote improvements in carbon emission performance, and the robustness analyses of parallel trend testing, placebo testing, the exclusion of other pilot policies, the replacement of regression models, and instrumental variable methods support this research conclusion. Regional integration construction primarily improves carbon emission performance through resource allocation, economies of scale, and green innovation. Compared to low-level carbon emission performance cities, upstream cities, natural resource-reliant cities, and riverside cities, regional integration construction can more strongly promote improvements in high carbon emission performance cities, middle- and downstream cities, non-natural-resource-based cities, and non-riverside cities.

The carbon emission performance in this study encompasses multifaceted dimensions, including carbon reduction, pollution abatement, green expansion, and growth, serving as pivotal indicators for low-carbon, high-quality development. Notably, prior research predominantly focused on the singular dimensions of regional integration, such as its socio-economic or environmental impacts, often overlooking the holistic effects of the Yangtze River Economic Belt's regional integration construction. Moreover, while a plethora of studies employ the DID model to assess the environmental implications of regional integration, they frequently neglect the endogeneity concerns between regional integration and carbon emissions. To address this potential endogeneity bias, our study leverages river density and river length as instrumental variables for regional integration construction, thereby mitigating inherent model endogeneity. Utilizing the DID model, complemented by a series of robustness checks and endogeneity analyses, this study ensures the reliability and validity of its empirical findings. Furthermore, the theoretical elaboration and empirical validation of the three transmission mechanisms—resource allocation, economies of scale, and green innovation—offer profound insights into the intricate dynamics of how regional integration influences carbon emission performance.

The conclusion of this study may have the following practical impacts on the Yangtze River Economic Belt. Firstly, in the process of regional integration construction, we mentioned resource allocation and green innovation as key factors in improving carbon emission performance. This may lead to the government formulating policy documents that are conducive to cracking down on obstacles to factor flow and incentivizing enterprises to invest more in green technology and innovation. Secondly, the conclusion of this study may promote cooperation and exchange within the Yangtze River Economic Belt. For example, cities with a high-level carbon emission performance can share their successful experiences and best practices with other cities, helping the entire economic belt to achieve low-carbon development. Finally, the conclusion of this study indicates that the Yangtze River Economic Belt has potential and opportunities for low-carbon development, which may attract external investors and partners to participate in cooperation or investment in the region.

In addition, the conclusions of this study may have a profound impact on the policy making, resource allocation, technological innovation, and long-term planning of policy makers and relevant stakeholders in areas other than the Yangtze River Economic Belt. Firstly, the conclusion of this study provides a clear path for other regions to improve carbon emission performance by promoting regional integration. This may lead governments in other regions to place greater emphasis on the role of regional integration when formulating relevant policies. Secondly, the conclusion of this study emphasizes the key role of resource factor allocation and green innovation in improving carbon emission performance in regional integration construction. This may prompt decision makers in other regions to re-examine and adjust resource allocation strategies in regional integration construction, ensuring optimal utilization of resources within the region, and incentivizing governments and enterprises in other regions to increase investment in green technology and product research and development, thereby promoting low-carbon economic development. Finally, the conclusion of this study may prompt governments in other regions to pay more attention to the relationship between regional integration and carbon emission performance when formulating long-term plans, ensuring consistency between long-term plans and low-carbon development goals.

5.2. Policy Implications

Based on the above research conclusions, this study proposes the following policy recommendations:

(1) The government should formulate policy measures to promote the rationalization and optimization of cross-regional resource allocation in the Yangtze River Economic Belt and improve resource utilization efficiency. For example, governments could consider establishing cross-regional resource-sharing mechanisms to promote the rational flow and allocation of resource elements and reduce unnecessary growth of carbon emissions. Authorities can also support and encourage enterprises to merge and restructure to form economies of scale and reduce carbon emissions per unit of output. By providing fiscal and tax incentives, enterprises can be encouraged to adopt clean energy and efficient energy technologies to further reduce carbon emissions. In addition, the government should increase support for green technology research and innovation in the Yangtze River Economic Belt and encourage enterprises to increase investment in clean production technology and low-carbon technology. Equally, establishing intellectual property protection systems, providing good environment and market mechanism for green innovation, stimulating the innovation vitality of enterprises, and promoting the widespread application and adoption of green technologies would all contribute to this objective.

(2) The government should establish differentiated carbon emission reduction targets based on the status and potential differences in carbon emissions in different types of cities. For cities with a high-level carbon emission performance, middle- and downstream cities, non-natural resource-oriented cities, and non-riverside cities, more specific and challenging goals should be set, to provide motivation to reduce emissions. For cities with a low carbon emission performance, the government should increase support for green technology research and innovation, establish special funds, encourage enterprises and research institutions in cities with a high-level carbon emission performance to increase investment in green technology innovation and promote technological breakthroughs and applications, to achieve carbon emission reduction and efficiency improvement. For upstream cities, the government should strengthen the integration and rational allocation of resource elements, optimize resource alloca-

tion, reduce unnecessary growth of carbon emissions, encourage upstream cities to strengthen their environmental protection and ecological construction, improve ecological efficiency, and reduce carbon emissions by promoting cross-regional resource coordination and flow. For natural resource-based cities, the government should encourage industrial structural adjustment, transformations, and upgrades. There is a need to guide natural resource-based cities towards transforming themselves into green, high-tech, and service-industry-based economies and reducing the proportion of traditional high-carbon industries. The government should strengthen cooperation and exchange between cities along the Yangtze River and non-riverside cities, establish a coordination mechanism for carbon emission reduction policies in the Yangtze River Economic Belt, unify policy direction and standards, and promote regional cooperation for win–win results.

5.3. Limitations

Improving the carbon emission performance of enterprises is a fundamental aspect of economic low-carbon transformation. This study only examines the impact of regional integration construction in the Yangtze River Economic Belt on urban carbon emission performance at the urban level and the mechanisms behind this change. In the future, data from Chinese listed companies and industrial enterprises should be used to examine the impact of regional integration on corporate carbon emission performance and the mechanisms behind this. In addition, this research will continue, with investigations of the spatial spillover effect of regional integration construction in the Yangtze River Economic Belt on urban carbon emission performance.

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Can Low-Carbon Pilot City Policies Effectively Promote High-Quality Urban Economic Development?—Quasi-Natural Experiments Based on 227 Cities

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Abstract: To explore the relationship between low-carbon pilot city policies (*LCC*) and the high-quality development of urban economy, this paper calculates the high-quality development index based on five dimensions to construct a double-difference model for empirical research, taking the data of 227 cities in China from 2004 to 2019 and the second batch of low-carbon pilot cities as the main research object. The research conclusions are as follows: (1) The *LCC* has promoted the high-quality economic development of the pilot cities, and has long-term effects, which are mainly reflected in three dimensions: Innovative development, residents' life, and urban public services. (2) The promotion effect is mainly reflected in the big cities, as well as the eastern and central regions. (3) The intermediary function is embodied in three aspects: Industrial upgrading, urban technological innovation, and urban investment.

Keywords: low-carbon pilot city policies; high-quality economic development; industrial structure; urban innovation

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1. Introduction

Since China's reform and opening-up, the country's economy has achieved rapid development for more than 40 years and has now become the second-largest economy in the world. However, while promoting the sustainable development of China's economy, the traditional economic growth method has also brought about many environmental pollution problems, such as haze weather and river pollution. In the long run, this development mode of economic growth at the cost of environmental damage is bound to be unsustainable, while a green, low-carbon, and circular development mode are imperative.

To deal with global climate issues, China should also achieve low-carbon development. Since the introduction of low-carbon economy in 2003, all countries in the world have made great efforts to develop low-carbon technologies and actively introduced low-carbon policies to promote the development of low-carbon economy. Countries represented by France, Sweden, and Denmark have explored new low-carbon development models and new economic growth points in energy, industry, construction, transportation, life, and ecology by creating ecological low-carbon cities and towns. They have achieved remarkable results.

Based on the experience of low-carbon economic development in European countries, China has begun low-carbon city pilot policies with low-carbon emissions and high-efficiency production as the ultimate goal since 2010 in several provinces and cities. In 2010, China's National Development and Reform Commission identified the first batch of pilot regions for low-carbon city policies, including five provinces and eight cities. Then, the second and third batch of pilot lists were announced in 2012 and 2017, respectively. Since the announcement of the third batch of pilot lists, China has six low-carbon provinces and eighty-one low-carbon cities. Low-carbon provinces and cities are located in the three major regions of China's eastern, central, and western regions, and the pilot cities are located in thirty-one provinces, municipalities, and autonomous regions in mainland China. These cities are relatively evenly distributed. China selects pilot cities and implements the application and approval system. First, local-level cities put forward detailed low-carbon development plans, then China's National Development and Reform Commission will comprehensively consider their implementation plans. Based on the analysis of the implementation plan, the early urban low-carbon construction, and the layout of pilot urban areas, the primary list is determined. The cities on the primary shortlist are then evaluated and reviewed on-site to determine the final pilot list of pilots. In the practical sense of *LCC*, the policy incorporates five new development concepts of "innovation, coordination, greenness, openness, and sharing" in urban construction. *LCC* not only provides examples of the implementation effects of environmental policies, but also adds new impetus to high-quality urban economic development.

After the implementation of the *LCC*, scholars have also conducted various studies on the implementation of the policy. Dong Mei (2020) [1] believes that although the reduction degree of per capita carbon emissions or carbon intensity in each *LCC* area varies, most provinces and regions have achieved a reduction in per capita carbon emissions. The research by Deng Rongrong (2016) [2] also affirmed the inhibitory effect of *LCC* on urban carbon emissions. Shi Jiarui et al. (2015) [3] believe that although the carbon trading mechanism can effectively reduce carbon emissions, it will also have a certain negative impact on economic development. Therefore, the impact of *LCC* on economic development can be considered. This paper will study whether *LCC* affects the high-quality development of urban economy.

To specifically explore whether the urban economy has achieved high-quality development after the implementation of the *LCC*, this paper intends to use the data of 227 cities in China from 2004 to 2019 to comprehensively explore the impact of the *LCC* on the high-quality development of the urban economy. The contribution of the paper has the following three points: First, an evaluation system of the high-quality development of the urban economy has been constructed, which can be divided into five aspects: Innovative development, residents' life, openness to the outside world, environmental protection, and urban public services. We set up 16 evaluation indexes and calculated 227 comprehensive indexes of high-quality urban economic development using the entropy method. Second, the existing literature mostly uses indicators, such as pollutant emissions to measure the implementation effect of environmental protection policies, but there may be some unconsidered factors that affect the evaluation of policy effects. This paper will use the double-difference method (DID) to evaluate the impact of *LCC* on the high-quality development of urban economy. This method makes up the shortcomings of existing research and makes the results of this paper more credible. Third, different cities have different infrastructure construction, industrial development level, and size of the city. The effect of policy implementation may be different in cities of different development levels and scales. According to the scale of the cities and the region of the cities, this paper discusses the influence of *LCC* on high-quality development of cities in different sizes and regions. Fourth, to further explore the impact of *LCC* on urban high-quality development, the mediation effect is analyzed from three perspectives of urban technological innovation, industrial upgrading, and urban investment.

The rest of this study is organized as follows: The second section is the literature review. The third section introduces the theoretical basis of this study and thus presents the research hypothesis of this study. Section 4 presents the study design, variable selection, and data. In Section 5, empirical results are presented, including benchmark model regression results, high-quality development sub-dimension regression results, long-term effect regression results, regional heterogeneity analysis results, and impact mechanism analysis. In Section 6, the research conclusions are summarized and policy recommendations are proposed.

2. Literature Review

2.1. Research on the Relationship between Environmental Regulation and the Quality of Economic Growth

Wang Qunyong and Lu Fengzhi (2018) [4] pointed out that environmental regulation can promote high-quality economic development within a certain intensity threshold, and the impact is not significant if it exceeds this threshold. Tao Jing and Hu Xueping (2019) [5], Wang Xiahui and He Jun (2018) [6] found that environmental regulation is generally helpful to the improvement in economic quality. In terms of subdivision, environmental regulation significantly improves economic efficiency, green development, and social welfare, but does not significantly promote the upgrading of industrial structure. Liu Yaobin (2018) [7] believes that environmental regulation promotes the quality of economic development mainly through technological innovation, industrial structure, and FDI. Chen Shiyi and Chen Dengke (2019) [8] found that haze harms the quality of China's economic development through transmission channels, such as urbanization and human capital. Environmental governance can significantly promote high-quality economic development. Some scholars hold different views. Sun Yuyang and Song Youtao (2020) [9] believe that administrative-order environmental regulations have a promotion effect on the quality of economic growth, while market-incentive environmental regulation inhibits the improvement in the quality of economic growth. Wu Gezhi and You Daming (2019) [10] believe that at the national level, various types of environmental regulation inhibit technological innovation, and in the impact on green total factor productivity, only economic incentives and governance input environmental regulation tools play a promoting role.

2.2. Research on Low-Carbon Urban Policies in Other Countries

Ohnishi S (2018) [11] found that it is necessary to make efficient waste management systems for the transition to low-carbon cities. Tillie N (2018) [12] verified his hypothesis "densifying and greening leads to a more sustainable inner city" with the case study of Rotterdam inner city. Based on low-carbon city data in Europe, Wolff (2014) [13] verified that low-carbon city policies have a significant effect on reducing air pollution in transportation centers. Gehrsitz (2017) [14] has verified that Germany's urban low-carbon policy can improve the level of healthy urban development and suppress newborn infant mortality. Bulkeley H (2012) [15] found that cities have played a growing role in the fight against climate change over the past two decades. The researches of scholars on low-carbon urban policies show the importance of urban low-carbon development, and mainly focus on the specific measures and methods of urban low-carbon development. This paper finds that low-carbon city policies may bring about the impact of improving the health level of cities. Therefore, can low-carbon city policies bring about other impacts? This is a question worth considering.

2.3. Research on the Relationship between LCC and the Quality of Economic Growth

After China identified the first batch of *LCC* provinces and cities in 2010, scholars conducted extensive research on the relationship between *LCC* and technological innovation, industrial structure upgrading, and the quality of economic growth. Xu Jia (2020) [16] believes that the low-carbon city pilot policy can induce green technology innovation to a certain extent at the overall level of enterprises. Xiong Guangqin (2020) [17] further studied and found that the implementation of *LCC* had significantly improved the level of green technology innovation of high-carbon emission enterprises in pilot cities. This also verifies the "Porter Hypothesis". In terms of the impact on cities, Lu Jin (2019) [18] joined relevant urban policies, such as smart city pilots to examine the impact of *LCC* on urban technological innovation, and the results show that *LCC* can still promote urban innovation and development. Lu Jin and Wang Xiaofei (2020) [19] proposed that low-carbon urban policy has a significant impact on innovation and the upgrading of the industrial structure, and the policy has a positive spillover effect in space. After considering the impact of other related policies, such as innovative cities and new energy pilots, the low-carbon city policy has a slightly less promoting effect on the upgrading of the industrial structure. However, it still has a significant positive impact on the upgrading of the industrial structure. She Shuo and Wang Qiao (2020) [20] believe that the low-carbon pilot policy promotes the improvement in urban green total factor productivity. This policy has directly improved urban green total factor productivity by improving the level of urban innovation and promoting industrial upgrading, but the indirect effect of industrial structure transformation has not been verified. Gong Mengqi (2019) [21] found that the low-carbon pilot policy has a significant role in promoting foreign investment.

In summary, it can be found that scholars have achieved many achievements in environmental regulation and economic growth, *LCC* and industrial structure upgrading, urban economic growth, etc. Although the current research literature on environmental regulation and high-quality economic development is relatively abundant, there are still the following shortcomings: (1) At present, there are few studies on the impact of specific environmental regulations, such as *LCC* on economic development, especially with the *LCC* as the main variable, there is a lack of literature on its impact on the high-quality development of the urban economy. (2) In traditional research, indicators such as pollutant emissions are used to measure the implementation effect of environmental protection policies, which may affect our judgment on the policy effects. (3) Existing research affirms the role of *LCC* in improving the level of enterprise innovation and promoting the optimization and upgrading of urban industrial structures. However, on this basis, there is no clear conclusion on whether *LCC* has an impact on the high-quality development of the urban economy. This is the starting point and original intention of this study. Therefore, this paper intends to build a DID model to explore whether *LCC* has an impact on the high-quality development of urban economy and how it affects the development of urban economy. The high-quality development level of the urban economy is measured by a comprehensive index calculated by the entropy method.

3. Theoretical Analysis and Research Hypothesis

This paper will theoretically analyze the impact of the implementation of *LCC* on urban innovation and development based on the research by various scholars. Then, we will analyze whether industrial structure transformation, technological innovation, and urban investment play a role in this process.

3.1. How LCC Affects the High-Quality Development of Urban Economy

LCC cities should comprehensively consider their own economic development level, energy consumption structure, carbon emission status and other objective factors, reasonably set carbon emission targets, and formulate strict low-carbon environmental protection regulations to limit corporate carbon emissions [22], such as setting mandatory carbon emission standards and targets, implementing a strict industry access system, and introducing fiscal and taxation support policies for energy conservation and emission reduction [23], in order to achieve carbon emission reduction. Specifically, local governments impose carbon emission tax and energy tax on energy producers and users with high carbon emissions, which increases the environmental cost of enterprises in the production of high-pollution products [24]. However, the production cost of the enterprise may increase in the process. Due to the increase in pollution prevention and control costs, enterprises will face options, such as temporarily closing production lines, transferring production plants [25] or increasing R&D investment to achieve technological innovation. Due to the closure of production lines or the transfer of factories, a large number of sunk costs will be formed, and the increase in R&D investment can obtain innovation compensation [26,27]. The increase in the marginal production cost of enterprises brought about by environmental regulation will be detrimental to the improvement in enterprise performance [28]. From the perspective of rational people, most enterprises will choose the path of technological innovation to improve the innovation level of the whole city. The research by Bergek (2014) [29] also supports the idea that reasonable environmental regulation can promote technological innovation of enterprises. In addition, through the supervision of the public and the pressure of public opinion, the pilot cities encourage enterprises to raise their awareness of environmental protection to achieve carbon emission reduction, which can also promote technological innovation of enterprises to a certain extent [30].

In addition to the level of urban innovation, the high-quality development of the urban economy should have a wider scope, such as openness to the outside world, residents' life, environmental protection, and urban public services, thus further analysis is required. Low-carbon pilot policies can promote the improvement in urban innovation levels, thereby increasing the attractiveness of foreign investment [21]. For developing countries, improving trade openness may help in reducing the carbon emission intensity of industries [31]. Therefore, low-carbon pilot policies may promote the open development of cities while reducing carbon emissions. To reduce carbon emissions, enterprises in *LCC* areas will increase investment in technological innovation and improve production processes, which will increase the cost of enterprises in the short term. However, in the medium and long term, once the innovation investment is fully transformed, the technological level of the enterprise will be improved, the competitiveness of the enterprise will be enhanced, and the income of the enterprise will also increase significantly. The development and growth of various enterprises can also accelerate the regional economic growth, improve the per capita income level of the region, and improve the living standards of residents. The growth of urban economy will increase the attraction of the region to foreign investment, and promote the development of regional finance and the upgrading of industrial structure. In addition, the improvement in the technological innovation level of enterprises not only promotes the economic growth of the city, but also improves the social welfare level of the region, reduces the energy consumption per unit of output, and realizes the green development of the city. Therefore, Hypothesis 1 is proposed:

Hypothesis 1. *LCC policies can promote high-quality urban economic development.*

3.2. The Intermediary Mechanism of LCC Affecting the High-Quality Development of Urban Economy

The implementation of *LCC* can theoretically have an impact on the high-quality development of the urban economy by promoting regional innovation and development. What is the specific impact process? We conduct the following analysis: *LCC* emphasizes that each pilot region should give full play to the advantages of market allocation of resources, and guide enterprises to reduce carbon emissions through taxation or policy incentives. The environmental regulation based on market incentives is conducive to the increase in R&D investment of enterprises [32], forcing enterprises to upgrade equipment or invest in related technologies to improve profitability, thereby reducing the high cost of environmental regulation [33,34]. During this process, the regional investment will increase, and the production efficiency of enterprises invested to improve the level of innovation will increase [35]. In addition, enterprises that do not focus on innovation and some backward production capacity will gradually be eliminated [36]. Innovative enterprises have improved production efficiency [37], and have also realized the transformation and upgrading of the industrial structure. The development achievements promoted by technological innovation include not only the improvement in residents' income, but also the high-quality development achievements, such as the sharing of achievements brought about by economic growth, the enhancement of foreign investment attraction capacity, and the effective governance of the urban environment [38]. In the process of *LCC* affecting the high-quality development of urban economy, the improvement in regional investment and innovation levels as well as the upgrading of industrial structure play an important role. Therefore, the following research hypotheses are proposed:

Hypothesis 2. *Industrial transformation and upgrading is an intermediary mechanism for low-carbon pilot policies to affect the high-quality development of urban economy.*

Hypothesis 3. *Technological innovation is an intermediary mechanism for low-carbon pilot policies to affect the high-quality development of urban economy.*

Hypothesis 4. *Urban investment is an intermediary mechanism for low-carbon pilot policies to affect high-quality urban economic development.*

4. Model Setting and Variable Selection

4.1. Selection of Variables and Data Source

(1) The level of high-quality economic development ($Qua_{i,t}$): There are two approaches to measuring the level of high-quality economic development in existing research. One is to use a single indicator to measure, as Shangguan Xuming uses total factor productivity to measure the level of high-quality economic development (2020) [39]. The second is to use the multi-dimensional composite index to measure the level of high-quality economic development (Tao Jing (2019) [5], Liu Yaobin and Xiong Yao (2020) [7], Liu Jia (2020) [40]). Based on the availability data of pilot cities, this paper draws on the multi-dimensional evaluation index system of various scholars to construct an urban economic development quality measurement index system from five aspects: Innovation and development, residents' life, openness to the outside world, environmental protection, and urban public services. The comprehensive index was calculated by the entropy method, and the specific indicators are shown in Table 1.

Table 1. Evaluation index system of high-quality economic development.

Primary Indicators	Secondary Indicators	Unit of Measurement	Indicator Properties
Innovative development	Technology investment/financial expenditure	%	o
	Educational input/financial expenditure	%	o
	Number of patent applications	Piece	+
Residents' life	Financial deposit balance/Financial loan balance	%	o
	Per capita income of urban units	%	o
	The proportion of added value of the tertiary industry	%	+
	Total social retail consumption/Gross Regional Product	%	+
Openness to the outside world	Utilization of foreign capital	Ten thousand US dollars	+
	Number of foreign-funded enterprises	Piece	+
Environmental protection	Industrial Wastewater Discharge/Gross Regional Product	Ton/100 million yuan	−
	Industrial Soot Emissions/Gross Regional Product	Ton/100 million yuan	−
	Industrial SO2 Emissions/Gross Regional Product	Ton/100 million yuan	−
Urban public services	number of hospital beds per 10,000 people	Pc/10,000 people	+
	Green area per capita	Square kilometers/10,000 people	+
	Road area per capita	Square kilometers/10,000 people	+
	Public budget expenditure/revenue	%	o

Note: "+" in the table indicates a positive impact, "−" indicates a negative impact, and "o" indicates a moderate impact.

