Assessment of the Relationship Between Clean Energy Share and Air Quality Improvement in the Yangtze River Delta Region

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Abstract. The Yangtze River Delta uses a lot of coal, and it is also building clean energy fast, so it is a key area for China's energy shift and air cleanup. This paper looks at all studies on clean energy share and air gain in the region, and it lists three main links: first, direct smoke cuts; second, indirect help from plant upgrades and tech spillovers; third, policy push. The results show that more clean energy clearly cuts $PM_{2.5}$, but its effect on ozone is not steady, because weather and place differences change the outcome. Recent work cares more about small areas, many pollutants, and new math tools. Yet clear gaps remain: city differences are ignored, tech types are not studied enough, ozone change steps are not well tracked, and smoke from other provinces is under-counted. Future work should add city and tech gap checks and look at cross-border smoke. This review gathers the scattered proof, sorts out where views agree or differ, and gives a clear guide for regional low-carbon steps and air management.

Keywords: clean energy; air quality; Yangtze River Delta; regional heterogeneity; research review.

1. Introduction

1.1. Background and context

The 2022 China Energy Statistical Yearbook places coal's share of primary energy consumption in the Yangtze River Delta at 52%, making it the region's dominant fuel. Local production meets only 8% of total demand; net inflows from other provinces exceed local output by roughly twelve times. The region accommodates 11% of China's population while consuming 18.4% of national energy, so this heavy reliance on extra-provincial fossil supplies directly compounds local air pollution pressures [1].

Recent years have seen the YRD expand its non-fossil energy mix. Wind, solar and nuclear combined rose from 12% in 2015 to 22% in 2021. Yet fossil fuels still command the largest share. Incremental electricity demand is met predominantly by coal-fired generation imported from neighbouring provinces, so the nexus between energy use and degraded air quality persists [2]. Given the region's per-capita GDP leadership, its advanced deployment of renewable technologies, and the substantial health costs associated with local air quality, the YRD has drawn growing research attention as a natural laboratory for studying the environmental consequences of energy transition. That said, the existing literature on the clean energy – air quality relationship in this region remains piecemeal; systematic synthesis and cross-cutting comparisons are scarce.

1.2. Research problem or question (GAP)

Existing studies have furnished important insights into the clean energy – air quality nexus, yet they leave several gaps in synthesising the available evidence. First, most researchers adopt national or broad macro-regional units of analysis, relying on inter-provincial panel data that implicitly treat the YRD as a homogeneous entity. This aggregated approach masks local variations in the energy–emission–meteorology–transport chain, and consequently yields inconsistent estimates of the magnitude and even the direction of clean energy's effects [3,4]. Second, when characterising energy structure changes, the literature typically resorts to proxies such as total energy consumption or coal share; few efforts have systematically disaggregated technology-specific clean energy portfolios (solar, wind, biomass, natural gas, imported green power) or compared their relative pollution abatement potentials [4,5]. Third, air quality assessments remain overwhelmingly fixated on annual mean $PM_{2.5}$ concentrations. The YRD's compound pollution features—summertime ozone exceedances, heavy-pollution day frequencies (AFD), and population-weighted exposure concentrations (PWC)—receive far less attention, leaving the energy–air quality relationship only partially characterised [3].

These shortcomings call for a systematic synthesis that integrates fragmented empirical findings, reconciles heterogeneous results, and identifies points of convergence and divergence. The present review addresses this need for the YRD context, without undertaking new empirical estimations of our own.

1.3. Objectives of the study

This study conducts a systematic synthesis of empirical evidence with three core objectives: to summarize and compare existing empirical findings regarding the impacts of city- and regional-level clean energy development on multiple air quality indicators (AQI, $PM_{2.5}$, SO_2, O_3, AFD) across the YRD region; to synthesize evidence of policy-driven emission reduction effects within the energy-air quality chain and compare the consistencies and discrepancies between short-term and long-term impact conclusions drawn from prior studies; and to identify persistent research gaps including ozone response mechanisms, inter-provincial pollutant transport and regional heterogeneity through comprehensive literature review, before inductively proposing priority avenues for future research.

1.4. Significance of the study

1.4.1 Theoretical contribution

By systematically synthesizing city-level and regional evidence, this review clarifies the direct and indirect pathways through which clean energy affects multiple air quality metrics in the YRD. It addresses the fragmentation of existing research by organizing scattered findings into a coherent analytical framework, thereby providing a reference for regional-scale energy-air quality relationship research and enriching the theoretical discussion on regional heterogeneity in energy transition environmental effects.