(2) Upgrading of Industrial structure: We will analyze the upgrading of industrial structure from the perspective of advancement and rationalization. Among them, the advanced industrial structure (*ARS*) reflects the major industries in the region, and the calculation formula is:

$$ARS_{i,t} = \sum_{m=1}^{3} y_{i,m,t} \times m(m = 1, 2, 3) \quad (1)$$

Among them, $y_{i,m,t}$ represents the proportion of m industry in i city to the regional GDP in period t. By expanding the proportion of the output value of the three major industries, it represents the upgrading of regional industries from the primary industry to secondary and tertiary industries.

The measurement of industrial structure rationalization (*RIS*) is based on the method of Gan Chunhui et al. [41], and the formula is as follows:

$$RIS_{i,t} = 1 - \frac{1}{3}\sum_{i=1}^{3} |(Y_{i,t}/Y_t) - (L_{i,t}/L_t)| \quad (2)$$

The rationalization of industrial results mainly analyzes the matching degree between the proportion of industrial output value and the proportion of employment. $Y_{i,t}/Y_t$ represents the proportion of the output value of the three major industries in GDP. $L_{i,t}/L_t$ is the proportion of the employment of the three industries to the total employment proportion. The larger the value of $RIS_{i,t}$, the higher the degree of rationalization.

(3) Urban technological innovation (*IL*): Referring to the research by Lu Jin (2019) [18], it is expressed by total factor productivity, the input variables are labor and capital, labor is expressed by the number of employees in urban units, and capital is represented by fixed asset investment using the sustainable inventory method. The output variable is measured by the real GDP of the cities. Finally, the DEA measurement of total factor productivity is carried out using the solution software.

(4) Urban investment (*IV*): Urban investment refers to the investment in fixed assets of the whole society of the city (Unit: 10 billion yuan).

(5) Control variables: The variables related to the high-quality development of the urban economy were selected as control variables in combination with relevant research (2020) [38]: Human capital (K_1), expressed as the logarithm of the ratio of the number of college students to the registered population. The financial support (K_2), the public budget expenditure is expressed by the logarithmic value. The urban population (K_3) is expressed by the logarithmic value of the registered population at the end of the year. The urban construction (K_4) is expressed by the logarithmic value of the urban construction land. The labor productivity (K_5) is expressed by the local GDP and the number of employed persons and the ratio is expressed in logarithmic value.

4.2. Model Settings

Since the first batch of *LCC* is mainly targeted at a provincial level, and the third batch of pilots started late, this paper selects the second batch of *LCC* as the research objects by constructing a comprehensive index based on the measurement of high-quality economic development. Drawing on Beck's model (2010) [42], a double-difference model is built to incorporate the fixed effects of city and time into the basic model. The specific model settings are shown in Formula (1):

$$Qua_{i,t} = \beta_0 + \beta_1 LCC_{i,t} + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (3)$$

$Qua_{i,t}$ represents the high-quality economic development index of the city i in year t. *LCC* is a policy dummy variable. Since the policy was proposed at the end of 2012, the *LCC* takes 1 if the year of the pilot city is greater than or equal to 2013, and the rest of the years will be set to 0. The coefficient value β_1 represents the impact of *LCC* on the quality of urban economic growth. $X_{i,t}$ represents control variables, including human capital, regional financial support, population size, urban construction, and labor productivity. $\varepsilon_{i,t}$ is the random disturbance term, while γ_i and μ_t represent the fixed effects of region and time, respectively.

To verify the intermediary role of industrial structure upgrading and urban technological innovation in the process of *LCC* affecting the high-quality development of urban economy, this paper draws on Zhou Chaobo's intermediary model (2020) [43] for reference, and first tests whether *LCC* significantly improves the comprehensive index of high-quality urban economic development. Second, it tests whether *LCC* can significantly promote the upgrading of urban industrial structure, urban technological innovation, and urban investment. Finally, the paper examines whether there is a mediating effect between the upgrading of urban industrial structure and technological innovation. The model is built as follows:

$$ARS = \beta_2 + \beta_3 LCC_{i,t} + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (4)$$

$$RIS = \beta_4 + \beta_5 LCC_{i,t} + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (5)$$

$$IL = \beta_6 + \beta_7 LCC_{i,t} + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (6)$$

$$IV = \beta_8 + \beta_9 LCC_{i,t} + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (7)$$

$$Qua_{i,t} = \alpha_0 + \alpha_1 LCC_{i,t} + \alpha_2 ARS + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (8)$$

$$Qua_{i,t} = \alpha_3 + \alpha_4 LCC_{i,t} + \alpha_5 RIS + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (9)$$

$$Qua_{i,t} = \alpha_6 + \alpha_7 LCC_{i,t} + \alpha_8 IL + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (10)$$

$$Qua_{i,t} = \alpha_9 + \alpha_{10} LCC_{i,t} + \alpha_{11} IV + \theta X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (11)$$

ARS represents the advanced industrial structure and *RIS* represents the rationalization of the industrial structure. *IL* and *IV* represent the innovation level and investment level of the city, respectively. *X* represents the control variable. Equations (4)–(7) analyze whether the *LCC* has a significant impact on the advanced industrial structure, rationalization of industrial structure, technological innovation, and urban investment. Equations (8)–(11) are used to analyze the intermediary effect of *LCC* on high-quality economic development, testing whether the advanced industrial structure rationalization of industrial structure technological innovation and urban investment could be used as a mediating variable.

4.3. Data Introduction

In this paper, the data of 227 cities were selected from 2004 to 2019 as the research sample. The total sample size is obtained by multiplying the number of cities by 227 and the sample years by 16. After excluding the cities with missing data, there were 26 cities in the *LCC* experimental group and 201 cities in the control group. The data of each index are derived from the Chinese City Statistical Yearbook, the City Statistical Yearbook, and the Statistical Bulletin of National Economic and Social Development over the years, and some missing data were replaced by the interpolation method. Descriptive statistics of the data have been sorted out in Table 2:

Table 2. Descriptive statistics of urban panel data from 2004 to 2019.

Variables	Samples	Mean Value	Standard Deviation	Minimum	Maximum
Qua	3632	0.2956	0.0681	0.1797	0.5433
K_1	3632	4.5940	1.0793	0	8.7820
K_2	3632	14.3008	1.059	11.0624	198.0305
K_3	3632	15.1152	0.6769	12.6028	17.3465
K_4	3632	4.4372	0.8413	2.0794	7.5553
K_5	3632	10.6199	1.7579	5.7006	17.1473
ARS	3632	2.2646	0.1969	1.3182	9.6843
RIS	3632	0.8783	0.0681	0.5265	0.9972
IL	3632	0.1286	0.1185	0.0117	1
IV	3632	13.1749	16.6117	0	198.2418

5. Empirical Test

5.1. Baseline Model Regression Result

The baseline model regression results are shown in Table 3, where the (1) column represents the result without adding control variables, and the results show that *LCC* has a positive promoting effect on *Qua*. To explore whether the impact of the low-carbon pilot policy on the quality of urban economic development has changed under the influence of control variables, Columns (2)–(6) of Table 3 are the regression results of our gradual addition of control variables K_1–K_5. It can be seen from the results that the coefficients of the variables are significant with the increase in the control variables. The empirical results verify the correctness of Hypothesis 1 "*LCC* policies can promote high-quality urban economic development".

To analyze the specific dimension of the impact of the low-carbon pilot policy on the high-quality development of urban economy, the binary differential model is adopted for regression analysis, as shown in Table 4. It can be seen from the results that the impact coefficients of low-carbon pilot policies on urban innovation, residents' life, and urban public service dimensions are 0.0010, 0.0045, and 0.0032, respectively, but the impact on the development of opening-up and environmental protection is not significant. The research shows that *LCC*'s promoting effect on the high-quality development of urban economy is mainly reflected in three aspects: Innovative development, residents' life, and urban public service. The reason is that *LCC* can accelerate the progress of urban technology and bring about the rapid development of the regional economy, thus promoting the city to strengthen the investment in public services, and improving the living standards of residents.

Table 3. Baseline model regression result.

Variables	(1) *Qua*	(2) *Qua*	(3) *Qua*	(4) *Qua*	(5) *Qua*	(6) *Qua*
LCC	0.0094 ** (0.0014)	0.0087 *** (0.0014)	0.0084 *** (0.0014)	0.0083 *** (0.0014)	0.0085 *** (0.0135)	0.0089 *** (0.0122)
K_1		0.0022 *** (0.0007)	0.0020 *** (0.0007)	0.0019 *** (0.0017)	0.0019 *** (0.0007)	0.0021 *** (0.0002)
K_2			0.0044 *** (0.0006)	0.0046 *** (0.0006)	0.0045 *** (0.0006)	0.0046 *** (0.0006)
K_3				0.0124 *** (0.0028)	0.0134 *** (0.0028)	0.0111 *** (0.0099)
K_4					−0.0020 (0.0011)	−0.0020 (0.0005)
K_5						−0.0005 (0.0006)
Regional effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
_cons	0.2797 ***	0.1079 ***	0.2704 ***	0.0915 ***	0.0782 **	0.0641
R^2	0.5708	0.5734	0.5694	0.5794	0.5800	0.5867
N	3632	3632	3632	3632	3632	3632

Note: *** and ** indicate significant testing at the level of 1% and 5%, respectively. The values in the parentheses are the stable standard errors of the cluster.

Table 4. Dimensional regression analysis of *LCC* on high-quality urban development.

Variables	Innovative Development	Open to the Outside World	Residents' Life	Environmental Protection	Urban Public Services
LCC	0.0010 ** (0.0005)	0.0006 (0.0004)	0.0045 *** (0.0007)	−0.0006 (0.0035)	0.0032 *** (0.0050)
Control variables	Yes	Yes	Yes	Yes	Yes
Regional effects	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes
_cons	−0.2866 *	0.0301	−0.0470 ***	−0.262	−0.0771 ***
R^2	0.6210	0.4039	0.6703	0.2089	0.413
N	3632	3632	3632	3632	3632

Note: ***, **, * indicate that they passed the significance test at the level of 1%, 5%, and 10%, respectively. The values in parentheses are the stable standard errors of the cluster.

5.2. Long-Term Effect Test

The implementation of *LCC* may affect the resource allocation of the city for a long time, thus bringing about the long-term impact. With the help of the dual-difference long-term effect model (2010) [42], this paper further discusses the long-term impact of *LCC* on the quality of urban economic development. A multi-period *LCC* dummy variable is established, and the multiplication term of the dummy variable *Dj* and *LCC* in the *j* years after the *LCC* is substituted into the model. In addition, $Qua_{i,t}$ and its five-dimensional development index are used as the explained variables for regression. *Dj* represents the jth year after the implementation of *LLC*, and its value is 1, otherwise, it is 0.

$$Qua_{i,t} = \beta_5 + \sum_{i\,=\,0}^{4} \beta_i \times LCC \times D_i + X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \tag{12}$$

The long-term impact verification results of *LCC* are shown in Table 5. It can be seen from the results that the effect of the *LCC* was not significant in the first 2 years after the implementation of *LCC*, indicating that there was a lag in the promotion effect of the policy. From the second year after its implementation, the promotion effect of the *LCC* on the quality of urban economic development began to appear and continued until the 6th year. In terms of dimension, the impact of the *LCC* on innovative development, residents' life, and urban public service level also appeared in the second or third year, indicating that *LCC* had an impact on urban innovation development, residents' life, and urban public service level. It has a long-term promotion effect, but the promotion effect on innovation development disappeared in the sixth year.

Table 5. The long-term impact of *LCC* on the quality of urban economic development.

Variables	*Qua*	Innovative Development	Open to the Outside World	Residents' Life	Environmental Protection	Urban Public Services
$LCC \times D_0$	0.0027 (0.0029)	0.0010 (0.0005)	0.0010 (0.0005)	0.0016 (0.0015)	0.0006 (0.0013)	0.0006 (0.0011)
$LCC \times D_1$	0.0006 (0.0039)	0.0011 (0.0006)	0.0011 (0.0006)	0.0017 (0.0014)	−0.0004 (0.0013)	0.0010 (0.0011)
$LCC \times D_2$	0.0006 * (0.0039)	0.0013 * (0.0005)	0.0029 (0.0005)	0.0029 * (0.0015)	−0.0006 (0.0013)	0.0016 (0.0011)
$LCC \times D_3$	0.0027 *** (0.0039)	0.0012 ** (0.0005)	0.0012 (0.0005)	0.0028 * (0.0005)	−0.0009 (0.0014)	0.0021 * (0.0011)
$LCC \times D_4$	0.0030 *** (0.0012)	0.0011 ** (0.0006)	0.0011 (0.0009)	0.0030 *** (0.0015)	0.0011 (0.0014)	0.0022 *** (0.0011)
$LCC \times D_5$	0.0054 *** (0.0012)	0.0019 * (0.0010)	0.0011 (0.0010)	0.0044 *** (0.0015)	−0.0010 (0.0013)	0.0027 *** (0.0011)
$LCC \times D_6$	0.0046 *** (0.0012)	0.0012 (0.0011)	0.0009 (0.0010)	0.0040 *** (0.0015)	0.0011 (0.0013)	0.0036 *** (0.0011)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
_cons	0.0791 ***	−0.0285 *	0.0026	−0.0608 **	0.2239	−0.0813 ***
R^2	0.6784	0.5528	0.4038	0.6665	0.1924	0.5024
N	3632	3632	3632	3632	3632	3632

Note: ***, **, * indicate that they passed the significance test at the level of 1%, 5%, and 10%, respectively. The values in parentheses are the cluster robust standard errors.

5.3. Parallel Trend Test

To prevent spurious regression results caused by the high-quality development trend of the city itself before the *LCC*, it is necessary to conduct a parallel trend test between the experimental group and the control group. In this paper, Beck's multi-period DID model (2010) [42] was selected to test its parallel trend. The model settings are as follows:

$$Qua_{i,t} = \beta_0 + \beta_1 LCC_{i,t-6} + \beta_2 LCC_{i,t-5} + \cdots + \beta_{11} LCC_{i,t+4} + X_{i,t} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (13)$$

$LCC_{i,t+j}$ represents the implementation of the *LCC* in the city. If city i starts the *LCC* in $t \pm j$ year, then $LCC_{i,t+j}$ = 1, otherwise $LCC_{i,t+j}$ = 0. In this paper, 2012 is the base period, and the regression analysis is conducted for the 5 years before the pilot and 5 years after the pilot, respectively, t = 2013, and the value of j ranges from −5 to 5. It can be seen from the testing process that if the coefficient of $LCC_{i,t+j}$ is 0, it indicates that there is a parallel trend. It can be seen from Figure 1 that before the *LCC*, its confidence interval fluctuates around 0, while after the *LCC*, its confidence interval for the policy effect is far less than 0. As can be seen from Figure 1, before the implementation of the policy in 2013, the high-quality development index of the experimental group and the control group showed a parallel trend. However, the implementation of the *LCC* significantly expanded the difference in the high-quality development index between the experimental group and the control group. The double-difference model constructed in this paper has certain research significance.

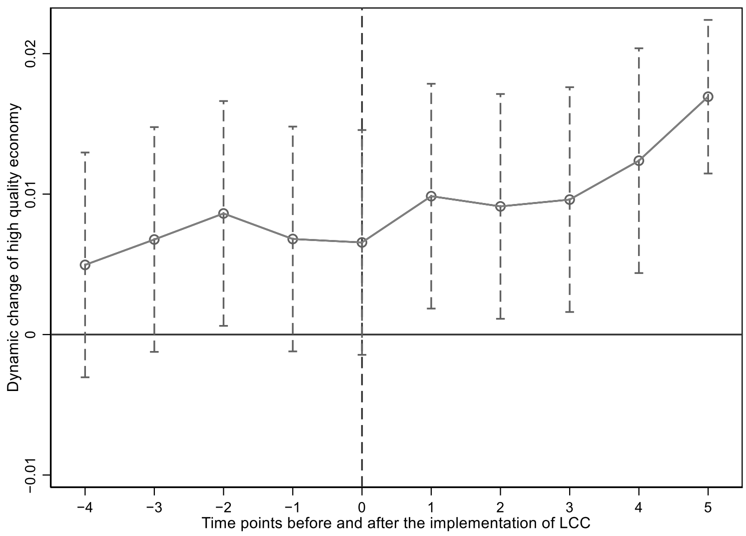

Figure 1. Parallel trend chart.

5.4. Robustness Check

(1) Join the first batch of low-carbon pilot cities

The provincial capital cities corresponding to the first batch of pilot provinces and the first batch of pilot cities are added to the regression to test the robustness of the conclusion that the *LCC* promotes the improvement in urban economic quality. The test results are shown in Table 6. It can be seen from the table that the coefficient of the *LCC* term is significantly positive and the addition of the control variables has no influence on the result, which verifies the robustness of the conclusion.

Table 6. Robustness test of adding the first batch of pilot samples.

Variables	*Qua*	*Qua*
LCC	0.0140 *** (0.0012)	0.0138 *** (0.0012)
Control variables	Yes	No
Regional effect	Yes	Yes
Time effect	Yes	Yes
_cons	0.0994 **	0.2704 ***
R^2	0.5912	0.5802
N	3632	3632

Note: *** and ** indicate that they passed the significance test at the level of 1% and 5%, respectively. The values in parentheses are the cluster robust standard errors.

(2) Method of PSM-DID

To overcome the shortcomings of using the difference-of-difference model in previous empirical research, the propensity score matching double-difference method (PSM-DID) was used to test the robustness of the empirical results. The test steps are as follows: First, we scored all sample cities using covariate and probit models before PSM matching. Then, based on the scores, we used the PSM method to match non-pilot cities with similar scores for pilot cities. Finally, we deleted the data of cities that failed to match, and then we used the remaining samples of 2016 for DID regression. The regression results are shown in Table 7. It can be seen from the results that the *LCC* variable has a significant positive impact on the comprehensive indicators of high-quality development, innovative development, residents' living standards, and the level of urban public services, which verifies the robustness of the previous results.

Table 7. Regression results based on PSM-DID.

Variables	*Qua*	Innovative Development	Open to the Outside World	Residents' Life	Environmental Protection	Urban Public Services
LCC	0.0057 *** (0.0014)	0.0011 ** (0.0005)	0.0026 *** (0.0007)	0.0007 (0.0005)	−0.0006 (0.0007)	0.0019 *** (0.0005)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
_cons	0.0627	−0.0304	−0.0563 ***	0.0035	−0.2231 ***	−0.07312 ***
R^2	0.5825	0.6210	0.6703	0.4034	0.1933	0.3275
N	2016	2016	2016	2016	2016	2016

Note: *** and ** indicate that they passed the significance test at the level of 1% and 5%, respectively. The values in parentheses are the cluster robust standard errors.

(3) Exclude the impact of Other Urban Policies

The Chinese urban policies introduced in recent years include not only *LCC*, but also policies such as smart city pilots in 2013, new energy demonstration city pilots in 2014, and innovative city pilots in 2010, as well as the environmental protection interview with environmental regulation significance in 2014 and 2015. These policies may affect the high-quality development of the urban economy. To exclude other relevant policy effects, these policy dummy variables are added for regression. *Inn*, *Ite*, *Et*, and *Ne*, respectively represent the double difference dummy variables of the first batch of innovation pilot cities, the first and second batch of smart pilot cities, environmental protection interview cities, and the first batch of new energy demonstration cities. The test results are shown in Table 8. From the results, the absolute value of the *LCC* coefficient has decreased, but it is still significantly positive, indicating that the results of this paper are relatively robust.

Table 8. Robustness test after adding other urban policies.

Variables	(1) *Qua*	(2) *Qua*	(3) *Qua*	(4) *Qua*
LCC	0.0055 *** (0.0014)	0.0062 *** (0.0014)	0.0089 *** (0.0062)	0.0079 *** (0.0014)
Ite	0.0086 *** (0.0009)			
Inn		0.0186 *** (0.0011)		
Et			0.0012 (0.0018)	
Ne				0.0011 (0.0011)
Control variables	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
_cons	0.0661 *	0.0883 **	−0.3626	0.0739 *
R^2	0.5904	0.6110	0.5384	0.5798
N	3632	3632	3632	3632

Note: ***, **, * indicate that they passed the significance test at the level of 1%, 5%, and 10%, respectively. The values in parentheses are the cluster robust standard errors.

5.5. Heterogeneity Analysis

Based on the analysis of the overall city sample, the sample is subdivided according to the differences in infrastructure and economic development of each city, and the influence of low-carbon pilot city policies on the quality of urban economic development in different cities is explored. Given this, this paper uses the urban resident population of 1 million in 2013 as the distinction, above 1 million people are divided into large cities, and the rest is divided into small and medium-sized cities, and the three major regions are adopted for regression. There are 67 large cities, 160 small and medium-sized cities, and 100 cities in the eastern region, 64 cities in the central region, and 63 cities in the western region. The distribution of the three regions is shown in Figure 2. From the regression results in Table 9, it can be found that the low-carbon pilot policy has a significant effect on promoting the high-quality economic development of large cities, while it has a negative effect on small and medium-sized cities. Moreover, it has a significant positive effect on the low-carbon pilot policy in eastern and central regions, while it has a significantly negative effect on western regions.

Table 9. Analysis of regional heterogeneity.

Variables	(1) Based on City Size		(2) Based on Three Regions		
	Large Cities	Small and Medium-Sized Cities	East	Central	West
LLC	0.0113 *** (0.0024)	−0.0035 * (0.0052)	0.0175 *** (0.0023)	0.0084 *** (0.01500)	−0.0057 * (0.0029)
control variables	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes
_cons	−0.1251	−0.1682 ***	0.0347	−0.5219 ***	0.2279 ***
R^2	0.5860	0.4663	0.5459	0.5459	0.4403
N	1072	2560	1600	1024	1008

Note: ***, * indicate that they passed the significance test at the level of 1% and 10%, respectively. The values in parentheses are the cluster robust standard errors.

Figure 2. Division map of eastern, central, and western China. Note: This image is made by ArcMap 10.7.

5.6. Mediating Effect Analysis

To explore the mediating effect of the low-carbon pilot policies on the quality of urban economic development, the mediating effect model of Equations (4)–(11) is used to analyze whether industrial structure upgrading and urban technological innovation can be used as intermediary variables to participate in the process of low-carbon cost affecting the quality of urban economic development. The regression results are shown in Table 10.

Table 10. Mediation effect regression results.

Variables	(1) *ARS*	(2) *RIS*	(3) *Qua*	(4) *IL*	(5) *Qua*	(6) *IV*	(7) *Qua*
LCC	−0.0122 (0.0142)	0.0160 *** (0.0039)	0.0084 *** (0.0014)	0.0430 *** (0.0041)	0.0043 *** (0.0013)	22.3508 *** (3.1615)	0.0375 *** (0.0044)
ARS							
RIS			0.0278 *** (0.0063)				
IL					0.1088 *** (0.0056)		
IV							0.0005 *** (0.0001)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−0.4000	−0.0940	0.0704 **	1.0617 ***	−0.0514	33.6586	0.3768
R^2	0.2712	0.5540	0.5821	0.6692	0.6231	0.2816	0.2171
N	3632	3632	3632	3632	3632	3632	3632

Note: *** and ** indicate that they passed the significance test at the level of 1% and 5%, respectively. The values in parentheses are the cluster robust standard errors.

As can be seen from column (1) in Table 10, there is no intermediary effect of advanced industrial structure in the process of *LCC* affecting the high-quality development of urban economy. It can be seen from column (2) that the *LCC* double-difference variable significantly promotes the rationalization of the industrial structure, and the existence of the intermediary effect can be further judged from column (3). From column (3), it can be seen that after adding the *RIS* variable, the *RIS* variable significantly promotes the high-quality development of urban economy, and the variable *LCC* is positive and significant, indicating that *LCC* played a certain role in the process of affecting the high-quality development of urban economy. Therefore, Hypothesis 2 "Industrial transformation and upgrading as the intermediary mechanism of *LCC* affecting the high-quality development of urban economy" has been verified.

To further analyze the mediating effect of technological innovation, it can be seen from column (4) in Table 10 that the variable *LCC* has a significant promoting effect on variable *IL*, which can be analyzed in the next stage. As can be seen from column (5), the coefficients of the variable *LCC* and *IL* are both significant, indicating that the mediating effect of *IL* exists, and it is a partial mediating effect. Therefore, Hypothesis 3 "Technological innovation is the intermediary mechanism through which *LCC* affects the high-quality development of urban economy" has been verified.

Columns (6) and (7) in Table 10 verify the mediating effect on urban investment. It can be seen from column (6) that the variable *LCC* has a significant promoting effect on variable *IV*, which can be analyzed in the next stage. It can be seen from column (7) that the coefficients of variables *LCC* and *IV* are both significant, indicating that *IV* plays a partial mediating role. Therefore, Hypothesis 4 "Urban investment is the intermediary mechanism for low-carbon pilot policies to affect high-quality urban economic development" has been verified.

6. Conclusions and Policy Recommendations

Based on the panel data of 227 cities in China from 2004 to 2019, this paper draws the following conclusions: First, the implementation of *LCC* has a significant effect on the quality of economic development in pilot cities, which verifies Hypothesis 1 that "*LCC* policies can promote high-quality urban economic development" and the effects are long-lasting. We divide the high-quality urban development indicators into five dimensions, including innovative development for further regression, residents' life, openness to the outside world, environmental protection, and urban public services. Further regression found that *LCC* mainly promotes the innovation and development of the city, the improvement in residents' living standards, and the urban public service level. Second, the low-carbon pilot policy has effectively promoted the quality of economic growth in large cities as well as central and eastern regions. However, the effect on small and medium-sized cities is not clear, and the impact on the western region is negative. Third, the *LCC* promotes the high-quality development of the urban economy by improving the level of urban technological innovation, which verifies Hypothesis 2 that "Industrial transformation and upgrading is the intermediary mechanism through which low cost affects the high-quality development of urban economy". Then, the upgrading of industrial structure is measured by the rationalization of industrial structure and the advancement of industrial structure. It is found that the promotion effect of low-cost enterprises on the high-quality development of urban economy is through the rationalization of industrial structure, rather than through the advanced industrial structure. Hypothesis 3 which states that "Technological innovation is an intermediary mechanism through which *LCC* affect the high-quality development of urban economy" is verified. Finally, urban investment plays a partial intermediary role in the impact of *LCC* on high-quality development of urban economy, whereby Hypothesis 4 which states that "Urban investment is an intermediary mechanism of low-carbon pilot policies on high-quality urban economic development" is verified. The reasons for this result are analyzed as follows:

First, the *LCC* has improved the level of urban innovation in the process of achieving low-carbon development. It can be seen that in the face of the government's requirement to reduce carbon emissions, enterprises reduce carbon emissions by increasing investment and improving production processes, and their technological innovation level has been improved. The improvement in the level of technological innovation of enterprises has enhanced the competitiveness of regional enterprises and promoted urban economic growth.

The development achievements driven by technological innovation include not only increases in the income of local residents, but also shares the social welfare brought about by economic growth. However, *LCC* mainly limits carbon emissions, and has insufficient treatment of other pollutants in cities; therefore, they have not been able to promote urban green development and the development of openness to the outside world. This may be due to the fact that the implementation of the *LCC* does not have preferential policies for openness to the outside world. This may be something to consider in the future.

Second, the industrial upgrading effect of *LCC* is more apparent. This is due to the fact that *LCC* emphasizes that each pilot region should give full play to the advantages of market-oriented resource allocation and internalize the external cost of environmental pollution through the introduction of policies. Given the cost pressure, enterprises adjust their product structure and increase investment in technological innovation and clean energy application technology. In this process, some enterprises that do not focus on innovation and backward enterprises are gradually eliminated, thereby improving the production efficiency of the entire industry and realizing the transformation and upgrading of the industrial structure.

Third, the low-carbon city pilot mainly promotes the high-quality development of large cities, due to large cities with perfect infrastructure and strict policy implementation procedures, which can better implement *LCC* compared with small and medium-sized cities, thereby giving full play to the role of innovation. The compensation effect improves the quality of urban development. Due to their limited conditions, small and medium-sized cities are still in the stage of cost increase and *LCC* restricts the high-quality development of their urban economy. The *LCC* mainly promotes the high-quality development of the eastern region. Since the eastern region has a relatively developed economy and a relatively solid industrial foundation, it is more conducive to improving the quality of economic growth through innovation. However, the industrial development of the central and western regions is relatively weaker than the eastern regions; even if we choose to increase the innovation input, we will still face the problem of increased costs first, and the compensation effect of innovation has not yet been brought into play. In addition, the openness degree of the eastern region is already at a high level, thus the low-carbon pilot project has not been able to effectively improve the openness degree of the city to the outside world.

Based on the conclusions, this paper presents the following policy recommendations:

First, the implementation of the *LCC* has achieved initial results. On this basis, each pilot city should take measures to consolidate the economic benefits brought by the policy, and make use of the resources or infrastructure advantages of each pilot city measures to further develop reasonable low-carbon implementation specific plans, such as increasing support for new energy vehicles as well as encouraging enterprises to use high-efficiency and low-consumption production equipment. This ensures that cities can achieve high-efficiency economic development under the condition of low-carbon development. In addition, the government should innovate financing methods, actively create conditions, and support enterprises to invest in fixed assets and innovation through franchising, investment subsidies, and other means. Moreover, formulating corresponding policies to expand foreign investment, in order to expand the openness of the city, can better promote the high-quality development of the urban economy.

Second, the quality of urban economic growth has been improved under the *LCC*, but from the empirical results, urban environmental protection and openness to the outside world have not been well developed. The original intention of implementing the *LCC* is to enable people to live a better life. Therefore, it is necessary to improve the green aspects of cities under the *LCC* and improve the quality of people's living environment. At the same time, under the guidance of reasonable policies, the innovative advantages brought by *LCC* will be utilized to promote the urban development of the greenness and openness.

Third, the impact of low-carbon pilot policies on different scales and residential cities. To further promote the coordinated development of cities, large cities can jointly establish a regional city circle with small and medium-sized cities to expand the radiation capacity of the central cities of the provincial capitals. This reduces the dependence of regional economy on a single large city, and the establishment of a city circle is more conducive to the smooth implementation of low-carbon pilot policies and other policies. To make the development of the three major regions more coordinated, the government should take measures to make the eastern region drive the development of the central and western regions. In the process, the government needs to perform appropriate macro-controls and make a reasonable configuration on the basis of the urban circle, giving full play to the location advantages of each city or city circle and implementing low-carbon policies rationally according to the industrial structure of each city. Small and medium-sized cities or cities in the central and western regions can strengthen economic cooperation with surrounding cities according to their own advantages. In this way, these cities can take advantage of regional cooperation, and promote the further upgrading of the industrial structure, improve the innovation level, as well as promote the high-quality development of the urban economy.

To further study the pilot policy of low-carbon cities, this paper presents the following research prospects. First, this paper only analyzes the implementation effect of the second low-carbon pilot city. In the future, further analysis of the third low-carbon pilot city can be conducted. Second, the pilot policies of low-carbon cities analyzed in this paper failed to carry out policy subdivision. Future research and analysis can be carried out according to specific policies and measures for cities to reduce carbon emissions. Third, the empirical analysis data on industrial transformation are collected based on the macro-level. In the future, the specific analysis of industrial transformation can be further based on the micro-level of the enterprise. Industrial transformation and upgrading can be based on the service industry for data collection. Fourth, the measurement of the comprehensive indicators of the high-quality development of the urban economy can be improved. For instance, for the analysis of urban innovation and development, the analysis of the welfare sharing of urban residents can be added to the residents' social insurance payment indicators. In the aspect of urban environmental protection, the waste disposal rate can be increased to make the comprehensive measurement of urban economic development quality more perfect.

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Article

Does the Environmental Information Disclosure Promote the High-Quality Development of China's Resource-Based Cities?

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Abstract: The high-quality development (HQD) of resource-based cities (RBCs) is the premise on which to ensure the healthy, stable, and sustainable development of China's economy. In this study, we use the global Malmquist–Luenberger index based on the slacks-based measure of directional distance function (SBM-DDF-GML index), which is an improved data envelopment analysis (DEA) model of the non-radial and non-oriented, to calculate the HQD level of 102 RBCs in China from 2003 to 2019. Then, we empirically evaluate the effect of environmental information disclosure (EID) on HQD improvement in RBCs by adopting the method of time-varying difference-in-difference with propensity score matching (PSM-DID) and investigate the heterogeneous effects of EID. Additionally, the mediating effect model is employed to explore the impact mechanisms of EID on the HQD. The results show that: (1) EID has a significant and positive effect on the HQD of RBCs, and this conclusion is still valid after a series of robustness tests. (2) EID plays a more effective role in the promotion of HQD in central RBCs, resource strong-dependent RBCs, growth RBCs, and regenerative RBCs than in other types of cities. (3) EID promotes the HQD of RBCs through the environmental pollution reduction effect and the industrial structure upgrading effect. These findings enrich the content of the relationship between EID and the HQD and present a feasible path for RBCs in China to achieve the HQD through environmental governance.

Keywords: resource-based cities; environmental information disclosure; high-quality development; PSM-DID method; mediating effects

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1. Introduction

Chinese resource-based cities (RBCs) have made extraordinary contributions to China's industrialization process, as well as to national economic and social development [1]. However, due to the excessive exploitation and dependence on natural resources and the traditional extensive development model of high energy consumption, high emissions, and low benefits, a series of contradictions, such as resource depletion, imbalance of economic structure, and ecological environment destruction, has inevitably accumulated [2–4]. It has seriously constrained the sustainable development of RBCs and even hindered the improvement of the quality of China's overall national economic growth, to a certain extent [5]. Moreover, globalization and increased competition have had a violent impact on such cities [6]. Accordingly, the importance of accelerating the transformation and sustainable development of China's RBCs cannot be overemphasized. The Chinese government always attached great importance to RBCs and has promulgated a variety of guiding policies for the transformation and sustainable development of RBCs since 2001, such as The Plan for the Sustainable Development of Resource-based Cities in China (*The Plan*) (2013) [7], Guiding Opinions on Classification and Cultivation of Resource-based Cities to Transform and Develop New Momentum (2017) [8], and so on. In particular, under the background of China's transition from high-speed development to high-quality development (HQD), the National Development and Reform Commission (NDRC) released the Implementation

Plan for Promoting the High-quality Development of Resource-based Areas in the 14th Five-Year Plan Period (2021) [9], which mentioned the HQD of RBCs for the first time and put forward further expectations for the development of Chinese RBCs from 2021 to 2025. Consequently, it is necessary and of great importance to explore a sustainable way for the HQD of RBCs.

The HQD of RBCs in China refers to the development status, with strong resource security, economic dynamism, a beautiful ecological environment, and people's good well-being [9]. It emphasizes the coordination and harmonization of quantity expansion and quality enhancement, and the transformation from "total expansion" to "structural upgrading and system optimization" [10]. Some scholars have adopted the multi-indicator measurement method to evaluate the level of HQD based on the multidimensional characteristics of HQD [2,11]. Meanwhile, because the development results of HQD include the welfare of residents, brought about by economic growth, as well as the use of resources and the cost of the ecological environment [12], the productive efficiency evaluation method, which takes into account both multiple inputs and multiple outputs containing environmental factors, could avoid the serious underestimation of the environmental costs of economic growth [13], and is therefore highly employed by a wide range of scholars in the calculation of HQD [14,15]. Moreover, the resource and environment regime, economic development level, industrial structure, and resource abundance are considered to be the possible factors affecting HQD [15–19].

At the same time, with the continuous improvement of material and cultural living standards, the quality of the ecological environment has become an essential indicator affecting people's health and happiness. In order to accommodate for the people's growing demand for a beautiful ecological environment, the Chinese central government has promulgated and implemented a range of laws on environmental governance, such as the Environment Protection Law, the Atmospheric Pollution Prevention and Control Law, and the Cleaner Production Promotion Law. Although these laws have been partially effective in pollution reduction and environmental protection, it is still hard to avoid the dilemma of "regulatory failure" caused by information asymmetry [20], which may lead to environmental management issues, such as high cost and low efficiency [21]. Fortunately, the rapid evolution of modern information technologies provides a breakthrough and critical opportunity for the introduction of new environmental governance measures based on the Internet platform [22,23]. In 2008, the Pollution Information Transparency Index (PITI Index) was jointly released by the Institute of Public and Environmental Affairs (IPE) and the US Natural Resources Defense Council (NRDC). It has systematically evaluated the level of regulatory information disclosure on urban pollution sources in China's key environmental protection cities since 2008; it guarantees the people's right to know and strengthens the monitoring of the government on environmental pollution data [24].

As an essential environmental governance policy, the implementation effects of the environmental information disclosure (EID) have attracted the close attention of researchers. Most scholars believe that EID can effectively promote environmental quality [25–28]. The reduction of scale effects, the optimization of industrial structure, and the enhancement of technological innovation are considered to be the key to reducing greenhouse gas emissions [26]. EID can also indirectly contribute to the reduction of total and per capita urban industrial pollution emissions by generating a positive interaction between government environmental enforcement and public environmental participation [27]. Moreover, EID could mitigate the negative externalities of air pollution by increasing government environmental spending, environmental employment, and infrastructure development [28]. However, some scholars have queried the effectiveness of EID. The main argument is that the environmental pollution behavior of private enterprises with political connections could not be significantly affected by EID, owing to the shelter effect of the Chinese local governments [29]. In addition, a large number of studies have demonstrated the beneficial role of EID in the development of regions [30,31] and enterprises [32–34]. Nevertheless, some scholars hold the opposite view, considering the mandatory EID to be an obstacle to the improvement of economic performance because of its consumption of limited resources in increasing environmental management activities [35]. As for the economic and social development of RBCs, most existing research has concentrated on the development or transformation performance assessment [36–38], influencing factors [39,40], and sustainable development paths [41–43]. Scholars have sought to evaluate the sustainable development level by using the index system [36,37] and the efficiency measurement model [38,42]. Social harmony, economic development, and environmental improvement are regarded as the most critical aspects in the construction of the indicator system [37]. Economic level, industrial structure, resource endowment, energy price, government intervention, and degree of openness are identified to have a significant impact on RBCs' transformation efficiency [39], along with other factors [38,40,41]. Some studies have also recognized the role of policy factors in the transformation of RBCs [44,45], such as the implementation of the National Sustainable Development Plan for RBCs [44], and the new energy demonstration city policy [45], which has remarkably facilitated the industrial structure upgrading and the green total factor productivity (GTFP) of RBCs, respectively. Furthermore, the structural effect, innovation effect, and financial support effect are considered to be impact paths of promoting GTFP [45].

Despite the growing literature, few studies have taken RBCs as the research object and attempted to figure out the relationship between EID and its HQD. That is, does the implementation of EID have a positive impact on the HQD of RBCs? If there is an impact, does the EID influence HQD the same across the different types of RBCs? Additionally, the specific mechanism path by which EID affects HQD is unclear. Therefore, to shed light on these issues, we take the disclosure of the PITI index as a quasi-natural experiment, using the sample of China's RBCs from 2003 to 2019 to perform an empirical study, by adopting the multiple regression model, the time-varying difference-in-difference with propensity score matching (PSM-DID) method, and the mediating effect model.

The main contributions of this study are reflected in the following aspects: (1) The implementation of EID may involve multiple stakeholders, including local governments, enterprises, and the public, whose behavior patterns would be influenced by the enforcement of this policy to a certain extent. Therefore, based on the stakeholder theory and the information asymmetry theory, this study builds a potential theoretical analysis framework of which EID affects the HQD of RBCs from the multi-governance perspective of the "government–enterprise–public" , which could enrich the theoretical research of environmental governance policy and the urban HQD field. (2) Compared with the economic growth quality, HQD pursues the synergistic development of the economy, society, and environment, and has a wider scope and higher requirements. To this end, the measurement of HQD should not only reflect the economic benefits but also needs to capture the cost of the resources and the state of the ecological environment. In this study, the global Malmquist–Luenberger index based on the slacks-based measure of directional distance function (SBM-DDF-GML index), considering resource and environmental constraints, is adopted to evaluate the HQD level of RBCs, reflecting the degree of coordination between ecological environment protection and social-economic development. It is helpful to gain an overall picture of the HQD of RBCs, and the model provides reliable data for empirical analysis. (3) In the empirical research section, we employ the PSM-DID method to effectively overcome the sample selectivity bias issue and take the air ventilation coefficient as an instrumental variable to further address the endogenous problem, which is conducive to accurately identifying the causal relationship between EID and the HQD of RBCs. In addition, we investigate a more comprehensive range of heterogeneity factors, including urban geographic location, degree of resource dependency, and urban development stage. In addition, the impact mechanism by which EID influences the HQD is further explored through the mediating effect model.

The remainder of this study is structured as follows: Section 2 introduces the theoretical analysis framework and research hypotheses. Section 3 presents the methods, research scope, and data sources. Section 4 reports the empirical results and corresponding analysis. Section 5 further conducts the heterogeneous analysis and the mechanism analysis. Section 6 draws the conclusions and discusses the policy implications.

2. Theoretical Analysis Framework

As a key policy instrument in environmental governance, EID can focus the public's attention on the supervision of local government's information disclosure and enterprise's environmental behavior, as well as their own interests through the reputation mechanism [46], which facilitates the formation of a polycentric governance system, consisting of three stakeholders: government, enterprises, and the public [47]. Therefore, the implementation of EID may indirectly affect the HQD of RBCs by influencing the behavior of the government, enterprises, and the public. To this end, we integrate the government, enterprises, and the public into the theoretical analysis framework of EID affecting the HQD of RBCs and attempt to elaborate the mechanism from the perspective of each subject.

The government plays a leading role in the Chinese environmental governance system. On the one hand, environmental information proposes a critical reference for the government to make various social and economic development policies. EID enables local governments to monitor the state of the urban ecology and environment, and accurately grasp the crucial issues of environmental governance through access to environmental information. As a result, local governments can formulate and promote the relevant laws and policies accordingly, to achieve the effective governance over all aspects of the sustainable economic and social operation. On the other hand, EID strengthens the supervision of the community to the local government. The monopoly profit generated by the exploitation of environmental resources tends to bring about the power rent-seeking of the government and government failure in environmental regulation [48]. EID makes it mandatory for local governments to report environmental-related information according to relevant regulations, instead of making trade-offs depending on the regulatory difficulties and the "reputation effect" [46]. It provides an external incentive for local governments to abandon the "worship GDP" performance assessment system and contribute to a win-win situation for ecological protection and economic development in RBCs.

Enterprises are the main body participating in market activities, which creates substantial economic value but causes severe ecological environment problems at the same time. EID is a prerequisite for the government and the public to monitor and supervise enterprises to fulfill their environmental responsibilities. Meanwhile, it is also an inevitable requirement for enterprises to comply with sustainable economic and social development. On the one hand, the disclosure of environmental information increases the exposure of enterprises' environmental pollution behavior. Consequently, polluting enterprises will face severe pressure from the government. The internalization of external environmental costs forces enterprises to improve their production processes and business models through in-depth introspection regarding their shortcomings rather than "ecological opportunistic" behavior [49]. It could optimize resource allocation efficiency and reduce the environmental pollutants emission, in order for enterprises to meet regulatory requirements. On the other hand, within the context of the global green and low-carbon development, enterprises will focus on green innovation in technology and equipment to adapt, guide, and even create consumer demand through cleaner products and services production. As a result, enterprises will occupy the "first competitive advantage" while taking the responsibility for environmental protection [50]. It provides an internal impetus for locals to build a modern industrial system by promoting the optimization and upgrading of industrial structures on the supply side and boosting the quality and efficiency of economic development in RBCs.

The ecological environment is closely related to the personal interests of the public. According to the theory of environmental rights, the public enjoys the right to know, participate, and supervise the environment [51]. Environment information is an essential source for the public to safeguard their legitimate rights and interests, and is the fundamental starting point for the public to participate in environmental protection. First, the public supervises the government's environmental governance and the enterprises' environmental performance by paying attention to environmental information, which resolves the "government failure" and the "ecological opportunism" behavior to some extent. In addition, it would thus improve the efficiency of its environment governance [52]. Second, EID will motivate the public to participate in environmental protection actively. It helps to form a green and low-carbon consumption concept and an energy-saving and environmentally friendly lifestyle throughout the society. Thereby, environmentally friendly products and services will obtain more trust and approval from stakeholders [53], which could encourage the optimization and upgrading of industrial structures from the demand side and then promotes the HQD of the city.

In a comprehensive view, EID could enhance the openness and transparency of urban environmental governance, facilitate the sharing and interaction of information among the government, enterprises, and the public, and alleviate a series of issues caused by information asymmetry. It is helpful to formulate and promote the environmental governance system with a "government lead, enterprise as the main body, and public participation", enhance the efficiency of urban resource allocation, reduce the environmental pollution, accelerate the green and low-carbon transformation of the industrial structure, and thus promote the HQD of RBCs.

According to the above theoretical analysis, we have formulated the following hypotheses:

Hypothesis 1 (H1). *EID can positively promote the HQD of China's RBCs in general.*

Hypothesis 2 (H2). *EID promotes the HQD of China's RBCs by the environmental pollution reduction effect and industrial structure upgrading effect.*

The specific impact mechanism of EID on the HQD of China's RBCs can be summarized in Figure 1.

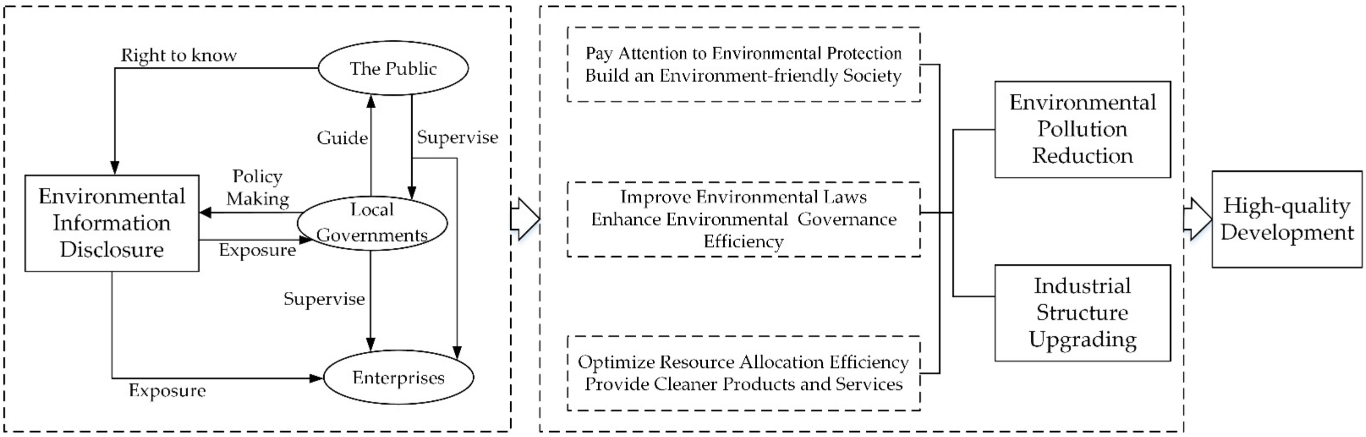


Figure 1. The impact mechanism of environmental information disclosure (EID) on the high-quality development (HQD) of China's resource-based cities (RBCs).