1.4.2 Practical contribution

This review consolidates empirical evidence on the air quality benefits associated with increased clean energy shares in the YRD, and summarizes the effectiveness of different policy instruments reported in existing studies. It provides a structured "evidence map" for regional policymakers, supporting evidence-based discussions on low-carbon energy transition and air quality improvement strategies, rather than direct policy guidance. The findings can also serve as a reference for other mega-city clusters facing similar energy and environmental challenges.

2. Review of Theories and Mechanisms

2.1. Direct Impact Mechanism of Clean Energy on Air Quality

Existing studies have identified two core direct impact mechanisms through which clean energy affects air quality. First, clean energy sources such as solar, wind, and biomass generate negligible pollutant emissions during operation [1]. From a source-control perspective, substituting fossil energy with these clean energy sources directly reduces emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. For instance, studies indicate that replacing coal-fired power generation with wind and solar power can lower pollutant emission intensity per unit of electricity by over 80% [2]. Second, the development of clean energy promotes the phase-out of inefficient and high-pollution fossil energy production capacity. As the deployment of clean energy expands, small-scale, high-emission, and low-efficiency fossil energy facilities are gradually withdrawn due to limited competitiveness, further decreasing total regional pollutant emissions. This mechanism has been observed in the Yangtze River Delta (YRD), where "coal-to-gas" and "coal-to-electricity" initiatives have directly reduced pollution from decentralized coal combustion [2].

2.2. Indirect Mediating Mechanism

Existing research suggests that the indirect impact of clean energy on air quality is mainly realized through three mediating pathways. First, in terms of industrial structure upgrading, many studies hold that the development of clean energy can drive the development of related industries such as new energy equipment manufacturing, new energy materials, and energy storage. The expansion of these low-carbon and environmental protection industries will promote the transformation of the regional industrial structure from a high-energy-consuming and high-pollution model to a low-carbon and green development model, thereby indirectly reducing pollution emissions [2]. Second, regarding technological progress spillover, relevant literatures point out that the research and development (R&D) and application of clean energy technologies (such as energy storage technology, smart grid technology, and efficient energy conversion technology) have obvious technological spillover effects [3]. These technologies can be extended and applied to traditional high-energy-consuming industries, promoting the improvement of energy utilization efficiency in traditional industries and reducing pollutant emissions per unit of output [3]. Third, in terms of energy consumption structure optimization, existing studies believe that the increase in the share of clean energy in the total energy consumption will optimize the overall regional energy consumption structure, reduce the dependence on coal and other high-pollution fossil energy, and thus weaken the sensitivity of air quality to the consumption of fossil energy [2].

2.3. Regulatory Role of Policy Instruments

Existing studies have explored the regulatory role of policy instruments in the chain of "clean energy development - energy structure adjustment - air quality improvement" and found that policy instruments can act on this chain through both direct and indirect channels [5,6]. From the perspective of direct channels, some literatures indicate that policy tools such as feed-in tariffs and tax incentives can reduce the levelized cost of renewable energy development and utilization, thereby accelerating the substitution process of renewable energy for coal and other fossil energy [5]. At the same time, stringent pollutant emission standards formulated by the government can force high-pollution energy production enterprises to withdraw high-pollution production units or switch to cleaner energy sources, achieving immediate emission reduction effects [6-8]. From the perspective of indirect channels, relevant research shows that cross-provincial green power trading policies can reallocate surplus renewable energy power to energy demand centers, forming spatial spillover effects and further improving regional air quality indicators.

However, existing studies on the above theories and mechanisms still have certain limitations. Most of the existing literatures focus on analyzing the short-term impact effects of clean energy on air quality, while there is a lack of sufficient longitudinal evidence on the persistence of these impact effects. In addition, the existing research also rarely involves the transaction cost barriers that may weaken the trading mechanism of clean energy, and the relevant theoretical discussion and empirical verification are relatively insufficient.