3. Materials and Methods

3.1. Model Design

3.1.1. SBM-DDF-GML Index

The data envelopment analysis (DEA) model is widely applied in academia because of its characteristics that do not require a specific production function form and because it can be applied to deal with systems with multiple inputs and outputs [47,54]. However, DEA typically ignores the bad outputs that are produced along with the desirable outputs [55]. Moreover, the radial and oriented problems can inevitably cause overestimated technical efficiency when there are nonzero slacks [13]. To this end, researchers have progressively extended and optimized the traditional DEA model. The slacks-based measure (SBM) maximizes input and output slacks [56], the directional distance function (DDF) and Malmquist–Luenberger (ML) index were proposed to take the undesirable output and environmental concept into account [55], and the slacks-based measure of directional distance function (SBM-DDF) allows for a non-radial scaling of outputs and inputs [57]. Even so, it fails to achieve the comparability of the inter-temporal production frontier [58]. In contrast, the global Malmquist–Luenberger index based on directional distance function (SBM-DDF-GML index) can effectively address the radial and oriented problems of the absolute GML index, and deals with the inconsistency and incomparability of the production frontier in SBM-DDF.

(1) The Global Production Possibility Set

The global production possibility set P^G has been constructed by Oh [59] to effectively achieve the consistency and comparability in the production frontier. Assuming that there are J decision-making units (DMUS), then each RBC is a DMU that transforms N kinds of inputs $x_{in} = (x_{i1}, x_{i2}, \ldots, x_{in}) \in R_N^+$ into M kinds of desirable outputs $y_{im} = (y_{i1}, y_{i2}, \ldots, y_{in}) \in R_M^+$ and K kinds of undesirable outputs $b_{ik} = (b_{i1}, b_{i2}, \ldots, b_{iK}) \in R_K^+$. The specific expressions of P^G are as follows:

$$P^G = \begin{Bmatrix} (x^t, y^t, b^t) : \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t x_{in}^t \leq x_{in}^t, \forall n; \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t y_{im}^t \geq y_{im}^t, \forall m; \\ \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t b_{ik}^t = b_{ik}^t, \forall k; \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t = 1, z_i^t \geq 0, \forall i \end{Bmatrix} \tag{1}$$

where i represents different RBCs, t represents different periods, z_i^t is the weight variable, $\sum\limits_{i=1}^{I} z_i^t = 1, z_i^t \geq 0$ represents variable return to scale (VRS).

(2) SBM-DDF

According to the research of Fukuyama et al. [57], this study takes into consideration the resource and environmental factors, which include input indicators of labor input, capital investment, and energy consumption, desirable outputs of economic growth and ecological efficiency, and undesirable outputs indicators of wastewater discharge, exhaust emission, and particulate emission. Then, we define the global SBM-DDF, covering undesirable outputs as follows:

$$\begin{gathered} \vec{S}_V^G\left(x^{t,i'}, y^{t,i'}, b^{t,i'}, g^x, g^y, g^b\right) = \max_{s^x, s^y, s^b} \frac{\frac{1}{N}\sum\limits_{n=1}^{N}\frac{s_n^x}{g_n^x} + \frac{1}{M+K}\left(\sum\limits_{m=1}^{M}\frac{s_m^y}{g_m^y} + \sum\limits_{k=1}^{K}\frac{s_k^b}{g_k^b}\right)}{2} \\ s.t. \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t x_{in}^t + s_n^x = x_{i'n}^t, \forall n; \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t y_{im}^t - s_m^y = y_{i'm}^t, \forall m; \\ \sum_{t=1}^{T}\sum_{i=1}^{I} z_i^t b_{ik}^t + s_k^b = b_{i'k}^t, \forall k; \sum_{i=1}^{I} z_i^t = 1, z_i^t \geqslant 0, \forall i; s_m^y \geqslant 0, \forall m; s_k^b \geqslant 0, \forall k \end{gathered} \tag{2}$$

where $(x^{t,i'}, y^{t,i'}, b^{t,i'})$ represents input, desirable output, and undesirable output vector, respectively, the definitions and calculations of which are detailed in the next section. (g^x, g^y, g^b) is the direction vector that indicates contracting input, expanding desirable output, and reducing undesirable output, respectively, and (s_n^x, s_m^y, s_k^b) is the slack vector that indicates the redundant input, insufficient desirable output, and excessive undesirable output, respectively.

(3) GML Index

With reference to the existing research [59], we construct the SBM-DDF-GML index as follows:

$$GML_t^{t+1} = \frac{1 + \vec{S}_V^G\left(x^t, y^t, b^t, g^x, g^y, g^b\right)}{1 + \vec{S}_V^G\left(x^{t+1}, y^{t+1}, b^{t+1}, g^x, g^y, g^b\right)} \tag{3}$$

where $\overrightarrow{S}_V^G\left(x^t, y^t, b^t, g^x, g^y, g^b\right)$ is the global SBM-DDF based on non-radial and non-oriented measurements. GML_t^{t+1} indicates the growth of the GML index from t to t + 1 period, $GML_t^{t+1} < 1$ indicates the decline of the GML from t to t + 1 period, and $GML_t^{t+1} = 1$ indicates that the GML index is stable from t to t + 1 period.

3.1.2. Time-varying Difference-in-Differences (DID) Method

The implementation of EID causes regional differences between environmental information disclosing RBCs (EID RBCs) and non-environmental information disclosing RBCs (non-EID RBCs) during the sample period, as well as temporal differences between disclosing cities before and after disclosure. Those two differences provide an excellent opportunity to conduct a quasi-natural experiment for capturing the net effects of EID on the HQD of RBCs by adopting the DID method. Moreover, the cities disclosing PITI index expanded from 113 in 2008 to 120 in 2013. Therefore, this study employs the time-varying DID method, which could control the two differences simultaneously and identify the net effect more accurately.

The benchmark regression model is constructed as follows:

$$HQD_{it} = \alpha_0 + \alpha_1 EID_{it} + \alpha_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{4}$$

where subscript i and t represent different cities and years, respectively. The dependent variable HDQ_{it} is measured by the value of the GML index. The explanatory variable EID_{it} is a policy dummy variable, indicating whether city i discloses environmental information in year t. α_0 is the constant term. The coefficient α_1 denotes the net and total effect of EID on the HQD. X_{it} represents a series of control variables affecting the HQD. λ_i and μ_t indicate city-fixed effects and year-fixed effects, respectively. ε_{it} is the error term.

3.1.3. Propensity Score Matching (PSM) Method

The implementation of EID in China may not be completely random but may instead be related to the individual heterogeneous characteristics of cities. To eliminate the sample selectivity bias caused by failing to meet the assumption of the random assignment of groups, this study uses the propensity score matching (PSM) method to match the control group to the treatment group with similar characteristics through an appropriate matching method [60,61]. Therefore, the method of time-varying difference-indifference with the propensity score matching (PSM-DID) method is adopted to more accurately identify the net effect of EID on HQD.

According to the application logic of the PSM method [62], the specific matching steps are as follows. First, the sample is divided into the treatment group and the group to be matched. Second, the propensity matching score is calculated by constructing a logit model, including six covariates that may affect the probability of a city being selected as a disclosing city, including economic development level (Econ), urban greening level (Green), infrastructure level (Infra), informatization level (Infor), financial development level (Fina), and resource endowment (Resou). Third, the K near neighbor matching method is applied. Then, each city in the treatment group could be matched with one city or multiple cities of extremely similar characteristics in the control group.

3.1.4. Mediating Effect Model

Based on the existing literature and the illustration in the theoretical analysis section, this study proposes two channels through which EID could promote the HQD of RBCs: reducing environmental pollution and boosting industrial structure upgrading. To verify these mechanisms, a stepwise regression approach is adopted to construct a mediating effect model by following the designs of Baron et al. [63] and Li et al. [64]. The specific form presents in formulas (5)–(7).

$$HQD_{it} = \beta_0 + \beta_1 M_{it} + \beta_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{5}$$

$$M_{it} = \eta_0 + \eta_1 EID_{it} + \eta_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{6}$$

$$HQD_{it} = \varphi_0 + \varphi_1 EID_{it} + \varphi_2 M_{it} + \varphi_3 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (7)$$

where M_{it} denotes the intermediary variable. The coefficient β_1 measures the impact of M on the HQD, η_1 measures the impact of EID on M, and the coefficient φ_1 indicates the direct effect of EID on the HQD. The indirect effect of EID on the HQD is calculated by the product of η_1 and φ_2. Other variables are set in accordance with the formula (4).

According to the test procedure of the mediating effect [65], if the signs of $\beta_1 \times \eta_1$ are consistent with that of α_1 mentioned in formula (4), then the mediating effect of M is $\beta_1 \times \eta_1$. Otherwise, the effect of EID on the HQD through M is manifested as a masking effect. In addition, if φ_1 and φ_2 are all significant, and φ_1 is less than α_1, the partial mediating effect of M between EID and the HQD is proved. If φ_2 is significant but φ_1 is not, it means that the total effect of EID on the HQD is completely realized by the mediating variable.

3.2. Variables and Measurements

3.2.1. Dependent Variable

High-quality development (HQD). In order to better reflect the HQD level of RBC, this study considers the dual constraints of energy consumption and environmental pollution, in addition to the traditional production factors of labor and capital. The specific input and output indicators are shown in Table 1.

Table 1. Evaluation indicator system for the global Malmquist–Luenberger index based on directional distance function (SBM-DDF-GML index).

Index	Type	Specific Indicator	Unit
Input	Labor input	Number of employees at the end of the year	10^4 persons
	Capital investment	Capital stock	10^4 yuan
	Energy consumption	Total energy consumption	10^4 tons of standard coal
Desirable output	Economic growth	Real GDP	10^4 yuan
	Ecological efficiency	Green coverage rate	%
Undesirable output	Wastewater discharge	Industrial wastewater discharge	10^4 tons
	Exhaust emission	Industrial SO_2 emission	10^4 tons
	Particulate emission	$PM_{2.5}$ concentration	mg/m^3

Input indicators include labor input, capital investment, and energy consumption, which are measured by the number of employees, capital stock, and total energy consumption in each city at the end of the year, respectively. In particular, the perpetual inventory method is employed to estimate the capital stock with the formula $K_{it} = K_{it-1}(1 - \delta_{it}) + I_{it}$ [66], where, K_{it}, I_{it}, δ_{it} denote the capital stock, the total investment in fixed assets, and the depreciation rate (set at 9.6%) [15] of the city i during t period, respectively. In addition, we take the product of the proportion of urban industrial output value in that of the province it belongs to and the total energy consumption of the province to measure the energy consumption of each city by referring to Cui et al. [2].

Output indicators include desirable output and undesirable output. Desirable output indicators include economic growth and ecological efficiency, measured by the real GDP deflated into the 2003 constant price and greening coverage rate of built-up areas of each city, respectively. Undesirable output indicators include wastewater discharge, exhaust emission, and particulate emission, measured by industrial wastewater discharge, industrial SO_2 emission, and $PM_{2.5}$ concentration of each city, respectively.

3.2.2. Independent Variable

Environmental information disclosure (EID). EID is the interaction term between $Treat_i$ and $Time_{it}$ dummy variables. $Treat_i$ represents whether a city discloses environmental information during the sample period. For RBCs that disclose environmental information, $Treat_i$ equals 1, otherwise, it equals 0. Namely, the corresponding variables of 35 RBCs in the treatment group are set as 1, while that of the other 68 RBCs in the control group are set as 0. $Time_{it}$ indicates whether year *t* is the EID implementation point of city *i*. $Time_{it}$ equals 1 for every year after city *i* discloses environmental information, otherwise, it equals 0.

3.2.3. Mediating Variables

(1) Environmental Pollution Reduction.

To comprehensively examine the impact mechanism of EID promoting HQD through environmental pollution reduction, we choose the urban industrial wastewater discharge intensity (Wastewater), industrial exhaust emission intensity (SO_2), and particulate emission intensity ($PM_{2.5}$) as mediating variables to represent the environmental pollution effect.

(2) Industrial Structure Upgrading.

To verify whether industrial structure upgrading plays an intermediary role between EID and HQD, the following two variables are selected as mediating variables. To be specific, the proportion of the added value of the secondary industry to GDP is applied to measure the changes in the secondary industry (CSI), and the ratio of the added value of the third industry to that of the secondary is adopted to represent the industrial structure upgrading (ISU) [67].

3.2.4. Control Variables

According to the practice of previous research [19,25,32,68–70], we introduce a vector of control variables to decrease the influence of other potential factors, as follows:

(1) Economic development level (Econ), calculated by GDP per capita, deflated into the constant price of 2003 in logarithmic form.
(2) Urban greening level (Green), calculated by the greening coverage rate of urban built-up areas.
(3) Infrastructure level (Infra), calculated by the urban road area per capita.
(4) Informatization level (Infor), calculated by the ratio of the number of Internet users to the total population.
(5) Financial development level (Fina), calculated by the ratio of the deposit and loan balances of financial institutions at the end of the year to GDP.
(6) Resource endowment (Resou), calculated by the number of employees in the extractive industry in logarithmic form.

3.3. Sample Selection and Data Sources

The sample period is from 2003 to 2019. This study begins with all prefectures and above RBCs covered in *The Plan* and the PITI index report. The relevant data are mainly derived from China City Statistical Yearbook (2004–2020), China Regional Economic Statistical Yearbook (2004–2020), China Statistical Yearbook (2004–2020), China Energy Statistical Yearbook (2004–2020), and the National Economic and Social Development Statistical Bulletin (2003–2019). In addition, the $PM_{2.5}$ concentration data are obtained from the Socioeconomic Data and Applications Center (SEDAC) of Columbia University. To ensure data availability, continuity, and comparability, we clean the data according to the following procedures. First, we exclude seven forestry cities (Jilin, Baishan, Heihe, Yichun, Mudanjiang, Daxinganling, and Lijiang), nine autonomous prefectures (Yanbian Korean, Tibetan Qiang of Ngawa, Liangshan Yi, Qiannan Buyi and Miao, Southwest Guizhou, Chuxiong Yi, Haixi Mongolian and Tibetan, Bayingol Mongolian, and Altay), and two special resource-type cities (Zigong and Jingdezhen). Second, we exclude five cities (Shuozhou, Bijie, Jinchang, Baiyin, and Karamay) with serious data deficiencies. Third, to avoid the influence of outliers, all continuous variables are winsorized at the top and bottom 1%. Fourth, missing data in some years are interpolated and supplemented. Thereby, the final city–year observations are 1734 for 102 RBCs, including the treatment group and control group consisting of 35 EID RBCs and 67 non-EID RBCs, respectively (see Figure 2). In terms of data analysis and processing, we mainly use the Stata 16.0 software.

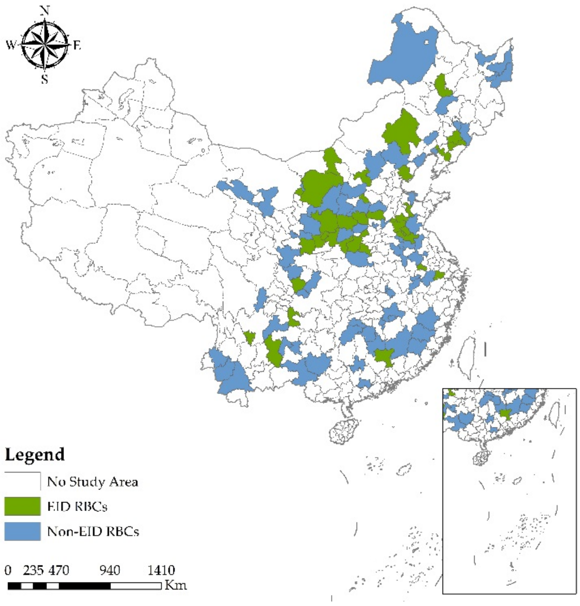


Figure 2. Spatial pattern of the EID implementation in China's RBCs. Note: The spatial distribution map shows the implementation scope of EID in China's RBCs and the comparison of spatial location between EID RBCs and non-EID RBCs.

Based on the above model and data, this study assesses the effect of EID on HQD in China's RBCs and then further explores the heterogeneous impact of EID as well as the impact mechanisms of EID on the HQD. All the key links and specific practices of the empirical research part of this study are shown in the flow scheme in Figure 3.

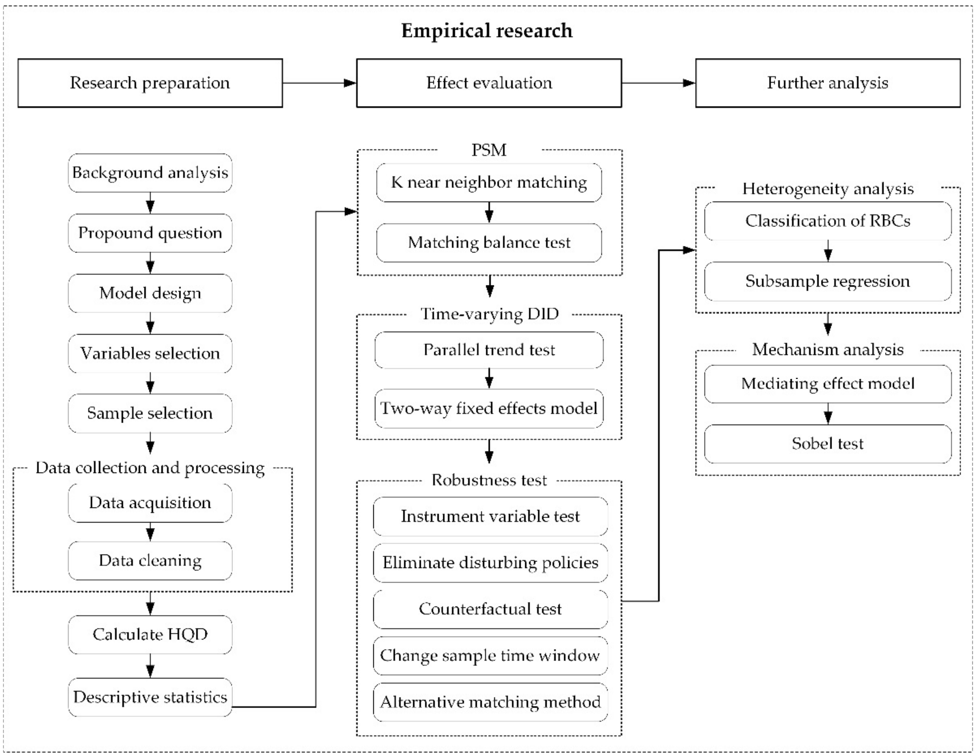
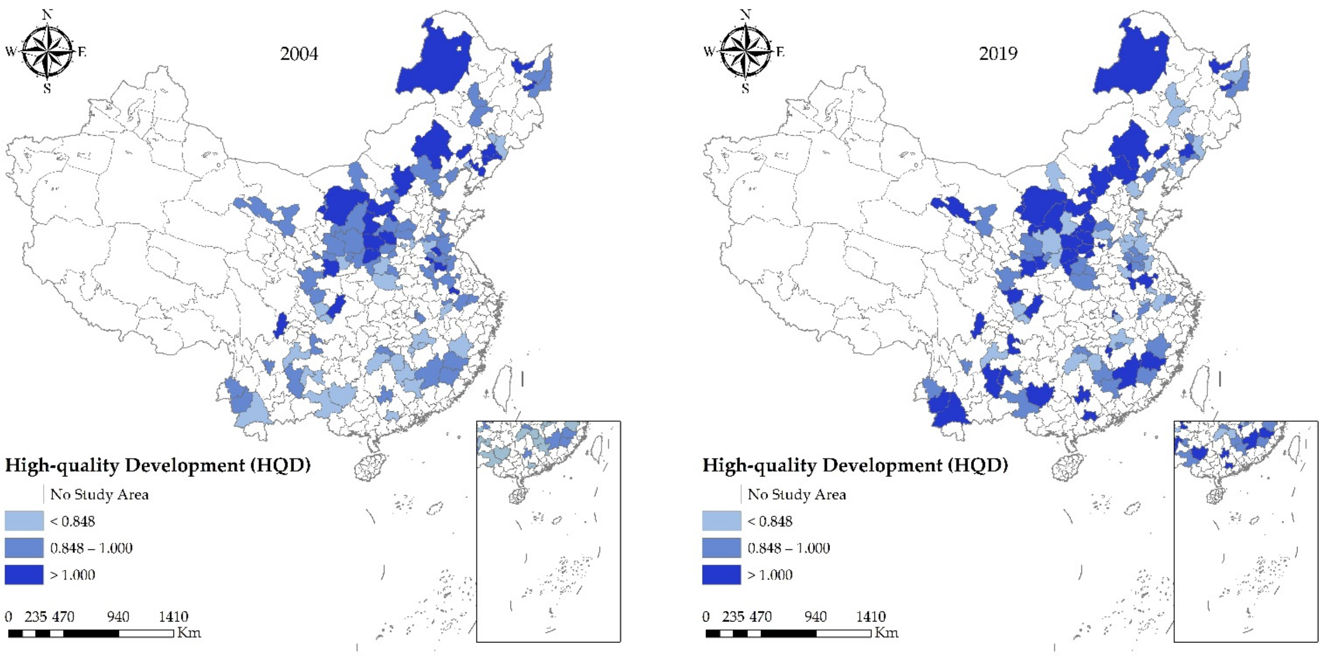


Figure 3. Flow scheme of empirical research. Note: This flow scheme illustrates the empirical research process of this study, presenting the details and main links of research preparation, effect evaluation, and further analysis.

4. Empirical Results and Discussion

4.1. Calculation of HQD

In this study, taking the labor input, capital investment, and energy consumption as production input indicators, economic growth and ecological efficiency as desirable indicators, and environmental pollutant emissions covering wastewater discharge, exhaust emission, and particulate emission as undesirable indicators (see Table 1), Max-DEA 8.0 software and the SBM-DDF-GML index are employed to measure the HQD in 102 of China's RBCs from 2003 to 2019. The GML index is a change rate value, which needs a regression treatment [71]. Suppose that all HQDs in 2003 are 1, then the HQD in 2004 would be the HQD in 2003 multiplied by the GML index: $HQD_{2004} = HQD_{2003} \times GML_{2003\text{–}2004}$. The HQD of other years can be calculated similarly. The spatial and temporal patterns of HQD in China's RBCs are illustrated in Figure 4, showing a general upward trend from 2004 to 2019. From the perspective of temporal distribution, there are 23 RBCs with an HQD great than 1 in 2004, and by 2009, the number has increased to 44. In addition, the spatial distribution of the HQD in RBCs is unbalanced.



(**a**) (**b**)

Figure 4. (**a**) Spatial pattern of the HQD of China's RBCs in 2004; (**b**) Spatial pattern of the HQD of China's RBCs in 2019. Note: The spatial distribution maps present the temporal and spatial variation characteristics of the HQD in China's RBCs. Owing to space limitations, only the results of HQD calculation for 2004 (**a**) and 2019 (**b**) are presented.

4.2. Descriptive Statistics

The descriptive statistics of the main variables are shown in Table 2. Panel A reports the descriptive statistics for the full sample. Panel B reports comparisons between the treatment group and the control group. As can be seen, almost variables are significantly different across the treatment group and the control group, which confirms the discrepancy between EID RBCs and non-EID RBCs.

4.3. Variable Multicollinearity Test

The results of the Pearson and Spearman correlation coefficient matrix are presented in Table 3. As we can see, the correlation coefficients among the variables are all less than 0.5, which indicates that there is no strong correlation between the variables in this study. Then we perform the variance inflation factor (VIF) test (see Table 4), which shows that the VIF value varied from 1.16 to 2.14 and far less than the cut-off of 10. Therefore, the variables pass the multicollinearity test.

Table 2. Sample descriptive statistics.

Panel A Summary Statistics for the Full Sample								
Variable	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**	**P25**	**Median**	**P75**
HQD	1734	0.848	0.327	0.312	2.271	0.616	0.825	1.000
EID	1734	0.234	0.423	0.000	1.000	0.000	0.000	0.000
Wastewater	1734	8.090	0.955	5.537	9.873	7.493	8.183	8.814
SO_2	1734	10.468	1.116	7.759	12.525	9.673	10.682	11.346
$PM_{2.5}$	1734	3.757	0.328	3.045	4.470	3.511	3.749	4.011
CSI	1734	49.887	11.470	23.782	78.650	41.950	50.250	57.840
ISU	1734	77.935	33.555	19.623	195.381	54.468	72.083	93.531
Econ	1734	9.223	0.548	8.040	10.764	8.871	9.173	9.558
Green	1734	9.223	0.548	8.040	10.764	8.871	9.173	9.558
Infra	1734	36.332	8.492	6.130	49.759	33.190	38.735	41.678
Infor	1734	13.983	7.226	3.280	39.820	9.270	12.250	16.880
Fina	1734	11.228	9.866	0.447	51.146	3.612	8.170	16.197
Resou	1734	189.243	65.737	79.265	403.318	141.490	176.400	223.975

Panel B Comparison between the Treatment Group and the Control Group								
Variables	**Treatment Group (N = 595)**			**Control Group (N = 1139)**			**Differences: Treatment-Control**	
	Mean	**Median**	**Std. Dev.**	**Mean**	**Median**	**Std. Dev.**	**Mean (t-test)**	**Median (z-test)**
HQD	0.908	0.887	0.321	0.817	0.777	0.326	0.092 ***	32.671 ***
EID	0.681	1.000	0.467	0	0	0	0.681 ***	1011.547 ***
Wastewater	8.410	8.499	0.890	7.922	8.014	0.945	0.487 ***	67.980 ***
SO_2	10.993	11.243	1.040	10.194	10.325	1.054	0.799 ***	161.197 ***
$PM_{2.5}$	3.842	3.856	0.339	3.713	3.704	0.314	0.129 ***	29.294 ***
CSI	55.315	55.040	9.223	47.051	46.560	11.511	8.264 ***	188.862 ***
ISU	67.657	63.837	26.330	83.304	76.662	35.619	−15.647 ***	−66.322 ***
Econ	9.520	9.522	0.501	9.068	9.037	0.506	0.452 ***	244.301 ***
Green	38.784	39.990	6.622	35.050	37.592	9.063	3.734 ***	52.322 ***
Infra	14.387	12.320	7.342	13.772	12.190	7.159	0.615 *	0.151
Infor	13.218	10.222	10.822	10.189	7.006	9.163	3.029 ***	32.671 ***
Fina	176.884	164.603	59.824	195.700	183.192	67.757	−18.816 ***	−23.092 ***
Resou	1.999	2.433	1.350	1.731	1.768	1.323	0.267 ***	52.322 ***

Note: This table shows the descriptive data on the composition of our sample. Panel A reports descriptive statistics for the full sample for the entire period (prefecture-level city data from 2003 to 2019). Panel B reports the values of mean, median, and standard deviation for the treatment group and control group, and the differences in mean and median values. All continuous variables are winsorized at 1% and 99% levels. * and *** indicate significance levels at 10% and 1%, respectively.

Table 3. The correlation coefficient matrix.

Variables	HQD	EID	Econ	Green	Infra	Infor	Fina	Resou
HQD	1	0.051 **	0.067 ***	0.029	−0.119 ***	−0.010	0.089 ***	0.175 ***
EID	0.082 ***	1	0.399 ***	0.361 ***	0.187 ***	0.379 ***	−0.041 *	0.078 ***
Econ	0.058 **	−0.109 ***	−0.447 ***	−0.057 **	0.076 ***	0.110 ***	0.476 ***	−0.326 ***
Green	0.046 *	0.324 ***	0.493 ***	1	0.383 ***	0.629 ***	0.095 ***	−0.024
Infra	−0.022	0.174 ***	0.297 ***	0.360 ***	1	0.476 ***	0.004	−0.155 ***
Infor	0.093 ***	0.347 ***	0.399 ***	0.494 ***	0.386 ***	1	0.315 ***	−0.049 **
Fina	0.122 ***	−0.035	−0.310 ***	0.019	0.001	0.356 ***	1	−0.076 ***
Resou	0.130 ***	0.071 ***	0.191 ***	−0.038	−0.180 ***	−0.096 ***	−0.041 *	1

Note: The lower left corner of the diagonal of the table is the Pearson correlation coefficient matrix. The upper right corner of the diagonal of the table is the Spearman correlation coefficient matrix. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

Table 4. The result of variance inflation factor (VIF) test.

Variable	VIF	1/VIF
Infor	2.140	0.468
Econ	2.100	0.477
Fina	1.630	0.612
Green	1.600	0.626
Infra	1.300	0.772
EID	1.250	0.799
Resou	1.160	0.865
Mean VIF	1.600	

Note: This table presents the variance inflation factor (VIF) and the tolerance (1/VIF) of the independent variables.

4.4. PSM Results

Figure 5a reports the common range of propensity score distribution of the treatment group and the control group after PSM, in which the *x*-axis represents the probability of a city being selected as a treatment city. It shows that the great majority of the observed values are in the common support region, which demonstrates that the data processed by PSM are applicable for the further DID estimation. Figure 5b is the result of the covariates standardized bias test, in which the *x*-axis represents the standardized bias between the treatment group and control group before and after being matched, and the *y*-axis represents the covariates involved in the logit model. As we can see, the standardized bias of covariates narrows significantly after PSM, which is considered to be suitable according to the 20% standard value of Rosenbaum et al. [60]. Furthermore, Figure 5c,d show the kernel density distribution curves before and after PSM, respectively, in which the *x*-axis represents the propensity score value, and the *y*-axis represents the kernel density of the propensity score. It reveals that the difference in propensity score between the treatment group and the control group has declined after PSM.

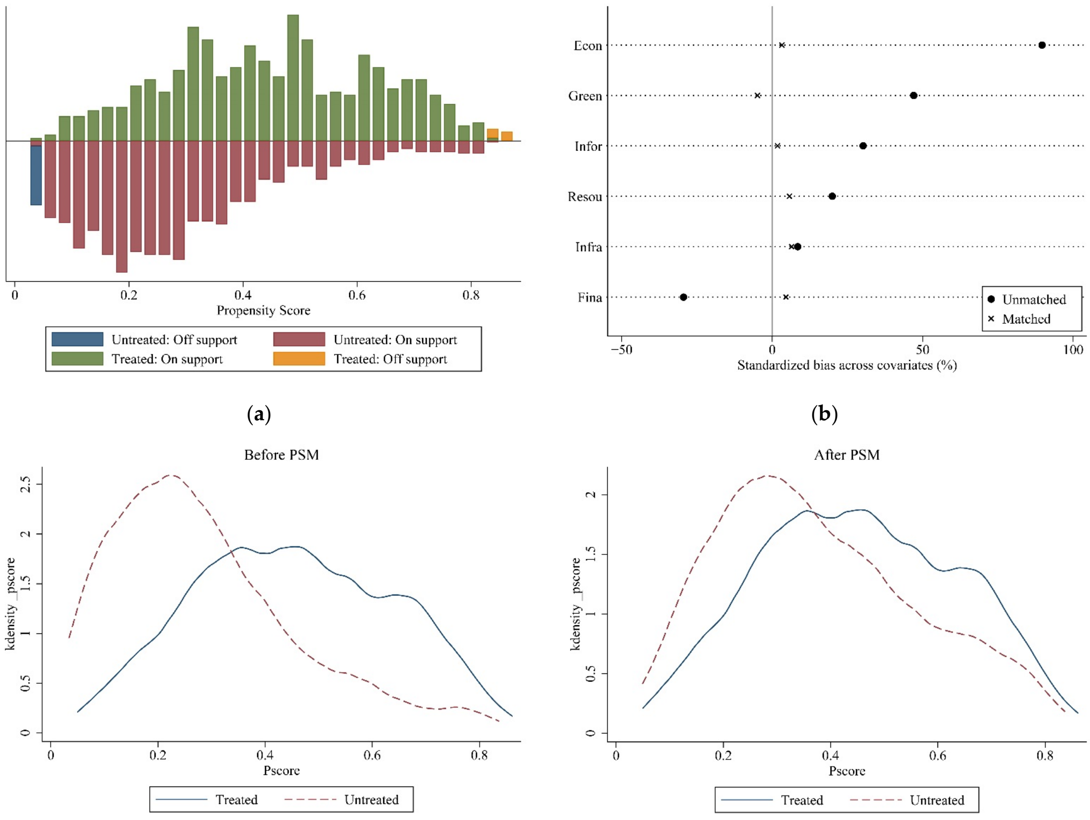
The matching balance test is then conducted to examine the distribution of the covariates between the treatment group and the control group. Table 5 provides the details of covariates before and after the PSM. As we can see, the overall differences of covariates decline significantly to less than 10%, which meets the requirement of no more than 20%. Moreover, the t-value for all covariates is not significant after PSM, demonstrating that there is no systematic difference between the treatment group and the control group after matching except for whether they are subject to the EID. In summary, the sample after PSM is suitable for further DID analysis.

4.5. Parallel Trend Test

The essential premise of the DID method is that the dependent variable requires to satisfy the parallel trend assumption, namely, the HQD of the treatment group and the control group should maintain a consistent trend before the exogenous shock of EID. Therefore, referring to the research of Beck et al. [72], the event study approach is adopted to conduct the parallel trend test, and the specific model is constructed as follows:

$$HQD_{it} = \delta_0 + \delta_{it} \sum_{j=-5}^{j=11} \delta_{t_0+j} EID_{it_0+j} + \delta_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (8)$$

where EID_{t_0+j} is the interaction term of $Treat_{\ i}$ and $Time_t$ dummy variables, indicating whether city i implements EID in year $t_0 + j$. The $Time_t$ dummy variables include time for 5 years before the EID implementation and 11 years after the EID implementation. Subscript t_0 indicates the first implementation point of EID. The coefficient δ denotes the variation in the HQD between the treatment group and control group at the jth year of the EID implementation. In addition, the other variables are consistent with formula (4).



(c) (d)

Figure 5. (**a**) Common support test; (**b**) Covariates standardized bias test; (**c**) Kernel density distribution of propensity score before Propensity Score Matching (PSM); (**d**) Kernel density distribution of propensity score after PSM.

Table 5. Balance test results of covariates before and after propensity score matching (PSM).

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Unmatched	**Mean**		**Bias (%)**	**Reduct Bias (%)**	***t*-Test**
	Matched	**Treated**	**Control**			
Econ	U	9.5201	9.0684	89.7	96.4	17.71 ***
	M	9.5075	9.4912	3.2		0.58
Green	U	38.784	35.050	47.0	89.6	8.89 ***
	M	38.740	39.128	−4.9		1.04
Infra	U	14.387	13.772	8.5	23.8	1.68 *
	M	14.298	13.830	6.5		1.22
Infor	U	13.218	10.189	30.2	94.1	6.13 ***
	M	13.195	13.017	1.8		0.3
Fina	U	176.88	195.70	−29.4	84.4	−5.71 ***
	M	177.87	174.93	4.6		0.86
Resou	U	1.9988	1.7314	20	71.3	3.97 ***
	M	1.9876	1.9108	5.7		0.99

Note: This table presents statistics of post-match differences in propensity score matching. Columns (2) and (3) present the sample averages of city characteristics in the treatment group and control group, respectively. Column (4) presents the bias of the differences between the treatment group and control group before and after being matched. Column (5) presents the absolute value of bias reduction in differences between the treatment group and control group after being matched. Column (6) presents the t-test values of the differences between the treatment group and the control group. * and *** indicate significance levels at 10% and 1%, respectively.

Figure 6 presents the dynamic trend of EID affecting HQD, in which the x-axis represents the time before and after the implementation of EID, the y-axis represents the margin effect of the EID on HQD, and dashed lines indicate the 95% confidence interval. As can be seen, the estimated coefficients of EID approach 0 significantly at a 95% confidence interval from 2004 to 2007, which demonstrates that there are no remarkable differences in HQD between the treatment group and the control group before the implementation of EID. At this point, the parallel trend hypothesis holds. Furthermore, the impact of EID on HQD starts to be significant after the implementation of EID and presents a relatively fluctuating trend over time in general. The possible reason is that the EID system in China is imperfect. For example, the majority of enterprises are still reluctant to disclose environmental information and shoulder environmental protection responsibilities consciously, which makes it difficult to form a long-term mechanism for promoting the HQD [68].

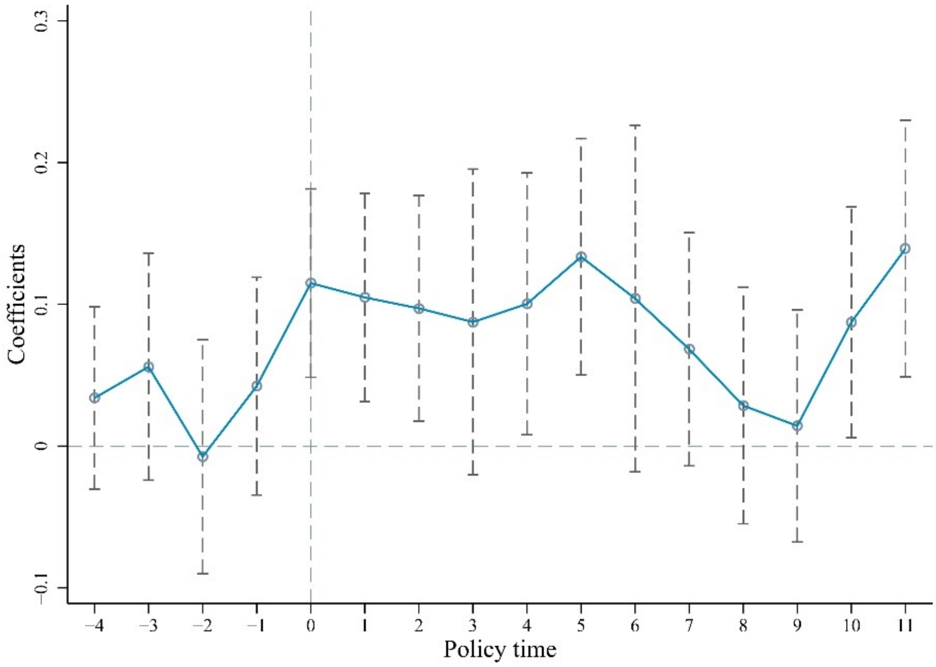


Figure 6. Parallel trend test. Note: This figure shows the dynamic trend of the HQD variation between the treatment group and control group from 5 years before the EID implementation to 11 years after the EID implementation.

4.6. Baseline Regression Results

The baseline regression results are shown in Table 6. Columns (1)–(3) show the regression results of the DID method and columns (4)–(6) present the regression results of the PSM-DID method. Columns (1) and (4) are the preliminary estimation results without the control variables added, showing that the EID implementation has a remarkable positive impact on the HQD of RBCs and passes the 1% significance test. Columns (2) and (5) report the regression results with the control variables, and the coefficients of EID are still positive and statistically significant at the critical levels of 10% and 5%, respectively. Columns (3) and (6) show the regression results with further consideration of two-way fixed effects, which show that the implementation of EID has significantly increased the HQD of RBCs. In particular, the estimated coefficient of column (6) indicates that the implementation of EID improves the HQD level of disclosing RBCs by 5.9% at a significance level of 1%. From this, hypothesis H1 is verified.

Table 6. Regression results of the baseline model.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	HQD	HQD	HQD	HQD	HQD	HQD
EID	0.064 ***	0.034 *	0.071 ***	0.052 ***	0.050 **	0.059 ***
	(3.431)	(1.673)	(3.411)	(2.665)	(2.407)	(3.206)
Econ		0.079 ***	0.233 ***		0.095 ***	0.356 ***
		(3.562)	(4.709)		(3.707)	(7.214)
Green		−0.001	0.014 ***		−0.003 **	0.014 ***
		(−0.534)	(14.040)		(−2.431)	(12.024)
Infra		−0.002	−0.006 ***		−0.001	−0.005 **
		(−1.343)	(−5.159)		(−0.683)	(−2.761)
Infor		−0.000	0.001		−0.002	0.001
		(−0.019)	(0.767)		(−1.343)	(0.481)
Fina		0.001 ***	−0.000		0.001 ***	0.000
		(5.237)	(−0.293)		(7.360)	(1.637)
Resou		0.025 ***	−0.010		0.021 ***	−0.011
		(4.074)	(−0.946)		(3.236)	(−0.922)
Constant	0.833 ***	−0.042	−1.369 **	0.849 ***	−0.157	−2.639 ***
	(93.070)	(−0.208)	(−2.723)	(81.967)	(−0.661)	(−5.415)
City FE	No	No	Yes	No	No	Yes
Year FE	No	No	Yes	No	No	Yes
N	1734	1734	1734	1383	1383	1383
R^2	0.007	0.050	0.380	0.005	0.068	0.381

Note: This table reports the baseline regression results from the estimation of formula (4). Columns (3) and (6) are the regression results that control for city-fixed and year-fixed effects. *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively. Standard errors in parentheses.

The regression results of the control variables are described as follows: (1) The estimated coefficient of economic development level (Econ) is significantly positive at the 1% level, indicating that the higher the level of economic development of a city, the more it can promote HQD. (2) The urban greening level (Green) is significantly positive at the 1% level, indicating that the increase in greening coverage is conducive to the development of the urban economy in a green and high-efficiency way. (3) The infrastructure level (Infra) is significantly negatively related to the HQD. The reason may be that massive, blind, and duplicative infrastructure construction generates excess and ineffective capacity, crowding out other types of investment, which is detrimental to the HQD of RBCs. (4) The effect of the informatization level (Infor) is positive, denoting that the information revolution is helpful to promote the quality and efficiency of urban development. (5) The effect of financial development (Fina) is positive but not significant, which may be attributed to the financial resource misallocation, resulting in the imbalance of economic structure and hindering the optimization and adjustment of the industry [73]. (6) The impact of resource endowment (Resou) on HQD is negative. This is probably because the excessive dependence on natural resources in RBCs squeezes out the positive factors such as technology innovation and talent reserve, and further impedes the HQD.

4.7. Robustness Test

In this section, a series of robustness tests are carried out to further justify the validity of the above empirical results.

4.7.1. Instrumental Variable Approach

To further address the potential endogeneity issue caused by the nonrandom layout of EID, the instrumental variable approach is employed to quantitatively investigate the impact of EID on the HQD after endogeneity elimination. Specifically, we select the air ventilation coefficient (VC) as an instrumental variable for EID by referring to Hering et al. [74]

and Chen et al. [75], and construct a two-stage least squares (2SLS) regression estimation model as follows:

$$EID_{it} = \theta_0 + \theta_1 VC_{it} + \theta_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (9)$$

$$HQD_{it} = \gamma_0 + \gamma_1 EID_{it} + \gamma_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (10)$$

where VC_{it} represents the air ventilation coefficient, which is obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). Other variables are set the same as in the baseline model.

The outcomes of the instrumental variable test are listed in columns (1) and (2) of Table 7. For the validity of the instrumental variable, the value of the Kleibergen–Paap rank Wald F statistic is beyond 10, indicating the rejection of the hypothesis of the weak instrumental variable. Meanwhile, the P-value of the Kleibergen–Paap rank LM statistic is significant at the 1% level, denoting the rejection of the hypothesis of under-identification. Thus, the above tests illustrate that the selection of our instrumental variable is appropriate. In addition, column (1) of Table 7 reports the first-stage regression result, which denotes that the VC is positively correlated with EID at the 1% significant level. The second stage regression result is presented in column (2) of Table 7. Compared with the baseline regression results in Table 6, the coefficient of EID increases remarkably after the instrumental variable is involved, indicating that the implementation of EID can indeed improve the HQD of RBCs and the potential endogeneity issues tend to understate the contribution of EID on the HQD.

Table 7. Results of robustness tests.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	First Stage	**2SLS**	**Eliminate Disturbing Policies**	**Two Lag Periods**	**Adjust Sample Period**	**Kernel Matching**
EID		0.865 ***	0.054 **	0.059	0.087 ***	0.062 ***
		(2.846)	(2.904)	(1.702)	(10.203)	(3.144)
VC	0.421 ***					
	(3.500)					
Emissions Trading Program			Control			
Constant	0.440	−4.722 ***	−1.515 ***	−1.254 **	−3.442 ***	−1.407 **
	(0.341)	(−3.092)	(−4.184)	(−2.751)	(−5.114)	(−2.850)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Endogeneity test	14.078 ***					
Kleibergen–Paap rank LM	12.16 ***					
Kleibergen–Paap rank Wald F	13.03					
N	1734	1734	1397	1734	793	1691
R^2	0.376	0.425	0.361	0.363	0.349	0.372

Note: This table examines the robustness of the effect of EID on HQD. All regressions control for city-fixed and year-fixed effects. ** and *** indicate 5% and 1% significance levels, respectively. Standard errors in parentheses.

4.7.2. Eliminate Disturbing Policies

In the estimation process of the impact of EID on the HQD, it is inevitable that there will be other environmental policy influencing factors, so that the estimation effect would be biased. In 2007, China launched the pilot project of emissions trading in 11 provinces, which is a market-based environmental regulatory policy that may affect the HQD. Therefore, the interaction term of this policy and time is involved as a control variable in our baseline regression model, by referring to Tao et al. [76]. Column (3) of Table 7 shows the estimated coefficient of EID after eliminating the disturbing policies, which is in line with the baseline regression results, proving the robustness of the baseline results in this study.

4.7.3. Counterfactual Test

The counterfactual tests are conducted to exclude other random factors. First, referring to Tang et al. [77], the implementation point of EID is delayed for two years, and the coefficient is re-estimated. Column (4) of Table 7 shows that the estimated coefficient of the fictitious EID intervention is not significant, verifying that the promotion of the HQD is indeed due to the implementation of EID rather than other policies. Second, a placebo test is performed by randomly selecting the pseudo treatment group 1000 times. Thus, 1000 estimated coefficients are obtained and plotted on the kernel density distribution map, as shown in Figure 7, where the *x*-axis represents the t-statistic value of the estimated interaction term coefficients and the *y*-axis represents the density of the t-statistic value. We can find that only a few of the t-statistic values exceed that of the baseline model in Table 6, which proves that the promotion effect of EID on the HQD is not seriously affected by the non-observed factors. In summary, the baseline regression results in this study are robust.