3. Review of Regional Current Situation

3.1. Status of Clean Energy Development in the YRD Region

Official statistics and recent studies put the YRD at the forefront of China's clean energy transition, and the region's development trajectory captures both national energy transformation trends and its own distinct features, which is why it has become a focal point in the literature [2]; on energy structure evolution, data from the 2022 China Energy Statistical Yearbook and provincial "14th Five-Year" energy plans show that non-fossil energy's share in primary consumption went from 12% in 2015 to 22% in 2021, then rose further to roughly 25% in 2022, always outpacing the national average [1,2]; within this shift, two features stand out — large-scale capacity expansion and cross-regional allocation—as wind and solar installations have grown, distributed photovoltaic capacity ranking first nationally, a pattern that matches the region's abundant industrial park and building rooftop resources, and cross-provincial green power trading has also expanded, exceeding 10 billion kWh in 2023 and offering a mechanism for optimising clean energy distribution across provincial boundaries [2]. But the literature keeps highlighting structural deficiencies in the YRD's energy system, and these deficiencies drive much of the current research [2]; coal still accounts for over 50% of primary energy consumption—52% in 2021—showing that fossil fuel path dependence hasn't really been broken [1]; this coexistence of a high-carbon base with accelerated clean energy deployment complicates the impact mechanism of clean energy substitution on air quality, making the YRD a test case for evaluating the environmental dividends of energy transition, and it also explains why studies have moved beyond national-scale analyses to focus on intra-regional heterogeneous effects [2]; also, the internal makeup of clean energy is lopsided—biomass and geothermal development lag, and even wind and solar expansion faces constraints from resource distribution and grid absorption capacity [2]—and this uneven profile corresponds to the research gap identified in the introduction, the lack of technology-specific portfolio analysis, underscoring the need to assess differential emission reduction potentials across clean energy types, a theme we take up in the research trends section.

3.2. Status of Air Quality in the YRD Region

Monitoring data, environmental bulletins, and empirical studies paint a picture of overall improvement in YRD air quality alongside persistent compound pollution challenges, features that have shaped subsequent studies' indicator choices and research designs [3,4]; on core pollutant control, $PM_{2.5}$ concentrations have declined steadily, with regional annual averages dropping from 60 $\mu g/m^3$ in 2015 to roughly 30 $\mu g/m^3$ by 2022 and good air quality days exceeding 85% of the year, and this positive trend gives us the baseline for evaluating the environmental benefits of clean energy substitution [3]. But the region's air quality also faces multiple structural difficulties that have pushed research paradigms to evolve [4]: one is the pollution regime shifting from single-pollutant dominance to compound pollution, where ozone now emerges as the primary summer pollutant, average concentrations in some industrial cities have exceeded the national secondary standard, and this transitional pattern—$PM_{2.5}$ going down while ozone goes up—renders single-pollutant analyses inadequate and directly drives the "multi-pollutant synergy" research trend we discuss later; another difficulty is the marked spatial heterogeneity in pollution distribution, with heavy-pollution day frequencies (AFD) staying elevated in industrial-intensive zones and the region's dense population, 11% of the national total, yielding relatively high population-weighted exposure concentrations (PWC) [1,4], and these spatial and exposure dimensions expose the limits of regional homogeneity assumptions, steering research toward finer spatial disaggregation and exposure-oriented metrics, trends we take up in later sections [3,4]. The YRD's air quality profile thus not only offers rich empirical ground for testing the environmental effects of clean energy but also clarifies the key directions where existing research needs to push forward, laying the empirical groundwork for the literature review that follows.

4. Research Progress and Trends

4.1. Research Progress on the Relationship Between Clean Energy and Air Quality

4.1.1 $PM_{2.5}$ Association

City-level panel studies have largely agreed that the share of non-fossil energy has a significant negative correlation with $PM_{2.5}$ concentration, each 1-percentage-point rise in renewable energy's share of primary consumption bringing a 0.8% to 2.1% drop in $PM_{2.5}$ [3,4]—a finding that confirms the emission reduction effect of clean energy substitution on $PM_{2.5}$ in the YRD; but the stability of this correlation hasn't been settled, since Wang et al. (2022) noted that synoptic variability, including atmospheric circulation and diffusion conditions, can weaken clean energy's impact on $PM_{2.5}$ sharply, and their study shows that under winter stagnant weather, the mitigation effect gets cut by up to 40%, leaving regression coefficients statistically insignificant [4]; so the environmental benefits of clean energy in reducing $PM_{2.5}$ are constrained by meteorological conditions and don't hold uniformly across time.

4.1.2 Policy Instruments

Existing quasi-experimental studies have obtained relatively consistent findings on the short-term effects of policy instruments. Feed-in tariffs and stricter pollutant emission standards have shown obvious emission reduction effects: within the first year of implementation, these policies can reduce the quarterly $PM_{2.5}$ concentration by 3% to 6% [5]. In addition, cross-provincial green power trading policies have demonstrated supplementary environmental benefits. By replacing coal-fired power generation in demand centers with surplus renewable energy, such policies can further reduce regional $PM_{2.5}$ concentrations by 1% to 2% [3].