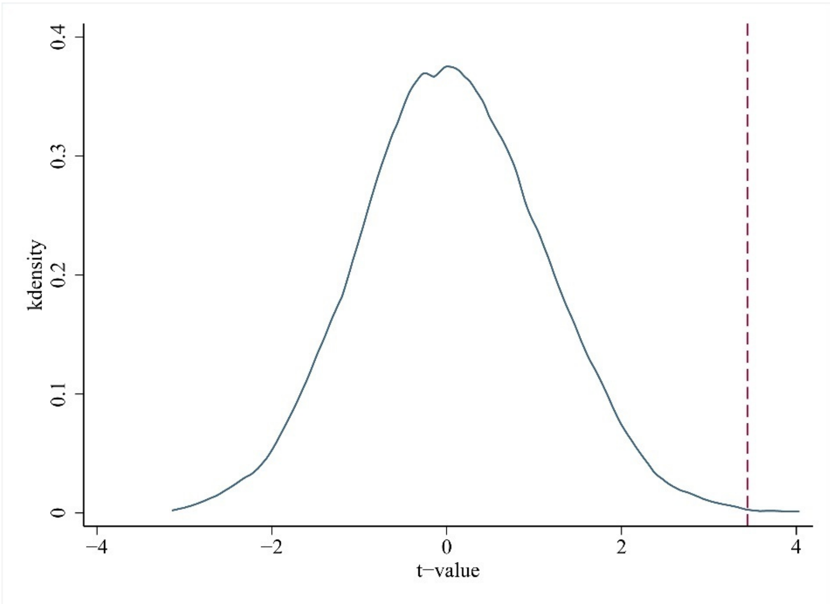


Figure 7. Distributions of t value of estimated coefficients for the placebo test. Note: This figure shows the distribution of the t-statistic values for the estimated coefficients of the variable HQD over the process of repeating the random selection of the treatment group 1000 times.

4.7.4. Change the Sample Time Window

In this study, the baseline regression is based on the relatively long period from 2003 to 2019. To eliminate the interference of other environmental policies on the effect of EID, we adjust the sample period to 2003–2012 and perform the parameter estimation again. The regression result is presented in column (5) of Table 7, which shows that the estimated coefficient of EID is significantly positive after the sample period is adjusted. Therefore, the robustness of the estimation results of the baseline regression model is verified.

4.7.5. Alternative Matching Method

To verify whether the method of PSM affects the accuracy of the benchmark results, we adopt the kernel matching method to rematch the research samples and perform the DID regression. According to column (6) of Table 7, the coefficient of EID is still significantly positive, which indicates that the promotion effect of EID on the HQD is estimated to be robust.

5. Further Analysis

5.1. Heterogeneity Analysis

In this section, we explore three factors that may contribute to the heterogeneous impact of EID on the HQD, including urban geographic location, urban resource dependency degree, and urban development stage. The spatial pattern of China's RBCs under the three classifications drawn by ArcGIS 10.8 is shown in Figure 8.

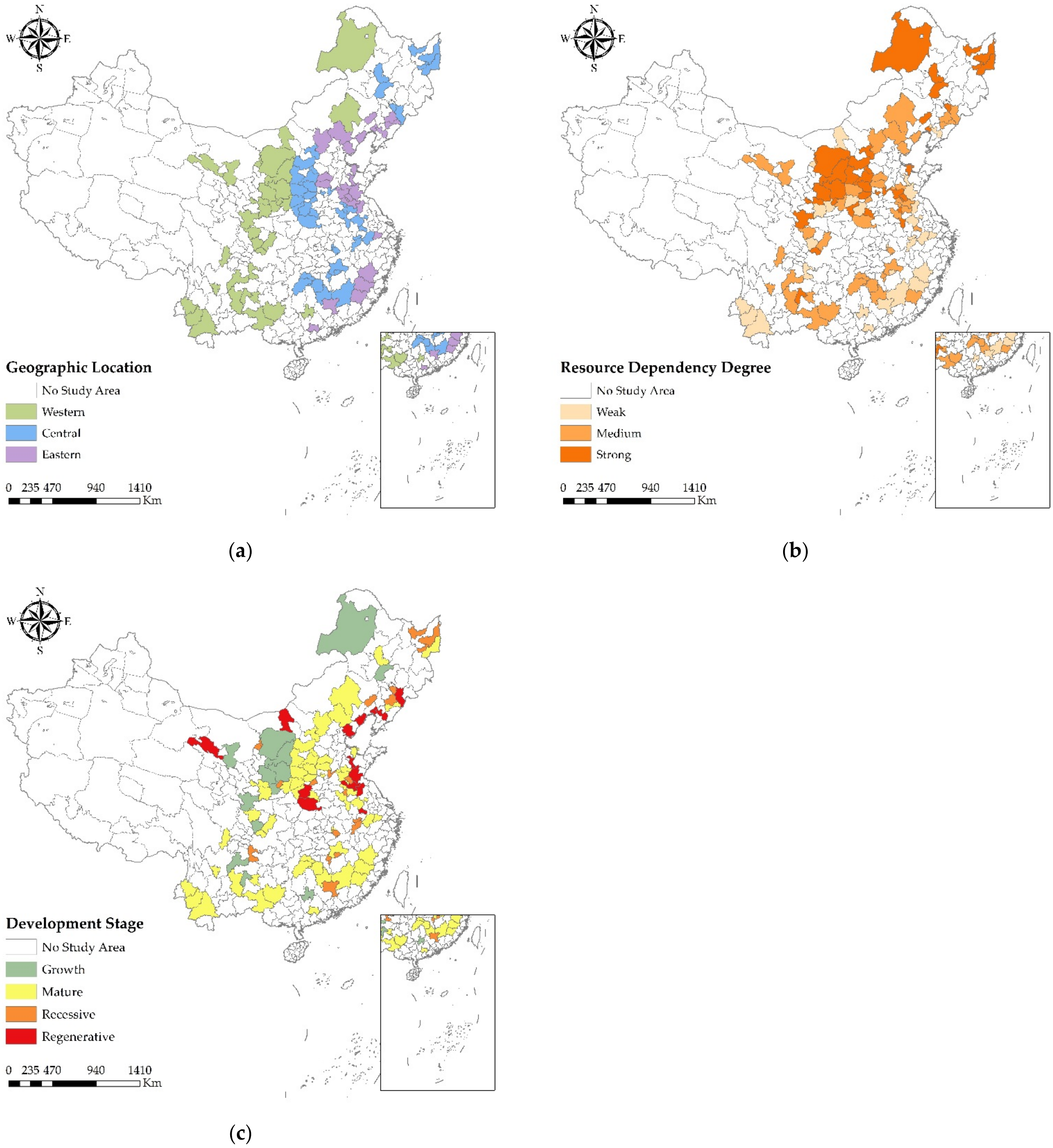


Figure 8. (**a**) Spatial pattern of urban geographic location in China's RBCs; (**b**) Spatial pattern of urban resource dependency degree in China's RBCs; (**c**) Spatial pattern of urban development stage in China's RBCs. Note: This figure presents the spatial layout of different types of RBCs in China.

5.1.1. Heterogeneity of Urban Geographic Location

There are spatially unbalanced characteristics among different regions in terms of urban economic development level, industrial structure, and so on. To explore the heterogeneous effect of EID on the HQD caused by the geographic location, the overall research sample is divided into western, central, and eastern regions based on urban geographic location, as shown in Figure 8a. Regressions are then conducted separately for each region (see Table 8). Columns (1)–(3) show that the estimated coefficients of EID are positive in all regions. However, only the coefficient of the central RBCs is significant, indicating that the effect of EID on the HQD is different across geographic locations. The possible reasons are as follows. At present, the disparity in economic development across regions in China still exists objectively. Benefiting from the reform and opening-up policies and its location, the eastern RBCs have a first-mover advantage in finance, talents, and technology, which leads to a relatively weak shock of external policies on its HQD. For the western RBCs, on the one hand, the government may strenuously pursue economic overtaking due to the pressure of political performance rather than to emphasize the implementation of environmental governance. On the other hand, although the western region is abundant in natural resources, its excessive dependency on resource extraction may also plunge it into the resource curse [78], thus impeding its transformation and HQD.

Table 8. Regression results of the heterogeneity analysis.

Variable	Geographic Location			Resource Dependency Degree			Development Stage			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Western	Central	Eastern	Weak	Medium	Strong	Growth	Mature	Recessive	Regenerative
EID	0.047	0.111 ***	0.059	0.023	0.009	0.131 **	0.126 *	0.047 **	0.066 **	0.105 **
	(0.870)	(4.059)	(1.512)	(0.722)	(0.298)	(2.696)	(2.002)	(2.679)	(2.770)	(2.516)
Constant	−3.166 ***	−2.161 ***	−4.492 ***	−1.711 ***	−2.470 ***	−2.896 ***	−3.596	−2.374 ***	−1.871 ***	−3.935 ***
	(−3.515)	(−2.925)	(−8.031)	(−3.973)	(−4.090)	(−3.336)	(−1.617)	(−3.355)	(−3.573)	(−5.735)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	401	595	387	390	488	505	149	716	313	205
R^2	0.319	0.467	0.530	0.575	0.416	0.346	0.371	0.457	0.449	0.630

Note: This table reports the heterogeneous effects of EID on HQD. Columns (1)–(3) show the heterogeneity of urban geographic locations. Columns (4)–(6) are the regression results of the heterogeneity test in resource dependency degree. Columns (7)–(10) present the regression results of the heterogeneity test in the development stage of RBCs. All regressions control for city-fixed and year-fixed effects. *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively. Standard errors in parentheses.

5.1.2. Heterogeneity of Urban Resource Dependency Degree

Resource dependency is the essential characteristic of RBCs, and is also a significant basis for the government to formulate transformation policies for RBCs. As to determine whether the effect of EID on the HQD is heterogeneous among cities due to resource dependence, China's RBCs are categorized into strong-dependent RBCs, medium-dependent RBCs, and weak-dependent RBCs, according to the division criteria of Yan et al. [79] (see Figure 8b). Regressions are independently performed for the three sub-samples, and the estimated results are shown in columns (4)–(6) of Table 8. The regression coefficient of EID is significantly positive in strong-dependent RBCs, while the coefficients of weak-dependent and medium-dependent RBCs are not significant, demonstrating the heterogeneous influence of different resource dependency degrees on the HQD enhancement. This is probably because weak-dependent and medium-dependent RBCs are less dependent on resource-based industries for development than strong-dependent RBCs. Therefore, the HQD of the first two types of RBCs is less likely to fluctuate significantly with the implementation of policies related to the resource and environment.

5.1.3. Heterogeneity of Urban Development Stage

RBCs at different stages of development vary in their development priorities and face distinct challenges. Based on *The Plan*, we classify the research sample into four groups of growth, mature, recessive, and regenerative RBCs according to the development stage of the RBCs (see Figure 8c). Columns (7)–(10) of Table 8 present the regression results, indicating that the impacts of EID on the HQD are remarkably positive in the cities of all four stages. Specifically, the growth and regenerative RBCs have a greater response to EID while the mature and recessive RBCs do not. This might be attributed to the differences in resource security capacity and sustainable development capacity across the different stages of RBCs. Although the mature RBCs are in a stable phase of resource exploitation, they are also facing the difficulties of a single industrial structure and insufficient endogenous power for urban transformation. Meanwhile, regressive RBCs are confronted with the prominent issues of resource exhaustion and ecological environment destruction, which result in a lower gathering capacity for capital and talents and difficulties in forming complete replacement industries in a short period.

5.2. Mechanism Analysis

5.2.1. Environmental Pollution Reduction Effect

The regression results are reported in Table 9, which show that the estimated coefficients of EID in columns (2), (5), and (8) are negative at the significance level of 5%, 10%, and 5%, respectively, indicating that EID has significantly reduced the discharge of wastewater, as well as the emission levels of SO_2 and $PM_{2.5}$. Columns (3), (6), and (9) reflect the regression results of EID on the HQD after controlling for environmental pollutants. We can see that the estimated coefficients of EID are lower in columns (3) and (9) and are no longer significant in column (6) compared to the baseline regression results in Table 6, indicating that pollution reduction is an essential mechanism for EID to affect the HQD. In addition, the above regression results pass the Sobel test at least at the 5% significance level, illustrating the robustness of the empirical results. It can be concluded that the implementation of EID could drive polluting industrial enterprises to phase out backward production capacity, improve resource allocation efficiency, and pay attention to energy conservation and environmental pollution reduction, so as to promote the HQD of RBCs. In other words, the implementation of EID can contribute to the improvement of HQD by reducing environmental pollutants.

Table 9. Regression results of environmental pollution reduction effect.

Variable	(1) HQD	(2) Wastewater	(3) HQD	(4) HQD	(5) SO_2	(6) HQD	(7) HQD	(8) $PM_{2.5}$	(9) HQD
EID		−0.172 **	0.025 *		−0.158 *	0.028		−0.033 **	0.050 **
		(−2.706)	(1.941)		(−2.083)	(1.091)		(−2.447)	(2.797)
Wastewater	−0.199 ***		−0.198 ***						
	(−14.218)		(−13.733)						
SO_2				−0.201 ***		−0.200 ***			
				(−11.964)		(−11.445)			
$PM_{2.5}$							−0.280 **		−0.264 **
							(−2.378)		(−2.262)
Constant	−1.101 **	7.381 ***	−1.178 **	−0.888 **	8.348 ***	−0.973 **	−1.315	4.249 ***	−1.517 *
	(−2.520)	(5.176)	(−2.592)	(−2.763)	(10.477)	(−2.680)	(−1.643)	(14.318)	(−1.925)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1383	1383	1383	1383	1383	1383	1383	1383	1383
R^2	0.489	0.308	0.489	0.497	0.679	0.498	0.385	0.687	0.387
Sobel		3.835 ***			3.730 **			2.718 ***	

Note: This table reports the regression results for the mediating effect of environmental pollution reduction including wastewater, SO_2, and $PM_{2.5}$. All regressions control for city-fixed and year-fixed effects. *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively. Standard errors in parentheses.

5.2.2. Industrial Structure Upgrading Effect

The corresponding regression results are presented in Table 10. According to the mediation effect test procedure, the estimated coefficient of EID in column (2) is significantly negative at the 1% significant level after controlling the city and year fixed effect, and the estimated coefficient of EID in column (3) is positive at a 5% significant level, which denote that the implementation of EID promotes the HQD by contracting the added value of the secondary industry. In column (5), the estimated coefficient of EID on ISU is significantly positive at the 1% confidence level, which indicates that EID has effectively increased ISU. The estimated coefficient of EID on the HQD in column (6) is still significant at a 1% critical level, demonstrating that ISU is an essential path for EID to influence the HQD improvement. Furthermore, the mediating effect of CSI and ISU both pass the Sobel test significantly, which demonstrates that the above results are valid. Consequently, EID may stimulate the invention and creation of new technologies, new products, and new processes, which will then accelerate the transformation and upgrading of industrial structures, thus promoting the improvement of the HQD. That is, the implementation of EID can stimulate the HQD through industrial structure upgrading.

Table 10. Regression results of industrial structure upgrading effect.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	HQD	**CSI**	**HQD**	**HQD**	**ISU**	**HQD**
EID		−1.926 ***	0.051 **		5.708 ***	0.051 ***
		(−4.393)	(2.804)		(3.288)	(3.063)
SCI	−0.005 **		−0.004 **			
	(−2.665)		(−2.461)			
ISU				0.001 ***		0.001 ***
				(4.786)		(4.598)
Constant	−2.815 ***	−67.810 ***	−2.928 ***	−2.832 ***	222.972 ***	−2.953 ***
	(−5.151)	(−5.251)	(−5.524)	(−5.388)	(6.838)	(−5.719)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	1383	1383	1383	1383	1383	1383
R^2	0.383	0.586	0.385	0.386	0.591	0.388
Sobel		2.643 ***			2.471 **	

Note: This table reports the regression results for the mediating effect of industrial structure upgrading. All regressions control for city-fixed and year-fixed effects. ** and *** indicate 5% and 1% significance levels, respectively. Standard errors in parentheses.

In summary, the implementation of EID can enhance the HQD and improvement of RBCs by reducing environmental pollution and boosting industrial structure upgrading. Thus, hypothesis 2 is supported.

6. Conclusion and Policy Implications

This study treats the EID implementation in 2008 as a natural exogenous shock and constructs a quasi-natural experiment using panel data of 102 RBCs in China from 2003 to 2019. We first measure the HQD levels for each RBC by adopting the SBM-DDF-GML index of an improved DEA model, which takes capital, labor, and energy as input factors, economic and ecological benefits as desirable outputs, and environmental pollutant emissions as undesirable outputs. On this basis, the PSM-DID method and the mediating effect model are employed to systematically investigate the effect and the impact mechanisms of EID on HQD. The main findings of this study are as follows: (1) In general, there is an upward trend of the HQD of RBCs in China from 2004 to 2019. Meanwhile, the implementation of EID can significantly promote the HQD of RBCs, and the conclusions remain unchanged after performing a series of robustness tests, which confirm that the baseline results are stable. (2) EID promotes HQD more significantly for central RBCs and resource strong-dependent RBCs than cities in other locations and with other degrees of resource dependency. In terms of the stage of urban development, EID has a greater contribution to HQD in growth and regenerative RBCs. (3) Environmental pollution reduction and industrial structure upgrading are critical transmission mechanisms by which EID facilitates HQD.

Based on the above conclusions, this study has the following practical insights for RBCs' HQD in China: (1) The government should further extend the scope and intensity of EID implementation. At the same time, the characteristics across different types of RBCs, including geographic location, resource dependence, and development stages, should be considered in the formulation of HQD strategies. (2) The government should speed up the modernization process of the national environmental governance system and accelerate the establishment of a multi-governance platform for EID covering the government, enterprises, and the public, so as to better serve the transformation and HQD of RBCs. (3) The government needs to focus on environmental pollution reduction and pay more attention to the crucial role of industrial structure adjustment on the HQD of RBCs. Meanwhile, the government should motivate enterprises to reduce environmental pollution and optimize resource allocation efficiency and guide the public to actively participate in environmental governance.

This study has certainly complemented the academic gap in the relationship between EID and HQD, but there are still some limitations that warrant future research. First, we regard the release of the PITI index as a quasi-natural experiment, focus on the policy shock of EID on HQD, and reveal the "black box" of EID affecting HQD. However, whether the influence of EID on HQD varies with the heterogeneity of the PITI index remains to be investigated. We could construct a threshold model to quantify the effect of EID on HQD under different PITI index values in further research. Second, the scope of this study is set at the macro level of RBCs. However, the policy impact of EID on the HQD of various industries and different types of enterprises is also worthy of discussion in the follow-up research. Third, this study mainly performs quantitative empirical research based on China's RBCs and lacks a multi-angle demonstration of different methods such as comparative study and qualitative case studies, which are all worthy topics for continued research in the future. To be specific, comparative studies with western EID theories and practice will help China to enhance its environmental governance and HQD by combining its own urban characteristics and advanced experience in the West. Furthermore, the survey-based case studies would be conducive to deeply revealing the intrinsic mechanisms of EID affecting HQD.

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Impact of Regional Environmental Regulations on Taiwanese Investment in Mainland China

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Abstract: Based on the perspective of regional differences and decentralization, this article investigated the impact of environmental regulations on Taiwanese investment in mainland China from theoretical and empirical perspectives, and analyzed whether local governments are competing to lower environmental standards to attract Taiwanese investment so as to maintain their comparative advantages. This paper constructed a theoretical model through a two-stage game model. With the panel data of each province in Mainland China from 2006 to 2016, the theoretical propositions were empirically tested through the system GMM estimation method. The results show that the environmental regulation policies adopted by the local governments in the mainland have a significant inhibitory effect on the investment volume of Taiwan-funded enterprises, and the interaction between environmental regulations and local tax burden levels also has a negative effect on Taiwanese investment. Local governments have the motive to reduce environmental regulations to attract investment.

Keywords: environmental regulation; Taiwanese investment in mainland China; system GMM

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1. Introduction

Since Taiwanese-invested enterprises invested in the mainland of China in the late 1980s, the vast market potential, cheap labor costs, and leap-forward development of the infrastructure in the mainland have been favored by Taiwanese-invested enterprises. Taiwanese-invested enterprises have gradually become important promoters for the mainland of China to undertake international industrial transfers. At the end of 2019, the mainland had approved a total of 112,442 Taiwanese-invested projects. At present, nearly 70–80% of Taiwan's listed (counter) companies and tens of thousands of Taiwanese small and medium-sized enterprises and freelancers operate in the mainland. As the mainland's economy enters a new normal, the demographic dividend is gradually disappearing, and the environmental carrying capacity continues to weaken. The mainland's inspection standards for Taiwanese-invested enterprises have become increasingly strict, which undoubtedly puts forward higher requirements for Taiwanese-invested enterprises that are mainly concentrated in manufacturing industries. As a result, Taiwanese-funded enterprises need to reconstruct investment strategies, change business strategy models, and adjust industrial layout. Thus, since the reform and opening up, whether the goal of economic catch-up will prompt local governments to lower environmental standards so as to attract Taiwanese enterprises is an issue that needs to be studied in the current development of a green economy.

According to the *2020 Research Report on China's Top 500 in Foreign Trade*, among the top 100 Chinese mainland export companies in 2019, 32 were Taiwanese-invested enterprises, contributing to more than 40% of the total exports. The development and upgrading of Taiwanese-invested enterprises in the mainland is of great significance to the economic development and industrial structure optimization of the mainland. Taiwanese investment in mainland China is mostly concentrated in manufacturing (more than 50%). Although the proportion of Taiwanese investment in manufacturing has declined in recent years, it was still as high as 73.5% in 2016. Moreover, in the manufacturing industry, high-energy-consuming industries such as electronic component manufacturing, chemical material manufacturing, paper product manufacturing, and nonmetallic mineral product manufacturing account for more than 70%, please refer to Appendix A (Nie Pingxiang, 2017) [1]. Different from the foreign investments, which mainly focus on setting up offices or R&D centers in the mainland, Taiwanese investment is dominated by heavily polluting foundry enterprises, which need lots of land to build factories. Taiwanese businessmen are therefore more affected by the environmental regulations of mainland China than foreign businessmen. Taiwanese-invested enterprises are increasingly affected by the mainland's differential environmental regulations. Taking the Taiwanese Investment Zone in Kunshan as an example, in an environment remediation action carried out by the Kunshan government in September 2007, nearly two hundred Taiwanese-invested companies were shut down due to serious pollution emissions. Following up Kunshan, more than a dozen Taiwanese-invested enterprises in Zhuhai were required to limit production and emissions for three days due to air pollution restrictions. In recent years, Taiwanese businesses have faced multiple challenges in the mainland, including rising operating costs and stringent new environmental regulations, according to the *2017 Report on the Investment Environment and Risk Survey in Mainland China* published by the Taiwan Electrical and Electronic Industry Trade Union at the end of September 2017.

In the past 40 years, on the one hand, Taiwan's investment in the mainland has had obvious regional differences; on the other hand, due to the differences in natural conditions and regional economic development between provinces and regions of provinces in mainland China, the level of economic development and environmental regulations have also shown a significant difference, please refer to Appendix B. Is the change in the distribution of Taiwanese-invested enterprises on the mainland related to regional differences in environmental regulations? Are regional differences in environmental laws and regulations one of the important driving factors for Taiwan's investment to move westward? These two issues are the focus of this article.

The literature review of this article covers two aspects. The first is about the impact of environmental regulations on the choice of investment location. The impact of environmental regulations on the location of Foreign direct investment is a hot issue in the international and environmental economics circles. Long and Siebert [2] incorporated environmental variables into the neoclassical general equilibrium model and found that environmental regulations affect the investment layout of enterprises through production cost channels. Levinson [3] pointed out that environmental regulations will drive companies to move to countries or regions with loose environmental regulations. John and Catherine [4] used sample data to analyze the impact of environmental regulations on FDI in various US states. Xing and Kolstad [5] found that loose environmental regulations are an important factor in attracting the transfer of pollution-intensive industries in the United States. The second is about research on the impact of environmental regulations on enterprises. It is generally believed that environmental regulations can affect the production and operating costs of enterprises by requiring enterprises to purchase pollution control equipment and technologies, restricting the location of and the method for pollution discharge, and restricting the combination of input and output elements in the production process (Xing and Kolstad, 2002) [5]. Moreover, as the impact of environmental regulations on standardizing corporate behaviors gradually increases, corporate performance will be further affected by environmental regulations. Based on the static analysis framework of the perfect competitive market of neoclassical economics, some scholars have studied and analyzed that strict environmental regulations will inevitably affect the profitability of enterprises and raise the barriers to entry of foreign capital. In order to avoid stringent environmental regulatory standards, companies will choose regions with looser environmental regulations to invest in so that they can maintain their market competitiveness and maximize benefits. Some scholars have also focused their research on the impact of environmental regulations on the total factor productivity of enterprises. Appropriate environmental regulations are not only conducive to improving the total factor productivity of enterprises, but this positive impact can effectively alleviate the negative effects of environmental regulations on the survival time of enterprises. Popp and Newell [6] pointed out that environmentally friendly technological advancements brought about by environmental regulations cannot offset all required losses of productivity.

This article attempted to use Taiwanese-funded enterprises as a research sample to explore the impact of environmental regulation on investment. Overall, the industries invested by Taiwan-funded enterprises in the mainland are dominated by manufacturing, and those industries with high pollution and high emissions account for a relatively large proportion. From a certain perspective, while providing Taiwan-funded enterprises with abundant production factors, the mainland has also undertaken a large number of high-pollution and high-emission industries in Taiwan. As the mainland enters a new stage in economy, on the one hand, how the mainland has shifted from the extensive growth model at the expense of the environment to the intensive green growth model with low energy consumption is an important path for the economy to shift to high-quality development, and local governments need to adopt corresponding measures, such as environmental regulation and other policies; on the other hand, due to the institutional characteristics of "decentralized governance" in the mainland, the central government and local governments often have certain differences in the implementation of environmental policies. The central government prefers to support low-carbon emission industries to implement sustainable development strategies, while local governments will compete by lowering regional environmental regulatory standards so as to attract more foreign investment, resulting in disrupted market mechanisms and causing environmental degradation (Ollivier, 2016; Fischer and Springborn, 2011) [7,8]. This provides a great possibility for local governments to independently adjust the implementation of environmental regulations.

Based on the above analysis, this article analyzed the "bottom-to-bottom effect" of environmental regulations and local governments introducing Taiwan-funded enterprise investment from both theoretical and empirical aspects. Specifically, a two-stage game model is first used to examine the interaction between provincial environmental regulations and Taiwan-funded enterprises, and to obtain theoretical propositions about provincial environmental regulations and the investment level of Taiwan-funded enterprises. Secondly, environmental regulations are introduced into the gravity model based on panel data composed of 23 provinces in mainland China from 2006 to 2016. Subsequently, detailed research conclusions are drawn by empirically testing the impact of environmental regulations on Taiwanese investment in mainland China and the investment potential of different regions.

2. Theoretical Analysis and Research Hypotheses

Mainland China has a vast territory, and the market environment, institutional quality, and cultural history vary in different regions. The bottom-line effect of environmental regulations on Taiwan-funded enterprises' investment is also difficult to show due to the homogeneous distribution among local governments. In local governments, environmental supervision is the most effective policy to promote the trade-off between investment and environmental protection. While some local governments are urging enterprises to accelerate the improvement of pollution control capacity and technological innovation through environmental regulations, and strengthen the improvement of environmental quality within their jurisdictions, in order to increase the intensity of investment promotion, there are also local governments competing by viciously lowering environmental regulatory standards. Improving performance evaluation during the tenure has led to the phenomenon whereby the implementation of environmental policies by the central and local governments often run counter to each other, which ultimately leads to differences in the effect of policy-driven changes in enterprises. The relocation of the Xiamen PX project to Gulei, Zhangzhou in 2007 is a typical case. This project was invested in by Taiwanese-funded enterprise Tenglong Aromatics (Xiamen, China) Co., Ltd. The original plan was to build a chemical plant with an annual output of 800,000 tons of paraxylene (PX) in Haicang District. Due to the potential for high pollution of xylene (PX), the project was jointly opposed by a hundred members of the CPPCC (Chinese People's Political Consultative Conference) and collectively resisted by citizens. Finally, the project was relocated to Gulei, Zhangzhou.

This section uses a two-stage game model to describe the game behavior of local governments and Taiwan-funded enterprises with the goal of maximizing their respective effects, thereby revealing the interactive effects of environmental regulations, regionally favorable Taiwan policies, and Taiwan-funded enterprises' output decisions. The analysis of government environmental decision-making in environmental economics literature can be traced back to Oates and Schwab (1988) and Cumberland (1979) [9,10]. The model proposed in this article draws on the imperfectly competitive market framework adopted by Barrett (1994) and other documents. The difference is that our model focuses on examining whether the local government has lowered the local environmental regulatory standards in order to attract Taiwan-funded enterprises to maximize the economic benefits of the region under the regional differences in the preferential policy for Taiwanese investment.

Given that mainland China is composed of multiple provinces (municipalities), then $i = 1, \ldots, n$. Each province (municipality) has one domestic-funded enterprise and one Taiwan-funded enterprise. Enterprises compete based on output within the region. Assuming that both domestic and Taiwan-funded enterprises produce the same product, the industry has a linear demand function $q = a - p$, where a is the market size, p is the price, and q is the output. Both the production cost and pollution control cost of an enterprise are proportional to the output. Under the above assumptions, the corporate profit functions of the i-th province (municipalities directly under the Central Government), respectively, represent:

$$\pi_i{}^d(q_i{}^d) = q_i{}^d[a_i - b(q_i{}^d + q_i{}^t)] - c_i{}^d q_i{}^d - (\theta_i{}^d - e_i)q_i{}^d,\ i = 1\ ,2,3\ldots \quad (1)$$

$$\pi_i{}^t{}_{(q_i{}^t)=} q_i{}^t[a_i - b(q_i{}^d + q_i{}^t) - c_i{}^t q_i{}^t - (\theta_i{}^t - f(w)\cdot e_i)q_i{}^t,\ i = 1\ ,2,3\ldots \quad (2)$$

Among them, π and c represent profit and production cost per unit output, respectively. All variables with superscript d correspond to domestic-funded enterprises and all variables with superscript t are related to Taiwan-funded enterprises. $\theta \succ 0$ is emissions per unit of production, while a smaller θ means that the company has cleaner technology. w is the adjustment function of Huitai policy. Regarding the adjustment effect of the "Huitai Policy", this article uses w in the theoretical model to represent the differences in the implementation of environmental regulations in various regions. In the empirical part, the two lagging periods of taxation variables are selected to measure the differences in the institutional environment. $e \geq 0$ is the emission standard set by the local government and $f(w)\cdot e \geq 0$ is the emission standard set by the local government for Taiwan-funded enterprises. Smaller e and $f(w)\cdot e$ mean stricter environmental standards. $\theta - e$ and $\theta - f(w)\cdot e$ represent the part of each unit of output that domestic-funded enterprises and Taiwan-funded enterprises need to govern themselves. In order to make the output non-negative within the scope of any standard environmental regulation, it is necessary to assume that the market size a is sufficiently large, that is,

$$a_{i\ \geq} 2max\left\{c_i{}^d + \theta_i{}^d, c_i{}^t + \theta_i{}^t\right\}. \quad (3)$$

In this model, environmental regulation, as a policy variable, is controlled by government policies, and is an endogenous variable. The mainland's policies on environmental regulation do not distinguish domestic and Taiwan-funded enterprises, but environmental regulation policies have regional differences in the specific implementation process. That is, in order to attract more investments, local governments will give preferential treatment to Taiwan-funded enterprises. For example, after the central government of mainland China issued *Several Measures for Promoting Cross-Strait Economic and Cultural Exchanges* *and Cooperation* (referred to as *31 Benefit Measures for Taiwan*) in 2018, 20 provinces and 49 cities with relatively concentrated Taiwanese-invested enterprises have successively launched specific benefit policies based on local conditions, including "Shanghai's 55 Benefit Measures for Taiwan", "Fujian's 66 Benefit Measures for Taiwan", "Jiangsu's 76 Benefit Measures for Taiwan", and "Tianjin's 52 Benefit Measures for Taiwan". Due to the different policies issued by local governments towards Taiwanese investment and the deviation in implementation, the impact of environmental regulations on domestic and Taiwan-funded enterprises may be heterogeneous.

The game process between manufacturers and local governments is divided into two stages: in the first stage, the provincial governments formulate environmental regulatory standards e_i, $i = 1, \ldots n$; in the second stage, domestic-funded enterprises and Taiwan-funded enterprises choose their own output according to local environmental standards to maximize profits. First, the enterprise regards the environmental standard e set by the government as a constant and chooses the optimal output under the condition of maximizing profit.

By deriving the output in (1) and (2), the following first-order conditions can be obtained:

$$q_i *^d (e_i) = 1/3b(M + C_i{}^t - f(w)e_i + 2e_i)\ , i = 1, 2, \ldots, n \quad (4)$$

$$q_i *^t (we_i) = 1/3b(M + \theta_i{}^d + 2f(w)e_i)\ , i = 1, 2, \ldots, n \quad (5)$$

where $M = a_i + \theta_i{}^t - 2c_i{}^d - 2\theta i^d$.

Judging from the slope of output to local environmental regulations in Equations (4) and (5), the following propositions can be obtained:

Proposition 1. *The lowered environmental regulatory standards by local governments will stimulate the production of high-polluting and high-energy-consuming enterprises.*

The implication of Proposition 1 shows that loose environmental regulations are attractive to enterprises. From the perspective of profit maximization, loose environmental regulations will reduce the pollution control costs of enterprises, thereby increasing their local investment and production.

Proposition 2. *Due to the regional differences in the strengths and implementation deviations of the local government's favorable policies towards Taiwanese investment, environmental regulations will have heterogeneous effects on Taiwanese-invested enterprises, thereby impacting the distribution of Taiwanese investment.*

Proposition 2 constitutes the main contribution of this article in examining the correlation of regional government environmental regulations and institutional environments with Taiwanese investment. Two inseparable aspects need to be considered when examining the government's use of environmental regulations to attract Taiwanese-funded enterprises. On the one hand, the inflow of investment by Taiwan-funded enterprises is negatively correlated with the intensity of environmental regulations; on the other hand, local governments are making environmental regulations. The comprehensive effect of the institutional environment will be fully considered in the standard. In order to attract Taiwan-funded enterprises, the governments of different regions will adjust the relevant policies of the institutional environment. When the comprehensive effect of the improvement of the institutional environment and environmental regulation in a certain region has a negative effect on the investment of Taiwan-funded enterprises, the local governments will also adopt competition to lower environmental regulatory standards.

3. Methods, Models, and Variables

3.1. Empirical Model Setting

Based on the above theoretical analysis, this part studies the impact of environmental regulations on Taiwanese investment in mainland China based on the Anderson and van

Wincoop's [11] gravity model analysis framework, and conducts empirical tests on the two propositions. The constructed measurement is model as follows:

$$LnTDI_{it} = \alpha + \beta_1 LnTDI_{it-1} + \beta_2 lnER_{it} + \beta_3 L_2Tax_{it} + \beta_4 lnER_{it} * L_2Tax_t + \gamma X_{it} + V_i + e_{it} \quad (6)$$

Among them, TDI_{it} represents the stock of foreign investment by Taiwanese businessmen in the *i*-th province (including municipalities directly under the Central Government) in year *t*. The statistics are from the monthly statistics of the Investment Review Committee of the Ministry of Economic Affairs of Taiwan in 2019. ER_{it} is the environmental regulations of the *i*-th province, L_2Tax_{it} indicates that the tax burden level lags behind the second period, and $\beta\gamma$ is the control variable. GDP_{it} is market size, Lab_{it} is labor cost, $Open_{it}$ is foreign trade dependence, Dis_{it} is geographic distance and $Infra_{it}$ is infrastructure level, α is the intercept that does not vary with the individual, β and γ are the coefficients to be estimated, μ_i is the individual effect, and ε_{it} is the random error term. Considering the availability and consistency of data, this paper selected 23 provinces (municipalities) and the sample period was established as 2006–2016.

3.2. Introduction and Description of Related Variables

Explanatory variables are the main factors that affect Taiwanese investment in mainland China. They are divided into core explanatory variables and control variables. The former includes environmental regulations, tax burden levels, and the interaction between environmental regulations and tax burden levels, and the latter includes GDP, geographic distance, labor costs, infrastructure, and foreign trade dependence.

3.2.1. Environmental Regulation (ERS)

There are no definite indicators on how to measure environmental regulations. In terms of indicator selection, in addition to the availability of data, whether the indicators themselves are relatively reasonable is also a key consideration. At present, domestic and foreign scholars mainly measure the intensity of environmental regulation from three aspects: First, from the perspective of cost, it is mainly measured from the cost of pollution control and investment expenditure. For example, Lanoie [12] used the proportion of pollution investment in the total cost of the enterprise to measure the degree to which the enterprise implements environmental regulatory standards. Second, from a performance perspective, some scholars measure it from the perspective of pollution discharge treatment compliance rate. For example, Cole and Elliott [13] used different emission densities, such as industrial wastewater rate, industrial SO_2 emission rate, and industrial solid emission rate, to calculate comprehensive environmental regulatory indicators. Some scholars have also constructed environmental regulatory indicators from the concept of unit pollution. For example, Domazlicky and Weber [14] measured the change in pollution discharge volume or pollution discharge intensity per unit output value under formal environmental regulations. Third, the number of laws and policies is used as an indicator to measure the intensity of environmental regulations.

By referring to and improving the method of Cole and Elliott [13], this paper used the carbon dioxide emissions per unit of GDP, i.e., carbon dioxide intensity, to measure the level of environmental regulation. There were three major reasons for this choice. The first reason was the availability of the data. If the environmental regulation indicators of each province (such as the indicator of total energy consumption control) are adopted, there will be missing data in some years or provinces and difficulties in data statistics. Second, in the context of a low-carbon economy, carbon intensity has become an obligatory target for the Chinese government in environmental regulation. In 2009, the Chinese government set a quantitative goal to control greenhouse gas emissions: the carbon emissions per unit of GDP are to be reduced by 40% to 45% by 2020 compared to 2005. In June 2015, Mainland China submitted the *Strengthened Actions to Address Climate Change—China's Nationally Determined Contributions* to the United Nations. This document further established the autonomous action goal of mainland China: by 2030, the carbon dioxide emissions per unit of GDP should be reduced by 60−65% compared to 2005. Third, existing studies have shown that there is Granger causality between environmental regulations and carbon intensity, and environmental regulations play a key role in regional carbon intensity. A lower carbon intensity means stricter environmental regulations. In those provinces with stringent environmental law enforcement, environmental regulations can significantly reduce carbon emissions, and the carbon intensity per unit of pollution and the amount of pollution per capita will decline greatly, even two years after the legislation (Shen et al., 2017; Bao et al., 2013) [15,16].

The carbon dioxide emission indicators used in this article were estimated based on the *Greenhouse Gas Emission Guidelines* issued by the IPCC (2006) and the standards and methods of the Office of the National Climate Change Coordination Group and the Energy Research Institute of the National Development and Reform Commission (2007). There are mainly two sources of carbon dioxide emissions: one is carbon dioxide emissions from the combustion of fossil energy, including coal, oil, and natural gas; the other is carbon dioxide from the cement production process.

The calculation formula for the CO_2 emissions from fossil energy combustion is as follows:

$$EC = \sum_{i=1}^{6} EC_i = \sum_{i=1}^{6} E_i * EF_i. \tag{7}$$

Among them, EC is the total CO_2 emissions of various energy consumption; i is energy types, including coal, gasoline, kerosene, diesel, fuel oil and natural gas; and E_i is the total consumption of various energy sources by province. EF_i is the CO_2 emissions coefficient.

The CO_2 emissions from the cement production process are calculated as follow:

$$CC = Q \times EF_{cement}. \tag{8}$$

CC is the CO_2 emission coefficient during cement production, Q represents the total cement production, and EF_{cement} represents the CO_2 emission coefficient for cement production. The consumption data of coal, oil, natural gas, and other energy sources, as well as the reference coefficients for converting each energy into standard coal, are all from the *China Energy Statistical Yearbook*, and the cement production data are from the CEIC China Economic Database. The CO_2 emission coefficients of coal, gasoline, kerosene, diesel, fuel oil, and other fossil fuel combustions are 1.776, 3.045, 3.174, 3.15, and 3.064, respectively; the CO^2 emission coefficients of natural gas and cement in the industrial production process are 2.167 and 0.527, respectively.

3.2.2. Control Variables

According to the characteristics of Taiwanese investment in mainland China, this article selected the following control variables:

According to the investment gravity model, the total amount of investment between two places is positively correlated with the economic scales of the two places, but negatively correlated with the distance between them. (1) Market size: Taiwan is an economy with a small market size. The regions long favored by Taiwanese-invested enterprises, such as mainland China, Southeast Asia, and the United States, have a huge market size, which is an important factor behind the location choice of Taiwanese-invested enterprises. In this paper, the GDP of each province was used to represent the potential market size and investment demand in Mainland China. (2) Distance cost (Dis): Taiwanese investment is mostly concentrated in the eastern coastal regions, and geographical proximity is an important factor as it means lower transportation costs. This article used actual geographic distance to measure, that is, as the geographic distance between the two sides of the strait gradually narrows, the flow of investment across the strait gradually increases. (3) Labor cost (Lab): Taiwanese investment in the mainland is mainly concentrated in foundry enterprises. These enterprises adopt a development mode of receiving orders from Taiwan, processing and manufacturing in the mainland, and selling products to overseas markets such as Europe and the United States. Enterprises with this business model are labor-intensive, and labor cost is an important factor in their location selection. In order to reflect the regional labor cost, this paper adopted the average wage of urban employees as a measure of labor cost. The higher the average wage of urban employees, the higher the average labor cost in the region. (4) Tax burden level (Tax): Preferential tax policies are more attractive to Taiwanese businessmen's direct investment in the mainland, and they play an important role in promoting cross-strait integration. This article used the proportion of local fiscal tax revenue in the current year's GDP to measure the level of tax burden in the general budget revenue of local fiscal revenues, and analyzes the effect of environmental regulations and tax burdens on Taiwan's direct investment in mainland China, taking into account the time lag of tax policy. The time lag of taxation is due to the fact that the transmission process of policy information itself takes a certain amount of time, and on the other hand, it is also due to the rigidity of economic operation itself. In the empirical process, this paper adopted the current period of tax burden, the first period, and the second period, but the current level and the first period are not significant. Due to space reasons, they are not listed in the main text. That is to say, the time difference between the implementation of the tax policy and the effect of the relevant economic entities' behaviors to produce the expected economic effect, the second period of the tax burden level has been selected as the proxy indicator of the tax burden level. (5) Infrastructure (Infra): A sound infrastructure is a factor investors must consider while choosing an investment place, because it is conducive to the agglomeration and diffusion of labor and other production factors, thus realizing the complementary advantages of production factors and resources. This article divides the total length of roads and railways by the total size of the region to measure the level of infrastructure construction in a region. (6) Openness (Open): Taiwanese-invested enterprises rely mainly on OEM production and their products are mostly sold to overseas markets. Thus, the level of regional openness is also a factor to be considered in the location selection of Taiwanese investment. This article used total import and export divided by GDP to measure the level of opening up. The source of the above data was the China Statistical Yearbook. The descriptive statistics of specific variables are shown in Table 1.

Table 1. Descriptive statistics of main variables.

Variable	Description	Observations	Mean	Standard Deviation	Minimum	Max
lnTDI	Taiwanese investment stock	253	13.878	1.831	9.7	17.75
lnERS	Strength of environmental regulations	253	0.598	0.439	−0.52	1.845
L2.Tax	Tax level	207	0.097	0.031	0.054	0.194
lnGDP	The level of economic development	253	9.703	0.694	7.745	11.343
lnLab	labor cost	253	10.575	0.456	9.628	11.737
lnDis	Geographic distance	253	13.999	0.517	12.431	14.667
lninfra	Infrastructure level	253	−0.294	0.744	−2.574	0.74
Open	Degree of openness	253	−1.563	1.048	−3.937	0.543

4. Analysis of Empirical Result

4.1. Empirical Test and Result Analysis

The methodology of this paper was based on the system GMM model for conducting empirical testing on the data of 23 provinces (municipalities) in mainland China from 2006 to 2016. First, the natural logarithm method was used to control the heteroscedasticity problem to a large extent. Second, the VIF (variance inflation factor) value was less than 10, which shows that there was no system multicollinearity problem among variables.

Taking into account the possible continuity of Taiwanese investment in the mainland, the current Taiwanese investment is likely to be affected by the amount of investment in the previous period. This article introduced the lagging period of Taiwanese investment into the model as an explanatory variable. This term is easily correlated with the error term. When the explanatory variable has endogeneity, both the fixed effect and random effect models may lead to estimation bias. Therefore, this paper adopted the system GMM method for estimation, and adopted the lagged second phase value of the explained variable as the instrumental variable. The system GMM method can use the difference equation and the level equation at the same time, so the instrumental variables are effective. The advantages of the system GMM estimation method are as follows: First, the problem of the time-invariant missing variables that affect the distribution of Taiwanese investment can be well resolved. Second, when estimating the endogenous variables of the model, the use of instrumental variables will ensure the estimation coefficients are consistent. Third, even if there are measurement errors, the use of instrumental variables will yield consistent estimates. Therefore, this paper used the system GMM method to estimate the equation.

The use of system GMM estimation methods needs to test the validity of instrumental variables. Arellano and Bover and Blundell and Bond proposed two statistical testing methods to test whether the instrumental variables of the system GMM method are effective. The first method is to use Arellano–Bond's autocorrelation (AR test) method to test whether the residuals in the difference equation have various orders of autocorrelation. In the AR test, the residual term is allowed to have first-order serial correlation, but not allowed to have second-order serial correlation. The second method is the Hansen overidentification test, which judges whether the moment conditional instrumental variables used in the estimation process are effective in general. The original hypothesis was that the instrumental variables are jointly effective.

According to the discussion of the previous estimation methods, it is believed that the system GMM estimation results are robust and reliable. The reasons are as follows: First, from the validity test results of the instrumental variables, the Hansen test cannot reject the null hypothesis that the instrumental variables are valid, which means that in the system GMM estimation, both the instrumental variables of the level equation and the difference equation are valid. Second, the results of Arellano–Bond statistic AR (2) show that there is no second-order serial correlation in the residuals of the first-order difference equation. It is therefore concluded that the instrumental variables are generally effective, and the estimated results of the system GMM are more reliable and robust. The estimated results of the system GMM in Table 2 will be analyzed below.