Nevertheless, there is a clear research gap regarding the long-term effects of these policies. No existing studies have quantitatively verified the persistence of the above policy effects beyond 5 years [5]. It remains unclear whether the emission reduction benefits of policy instruments can be sustained in the long run, or if they will weaken due to factors such as policy adjustments or technological changes. This has become a key point of contention in subsequent research.

4.1.3 Dynamic Patterns

Distributed-lag model studies have largely converged on a consistent picture: it takes a 1 to 2-year lag for incremental renewable capacity to turn into measurable air quality improvements, and once solar and wind capacity together tops about 15% of total generation capacity, the marginal benefit of clean energy for air quality tends to jump [5]; the dynamic response of ozone, though, stays unsettled, since changes in photochemical reaction regimes set off by clean energy substitution can temporarily push peak ozone concentrations higher, pointing to a possible short-term trade-off between bringing down $PM_{2.5}$ and controlling ozone pollution [4], and for the YRD context specifically, research on this trade-off is still thin, with no firm conclusion on whether clean energy's long-run build-out can suppress both $PM_{2.5}$ and ozone at the same time [4].

4.2. Research Trends

4.2.1 Finer Spatial Scales

To reduce the biases that come from assuming regional homogeneity, traditional aggregate analyses at the regional level have increasingly been abandoned in favour of studies at finer spatial scales, with a growing number of researchers now turning to city-level data or 1 km-grid emission inventories to capture spatial heterogeneity in the clean energy − air quality relationship [3]; one study, for instance, brought together OMI NO_2 column data and land-use regression models to map sub-city-level emission change curves across 41 YRD cities, cutting down those homogeneity-driven biases directly [3].

4.2.2 Multi-pollutant and Exposure Metrics

Research on air quality indicators is no longer confined to annual average $PM_{2.5}$ concentrations but has been expanding toward multi-pollutant and human exposure-oriented metrics, with peak ozone concentration, heavy-pollution day frequency (AFD), and satellite-derived population-weighted exposure concentration (PWC) now commonly folded into analytical frameworks [4]; this lets researchers build dose-response functions that account for multiple pollution stressors, producing a more comprehensive evaluation of clean energy's environmental benefits that lines up better with actual human health impacts.

4.2.3 Machine-learning and Causal Designs

Two trends have emerged in research methods: machine learning techniques like random-forest and gradient-boosting models are increasingly used to capture non-linear interactions among clean energy, meteorological conditions, and air quality, getting past the limits of traditional linear models; causal identification methods have kept advancing too, with spatial difference-in-differences and instrumental-variable strategies—transmission-line constraints serving as instruments, for example—widely applied to identify causal spillover effects of cross-provincial clean energy deployment on air quality, lending more credibility to the conclusions [4,5].

5. Conclusion

Current studies on clean energy and air in the Yangtze River Delta have moved forward, yet clear gaps remain. First, many papers treat the whole region as one block and ignore differences in industry, energy, and development among cities. The fact is that adding the same amount of renewable power cuts $PM_{2.5}$ by very different amounts in different cities, but no one has mapped this contrast in detail. Second, most articles use only one total figure, the "share of non-fossil energy," and do not split solar, wind, biomass, and other sources. Because these technologies work and cut emissions in different ways, failing to separate them makes it hard to tell which is better and hard to pick the best mix. Third, few studies look at how clean energy affects ozone. NO_x and VOCs react differently under different weather, and no one has calculated the point at which clean energy starts to bring ozone down. Finally, pollution that crosses provincial borders is overlooked; ignoring this incoming pollution leads to an overestimate of the gains from local clean energy and an underestimate of the need for cooperation between provinces, so the true link between energy and air is blurred.

To fill the gaps, future studies should first look at city-level differences. Combine high-resolution emission data and spatial zone models. Use industry type, energy plants, and city shape as adjusting factors. This can measure different impacts across city types and give targeted advice for regional energy and environment policy. Research should also strengthen technology-specific mix analysis. Use plant-level data and simple causal methods to work out how much pollution each clean energy technology can cut. Under local grid and resource limits, this helps pick the best technology mix.

In addition, the non-linear response of ozone must be made clear. Combine chemical transport models with machine learning and causal inference to find the turning point where clean energy changes ozone trends. See under what conditions both $PM_{2.5}$ and ozone can drop. Lastly, cross-province pollution transport must be put into the analysis frame. Couple air and space energy models and use a quasi-experimental design to work out the causal impact of outside pollution. These steps can count the true air gains, support joint policy between provinces, and give a solid science base for regional clean energy change.

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