Analysis of the Impact of Environmental Regulations on Taiwanese Direct Investment in Mainland China

It can be seen from Table 2 that models (2)–(4) are the regression results of environmental regulations, tax burden levels, and their cross-terms on Taiwanese direct investment in mainland China. From the results of model (2), it can be seen that the coefficient of environmental regulation was significantly positive at the 5% level, indicating that when the intensity of environmental regulation is low, Taiwan-funded enterprises will increase investment or expand reproduction in pursuit of high profits. Regulations are an important institutional threshold for foreign-funded enterprises, which can screen the entry of polluting Taiwan-funded enterprises. On the one hand, the intensity of environmental regulations will force a small number of polluting Taiwan-funded enterprises to withdraw from production, or some Taiwan-funded enterprises will voluntarily withdraw from production due to high environmental governance costs. On the other hand, the remaining Taiwan-funded enterprises generally have larger scales. These Taiwanese companies will inevitably increase investment in environmental protection equipment, support for R&D and innovation, and the transformation of production methods in order to comply with the requirements of mainland environmental regulations. This will undoubtedly accelerate the transformation and upgrading of Taiwan-funded enterprises in the region. It can be seen from Model (3) that the level of tax burden in mainland China is not a key factor for

Taiwanese investment in the mainland. Preferential tax policy is an important but not a decisive factor in attracting foreign investment. The change in the income tax rate has not inhibited the launching of Taiwanese capital into the mainland. Two important factors behind the increasingly expanding scale of Taiwanese investment in the mainland are the vast market and relatively low labor costs. Moreover, mainland China in 2008 promulgated the *Enterprise Income Tax Law of the People's Republic of China* and the *Regulations for the Implementation of the Enterprise Income Tax Law of the People's Republic of China* to integrate the income taxes of domestic and foreign enterprises into one, which eliminated the tax incentives for foreign-invested enterprises, including Taiwan-funded enterprises. Taiwan-funded enterprises and domestic enterprises began to enjoy the same treatment in income tax, and the tax incentives for Taiwanese-invested enterprises no longer exist. Thereafter, Taiwan-funded enterprises, which are mostly manufacturing factories, started to pay more attention to changes in labor cost and other production factors (Chen, 2012) [17].

Table 2. The impact of environmental regulations on mainland Taiwanese investment.

	System GMM				OLS
Variables and Constants	**Model (1)**	**Model (2)**	**Model (3)**	**Model (4)**	**Model (5)**
$\ln TDI_{t-1}$	0.779 *** (0.024)	0.583 *** (0.096)	0.635 *** (0.080)	0.657 *** (0.091)	0.96 2*** (0.014)
lnERS		0.609 ** (0.234)	0.606 ** (0.206)	0.813 ** (0.414)	0.201 * (0.114)
L2.Tax			−1.043 (2.687)	−0.011 (2.709)	−1.135 (0.870)
lnERS*L2.Taxt				−3.832 * (2.266)	0.179 * (0.097)
lnGDP	0.101 ** (0.043)	0.544 *** (0.132)	0.499 ** (0.226)	0.408 ** (0.141)	0.069 ** (0.034)
lnLab	0.040 (0.067)	0.264 (0.195)	0.254 (0.242)	0.159 (0.261)	0.033 (0.030)
lnDis	−0.201 ** (0.069)	−0.389 ** (0.187)	−0.348 ** (0.161)	−0.449 ** (0.213)	−0.158 ** (0.079)
lnInfra	0.194 *** (0.028)	0.403 ** (0.131)	0.349* (0.181)	0.363 ** (0.154)	0.053 ** (0.018)
Open	0.119 *** (0.020)	0.311 *** (0.057)	0.283 *** (0.049)	0.167 ** (0.067)	0.07 (0.043)
constant	4.857 *** (0.875)	3.492 (3.100)	2.790 (3.271)	5.610 (4.717)	2.403 (0.905)
controls	YES	YES	YES	YES	
n	230	230	230	230	
R^2 (Adjusted R^2)					0.9929
AR(1)Test value	−2.65 **	−2.11 **	−2.18 **	−2.13 **	
AR(2)Test value	0.575	0.564	0.412	0.430	
Hansen test *p* value	0.953	0.918	0.945	0.995	

Note: 1. This table shows the estimated results of the two-step system GMM. The standard deviations in parentheses, and the symbols ***, **, and * indicate that the variable passed significance test at the levels of 1%, 5%, and 10%. 2. Arellano–Bond AR(1) test and Arellano–Bond AR(2) test represent the first-order and second-order serial correlation tests of residuals, respectively; Hansen tests are about the validity test of instrumental variables. The original hypothesis was that the instrumental variables are valid. This is represented by the *p*-value of the statistic.

In order to test the compound effect of environmental regulation and tax burden level on Taiwanese enterprises, the interaction term of environmental regulation and tax burden level was introduced in model (4) to further test the robustness of the model. The statistical results show that environmental regulation was still significantly positive at the 5% level, and the interaction between environmental regulation and tax burden level was significantly negative, which has a significant compound effect on Taiwanese investment in mainland China. A comparison of the OLS regression results and the system GMM regression results shows that the regression results were robust. This time, the regression coefficient of the interaction term between environmental regulation and tax burden level was 0.813, which was larger than the coefficients of models (2) and (3), and was significant at the 5% level. This shows that under the same environmental regulation intensity, the higher the tax burden level in a region, the more significant the inhibitory effect of environmental regulations on Taiwanese direct investment. This means that local governments can reduce the inhibitory effect of environmental regulations on Taiwanese investment by reducing taxes and providing other preferential policies while attracting investment.

Among the control variables, GDP has a significant positive impact on Taiwanese investment, and geographical distance has a significant negative impact on Taiwanese direct investment, which conforms to the basic setting of the traditional gravity model, indicating that the market size is more attractive to Taiwanese investment. Compared with regions that are far away, Taiwanese businessmen prefer to invest in provinces (municipalities) that are closer to their geographical location. Taiwan is a small and densely populated island with a small domestic demand market and poor natural resources. It is a small economy that is heavily dependent on external markets. The mainland's coastal regions, which have a large market and are separated from Taiwan by the water, are the first choice for Taiwanese investment.

The coefficient of wage cost was not significant and the sign was positive. This cannot be interpreted as cheap labor no longer being one of the factors that attract Taiwanese investment. In fact, the current regional wage disparity in the mainland not only reflects the differences in labor costs, but also the differences in living costs and labor skills caused by various price levels in different regions. Since 2006, Taiwanese investment in the mainland has been in a stage of transformation and upgrading, and the scale of investment in high-tech and high value-added industries has gradually increased. These industries generally choose regions with concentrated talents, mature markets, and complete supporting facilities. Those regions are precisely the regions where prices are relatively high and wages are relatively high. The degree of openness and infrastructure are significantly positive, indicating that the degree of infrastructure perfection and the degree of integration into international subprojects are both key factors behind the location selection of Taiwanese investment. There are obvious regional differences in the level of infrastructure in the mainland. The high-speed kilometers and railway density in coastal and economically developed regions are significantly higher than those in the central and western regions. The degree of infrastructure perfection has always been one of the key factors for attracting Taiwanese investment. In the process of strengthening economic and trade exchanges with countries and regions around the world, and actively integrating into the global value chain, Taiwanese businessmen pay more attention to the degree of openness of investment regions. International factors have gradually become an important reference for Taiwanese businessmen to invest in the mainland and for the transformation and upgrading of Taiwan-funded enterprises.

4.2. Empirical Test Based on Spatial Heterogeneity

The mainland of the motherland has a vast territory, so the industrial structure and layout, the government's investment promotion policies, and the level of environmental regulations all have large spatial heterogeneity. Limited to the difference between the location and the national development policy, the distribution of Taiwanese investment in the mainland is different in different regions. Specifically, Taiwanese investment is more concentrated in the eastern region than in the central and western regions. Therefore, there may also be regional differences in the impact of environmental regulations on Taiwanese investment. To this end, this article further explored the possible impact of spatial heterogeneity on the investment of Taiwanese businessmen from the coastal and inland regions. Refer to Table 3 for empirical results.The coastal regions include Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi Zhuang Autonomous Region, and the inland regions include Shanxi, Inner Mongolia, Jilin, Heilongjiang Province, Anhui Province, Jiangxi Province, Henan Province, Hubei Province, Hunan Province, Sichuan Province, Guizhou Province, and Yunnan Province economic locations.

Table 3. The heterogeneous impact of environmental regulations in different regions on Taiwanese investment.

	Eastern Mainland			Midwestern Mainland		
Explanatory Variable and Constant Term	**Model (1)**	**Model (2)**	**Model (3)**	**Model (4)**	**Model (5)**	**Model (6)**
$lnOFDI_{t-1}$	0.866 *** (0.052)	0.757 *** (0.046)	0.894 *** (0.031)	0.754 *** (0.295)	0.854 *** (0.057)	0.857 *** (0.055)
lnERS	0.202 * (0.107)	0.273 * (0.146)	0.389 ** (0.129)	0.578 * (0.295)	0.257 ** (0.115)	0.557 (0.670)
L2. Tax		−1.373 (2.175)	−0.049 (1.149)		−2.37 (2.019)	−0.073 (0.434)
lnERS*L2.Tax			−2.382 ** (1.016)			−1.268 (6.133)
lnGDP	0.156 ** (0.071)	0.288 *** (0.078)	0.098 ** (0.048)	0.291 ** (0.110)	0.128 * (0.075)	0.184 ** (0.093)
lnLab	0.059 (0.087)	0.058 (0.185)	0.024 (0.129)	0.332 ** (0.159)	0.194 (0.169)	0.235 (0.258)
lnDis	−0.132 ** (0.055)	−0.262 ** (0.083)	−0.104 ** (0.038)	−0.384 ** (0.193)	−0.103 0.122	−0.176 ** (0.097)
lnInfra	0.022 (0.025)	0.020 (0.049)	0.046 (0.035)	0.158 * (0.088)	0.181 *** (0.036)	0.160 ** (0.059)
Open	0.134 ** (0.051)	0.185 ** (0.070)	0.106 ** (0.036)	0.223 ** (0.106)	0.091 ** (0.043)	0.174 (0.112)
constant	1.791 * (0.956)	3.774 (2.771)	1.926* (1.012)	2.767 (2.049)	0.539 (2.159)	0.237 (2.548)
controls	YES	YES	YES	YES	YES	YES
n	90	90	90	130	130	130
AR(1) test value	−2.08 **	−2.32 **	−2.01 **	−2.44 **	−2.13 **	−2.34 **
AR(2) test value	0.468	0.228	0.301	0.570	0.341	0.352
Hansen test *p* value	1.000	1.000	1.000	1.000	1.000	1.000

Note: 1. This table shows the estimated results of the two-step system GMM. The standard deviations in parentheses, and the symbols ***, **, and * respectively indicate that the variable passed significance at the level of 1%, 5%, and 10%. test.

In the eastern region as a whole, the market system is relatively complete, and the preferential tax policies for high-tech enterprises have been implemented earlier. Taiwanese businessmen are currently in the stage of transformation and upgrading. With a rising proportion of high value-added and high-tech industries, and improved infrastructure and convenient transportation, the eastern region has become a favored investment destination for Taiwanese. The regression coefficient of environmental regulation was positive and significant. The regression coefficient of the interaction term between environmental regulation and taxation on Taiwanese direct investment was also significantly negative, which once again shows that environmental regulation will inhibit Taiwanese investment under the dual effect of tax. The level of environmental regulation in the central and western regions did not have a significant effect on Taiwanese investment, and the effect of environmental regulation and its interaction with the tax burden level was also insignificant. The main reason is that the economic development is relatively backward, the degree of marketization is low, the environmental protection mechanism is not sound, and there are fewer ways to obtain foreign capital. Local governments therefore often relax environmental regulations as they compete to attract investment.

5. Simulation Analysis of the Potential of Taiwanese Direct Investment in the Mainland

In order to thoroughly examine the investment growth potential released by environmental regulations in different regions of mainland China, and to prioritize the selection of key promotion regions and take targeted measures when Taiwanese investment resources are relatively limited, this paper designed two different schemes to simulate and analyze the impact of environmental regulations on the investment growth potential of mainland China. Among them, "Simulation Plan 1" refers to the comparison between actual values and simulated values fitted by the model to measure the growth potential of Taiwanese businessmen's investment flows in the region; "Simulation Plan 2" refers to the improvement of the region's environmental regulations to the highest level in the region and the introduction of the empirical equation obtained in the previous article to simulate the investment potential brought about by the improvement of environmental regulations, and to finally obtain the investment potential of Taiwanese businessmen in the mainland of the motherland. The two kinds of simulation results follow.

The results in Table 4 show that the southwestern region has the greatest potential for direct investment from Taiwanese businessmen in the mainland. The value-added scale of the southwestern region is 14.832 billion US dollars, accounting for 82.22%. The southwestern region is rich in natural resources. The rapid economic growth in the coming years and the huge market scale and investment potential will induce changes in the location of Taiwan-funded enterprises. What needs attention is whether local governments will ignore environmental benefits in order to attract investment and pursue economic benefits. This requires the government to proceed from long-term benefits, make full use of local resource advantages, broaden the space for economic development according to local conditions, and transform resource advantages into economic advantages. This is followed by the southern region, with a total value added of 11.52 billion U.S. dollars, accounting for 12.42%. The central region and northeastern region followed closely behind. Taiwanese investment takes the Yangtze River Delta and Fujian and Guangdong provinces as the core regions. The southern region has gathered a large number of Taiwan-funded enterprises with its strong industrial foundation and technical strength. The central region, as an important transportation hub connecting both east and west and north and south, is a central province. The hinterland has become a major opportunity for opening up and advancing the two-way opening up of east and west. With the deepening of the national regional development strategy from the eastern coast to the hinterland and the gradient transfer of coastal industries to the central and western regions, how to release the geographical and industrial advantages of the central provinces is a core issue that the central region needs to consider when attracting Taiwanese investment. As a potential transfer region for Taiwanese-funded enterprises, the northeast region not only needs to introduce Taiwanese-funded enterprises, but also needs to upgrade and cultivate enterprises to promote Taiwan-funded enterprises to achieve cleaner production and reduce pollution emissions.

Table 4. Simulation results of mainland Taiwanese investment potential.

Region	Number of Provinces *n*	Actual Value S	Simulation Solution 1				Simulation Solution 2			
			Analog Value M	D = M − S	K = D/S	T = D*N	Analog Value M	D = M − S	K = D/S	T = D*N
North region	5	84.37	72.61	−11.76	−13.93	−58.8	71.253	−13.12	−15.55	−65.6
North-east region	3	25.18	38.72	13.54	53.77	40.62	37.517	12.34	49	37.02
Huadong region	7	1017.29	1001.73	−15.56	−1.52	−108.92	984.11	−33.18	−3.26	−232.26
Central region	3	42.72	62.93	20.21	47.31	60.63	60.97	18.25	42.72	54.75
South region	3	309.17	347.57	38.4	12.42	115.2	340.87	31.7	10.25	95.1
Southwest region	4	45.096	82.18	37.08	82.22	148.32	77.69	32.59	72.26	130.36

Note: The actual value and the simulated value are calculated based on the average value of the data in the past three years from 2014 to 2016. The actual value, S; the simulated value, M; the value added, D; and the total value added, T, are all in 100 million U.S. dollars. The specific gravity K is a percentage. North region includes Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia Autonomous Region, Northeast region, Liaoning, Jilin, and Heilongjiang; the eastern region includes Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong Province; the central region includes Henan Province, Hunan Province, and Hubei Province; the southern region includes Guangdong Province and Guangxi Province; and the southwest region includes Sichuan Province, Guizhou Province, and Yunnan Province. Due to the availability of data, the northwest region was not included.

After raising the level of environmental regulation in various regions to the highest level in the region, Taiwanese investment has a significant inhibitory effect on the improvement of the level of environmental regulation in the southwestern region, southern region, central region, and northeastern region. The main reason is that compared with eastern region and northern region, these regions have lower levels of environmental regulations. The level of environmental regulation has different effects on Taiwanese investment. Taiwan-funded enterprises have different ways of obtaining resources, innovation, and management models in different regions. This may lead to different behaviors and results of Taiwan-funded enterprises' environmental regulations in different regions. When formulating environmental regulatory policies, local governments should make heterogeneous plans for Taiwan-funded enterprises, formulate corresponding policies to attract Taiwan-funded enterprises to carry out technological innovation, and guide Taiwan-funded enterprises to transform and upgrade. In short, the investment growth potential of different regions of Taiwanese direct investment in mainland China is different, and each region needs to comprehensively weigh the local environmental regulations and policies and attract investment to stimulate the growth potential of the investment field.

6. Conclusions and Policy Recommendations

This article attempted to analyze the role of regional environmental regulations in mainland China in the location choice of Taiwan-funded enterprises. The estimation results show that regional environmental regulations have a significant inhibitory impact on the investment of Taiwan-funded enterprises. The research results of this paper show that environmental regulations are a tool for the game policy of investment promotion among governments, and local governments may sacrifice environment to promote regional economic growth. This also means that in the process of attracting investment, how to avoid the excessive pursuit of short-term effects of investment while ignoring environmental benefits and high-quality economic development are worthy of in-depth study.

The conclusion of this article is that the mainland's environmental regulations have a certain restrictive effect on Taiwanese investment, which is the result of the local government's "lowering effect" out of attracting investment. This is consistent with the research conclusions of other scholars such as Zhu Pingfang, Zhang Zhengyu, and Jiang Guolin, Zhang cai yun and Chen chen [18,19] on the impact of environmental regulations on FDI. However, the differences in the research conclusions of this article are as follows: First, in the empirical part, this paper investigated the heterogeneous impact of the different "benefit-Taiwan policies" in the eastern, central, and western regions on the environmental regulation effect. It was found that the regression coefficient of environmental regulations in the eastern region as a whole was positive, and the level of environmental regulations in the central and western regions had no significant impact on Taiwanese investment.

This shows that due to the differences in regional "benefit Taiwan policies", environmental regulations have a heterogeneous impact on the impact of Taiwanese investment. Second, with regard to the impact of the tax environment, the tax environment is a factor that cannot be ignored by foreign investment, but it has no significant impact on the overall Taiwanese investment, and its interaction with environmental regulations has regional heterogeneity. The regression coefficient of the interaction between environmental regulation and tax on Taiwanese direct investment was significantly negative in the eastern region, while the interaction between environmental regulation and tax level in the central and western regions was quite small.

The research in this article has reference value for the formulation and implementation of environmental policies and preferential policies for Taiwanese investment. Changes in environmental regulations have regional differences in the impact of Taiwan-funded enterprises' investment in mainland China, and the inhibitory effects of environmental regulations on the entry of Taiwan-funded enterprises and differences in environmental implementation are different. Based on the economic performance of the region, local governments have the motivation to lower environmental regulatory standards to absorb investment from Taiwan-funded enterprises. In the face of increasingly stringent environmental regulations on the mainland, how to promote Taiwan-funded enterprises to take root in the mainland will be an issue that needs to be considered in future policy formulation to benefit Taiwan. Environmental regulation is of great significance at the policy level to "screen" and "allocate" investment from Taiwan-funded enterprises.

The mainland has a vast territory, the level of regional economic development is quite different, and the degree of influence of regional environmental regulations on Taiwanese investment is also different. All regions need to choose appropriate environmental regulatory policies based on actual conditions. For eastern regions, on the one hand, it is necessary to more actively introduce technology-intensive, Taiwan-funded enterprises with environmental protection technology advantages, and at the same time, to further restrict and guide the transformation and upgrading of high-energy-consuming and labor-intensive Taiwan-funded enterprises; in the process of introducing Taiwan-funded enterprises in the central and western regions, apart from taking advantage of local resource endowments and actively cooperating with Taiwan-funded enterprises in the development of renewable energy projects such as wind and solar energy, it is necessary for them to pass environmental tax subsidies and other environmental regulations. It is necessary to regulate the local development of Taiwan-funded enterprises with high pollution and energy consumption. Mainland China has successively promulgated policies to benefit Taiwan, aiming to provide Taiwan-funded enterprises with equal treatment to invest in circular economy and environmental protection projects. For Taiwan-funded enterprises in the transitional period, a sustainable development direction is given from the perspective of ecological benefits.

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Appendix A

Table A1. Top Ten Industries for Taiwanese Manufacturing Investment in Mainland China, 2007–2016.

Rank	2007		2010		2014		2015		2016	
	Industry	Percentage	Industry	Percentage	Industry	Percentage	Industry	Percentage	Industry	Percentage
1	Electronic component manufacturing	27.68	Electronic component manufacturing	44.78	Electronic component manufacturing	24.52	Electronic component manufacturing	18.99	Computer electronics industry and optical product manufacturing	29.37
2	Computer electronics industry and optical product manufacturing	19.26	Computer electronics industry and optical product manufacturing	11.4	Computer electronics industry and optical product manufacturing	20.22	Computer electronics industry and optical product manufacturing	17.08	Electronic component manufacturing	22.12
3	Power equipment manufacturing	11.94	Nonmetallic mineral new product manufacturing	7.3	Nonmetallic mineral new product manufacturing	10.39	Nonmetallic mineral new product manufacturing	15.53	Chemial material manufacturing	11.05
4	Plastic products manufacturing	6.66	Power equipment manufacturing	6.3	Chemial material manufacturing	10.19	Paper product manufacturing	8.56	Non-metallic mineral new product manufacturing	4.65
5	Basic metal manufacturing	5.91	Machinery and equipment manufacturing	4.64	Basic metal manufacturing	5.99	Power equipment manufacturing	7.6	Chemical manufacturing	4.64
6	Machinery and equipment manufacturing	5.75	Plastic products manufacturing	3.83	Machinery and equipment manufacturing	4.83	Metal products manufacturing	5.06	Basic metal manufacturing	4.51
7	Metal products manufacturing	3.53	Metal products manufacturing	3.76	Power equipment manufacturing	4.57	Basic metal manufacturing	5.09	Machinery and equipment manufacturing	3.45
8	Non-metallic mineral new product manufacturing	2.64	Basic metal manufacturing	3.11	Metal products manufacturing	3.35	Machinery and equipment manufacturing	3.99	Power equipment manufacturing	2.72
9	Paper product manufacturing	2.04	Automobile and parts manufacturing	3.03	Automobile and parts manufacturing	3.09	Automobile and parts manufacturing	3.36	Rubber products manufacturing	2.72
10	Pharmaceutical Manufacturing	1.97	Food manufacturing	1.83	Food manufacturing	2.05	Plastic products manufacturing	3.34	Pharmaceutical Manufacturing	1.97

Appendix B

Regarding the relationship between the investment layout of Taiwanese businessmen and the spatial differences in regional carbon emissions.

In the past 40 years, there have been obvious regional differences in Taiwanese investment in the mainland. Taiwanese investment is mainly concentrated in the eastern coastal regions, followed by the central region, gradually shifting to north and west of China. In the early stage, Taiwanese investment in the mainland was mainly concentrated in Fujian and Guangdong, and then expanded to Jiangsu, Shanghai, Zhejiang, and other eastern coastal provinces and cities, forming two core regions of Fujian–Guangdong and Jiangsu–Shanghai–Zhejiang. In recent years, the Taiwanese investment has extended from the eastern coastal regions to the northwest. The central and western regions in particular have become popular places for Taiwanese investment because of their preferential investment policies, rich natural resources, cheap land, and low labor costs.

Due to the differences in natural conditions and the imbalance of regional economic development among China's provinces and regions, the level of economic development and the environmental regulations vary greatly. The overall regional difference in carbon intensity in the mainland is characterized as high in the west and low in the east; that is, the carbon intensity is high in the western region and low in the central and eastern regions, and the carbon intensity of the eastern coastal regions is significantly lower than the national average. This is mainly because the eastern coastal regions have developed economy and high level of social development, and the corresponding environmental regulatory measures are also stricter. By contrast, the western regions have abundant energy resources, and lag behind the eastern regions in the level of economic development. Thus the local governments have adopted weaker environmental regulations than the eastern regions in order to attract more investment. There is a strong spatial correlation between Taiwanese investment in mainland China and regional environmental regulation level.

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