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Carbon Mitigation and Environmental Co-Benefits of a Clean Energy Transition in China's Industrial Parks

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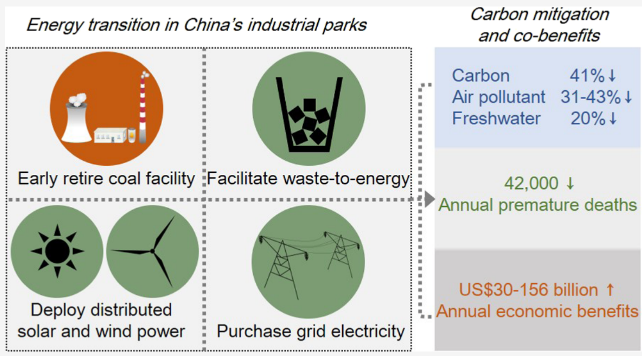
ABSTRACT: Industrial parks are emerging priorities for carbon mitigation. Here we analyze air quality, human health, and freshwater conservation co-benefits of decarbonizing the energy supply of 850 China's industrial parks. We examine a clean energy transition including early retirement of coal-fired facilities and subsequent replacement with grid electricity and onsite energy alternatives (municipal solid waste-to-energy, rooftop photovoltaic, and distributed wind power). We find that such a transition would reduce greenhouse gas emissions by 41% (equal to 7% of 2014 national CO_2 equivalent emissions); emissions of SO_2 by 41%, NO_x by 32%, and $PM_{2.5}$ by 43% and freshwater consumption by 20%, relative to a 2030 baseline scenario. Based on modeled air pollutant concentrations, we estimate such a clean energy transition will result in ~42,000 avoided premature deaths annually due to reduced ambient $PM_{2.5}$ and ozone exposure. Costs and benefits are monetized including technical costs of changes in equipment and energy use and societal benefits resulting from improvements in human health and reductions of climate impacts. We find that decarbonizing industrial parks brings annual economic benefits of US\$30−156 billion in 2030. A clean energy transition in China's industrial parks thus provides both environmental and economic benefits.



KEYWORDS: *industrial park, clean energy transition, carbon mitigation, water conservation, air quality, human health*

1. INTRODUCTION

As a common feature of industrialization, industrial parks, also known as industrial clusters, are booming globally with industrial enterprises increasingly sharing infrastructure within a small area.[1−3] China as a "world factory" has more than 2500 industrial parks (Figure 1) that provide industrial raw materials and manufactured goods to the world.[4] Industrial parks are major emitters of CO_2 and reducing their reliance on fossil fuels will help achieve China's climate and air quality goals. However, the decarbonization of industrial parks has drawn little attention to date. China's industrial parks emitted about 2.8 gigatons CO_2 in 2015 and contributed ~30% of national energy-related CO_2 emissions.[5] Their energy infrastructure was responsible for ~75% of their onsite greenhouse gas (GHG) emissions, indicating that decarbonization of industrial parks can largely occur through a transition of their energy systems.[5] Energy infrastructure has a long service lifetime that locks in carbon emissions, making it important to decarbonize industrial parks and their energy supply rapidly.[6]

Industrial parks are emission hotspots where targeted low-carbon engineering/policy interventions can substantially reduce emissions.[8,9] Low-carbon pathways for industrial parks include industrial structural change; energy efficiency improvements; decarbonization of their energy mix; and carbon capture, utilization, and storage.[5] Previous studies investigated the GHG mitigation potential and costs of improvements in coal-fired energy infrastructure in China's industrial parks, such as coal-to-natural gas (NG) retrofits of boilers and efficiency-oriented turbine upgrades.[10] However, China's climate targets require deep decarbonization of industrial parks. In addition, China has set targets for air quality improvements and water conservation.[11,12] Opportunities to simultaneously meet multiple environmental goals necessitate a comprehensive analysis that quantifies the implications of decarbonizing industrial parks for air quality, human health, and water stress.[13,14]

We explore the synergies for carbon mitigation, air quality, human health, and freshwater conservation of a clean energy transition in 850 of China's industrial parks that includes early

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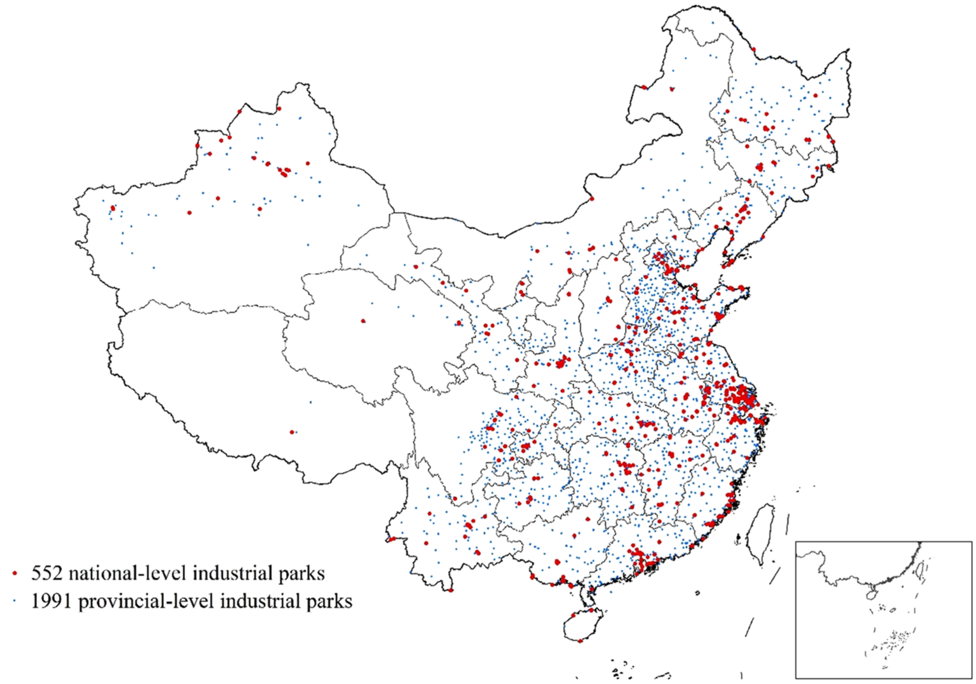

Figure 1. Geographic locations of industrial parks in China. National- and provincial-level industrial parks are established and supervised by central and provincial governments, respectively.[4] National-level industrial parks generally have better performance in resource management and pollution control than provincial-level ones, and most of them have initiated plans and strategies to foster their clean energy transition.[7]

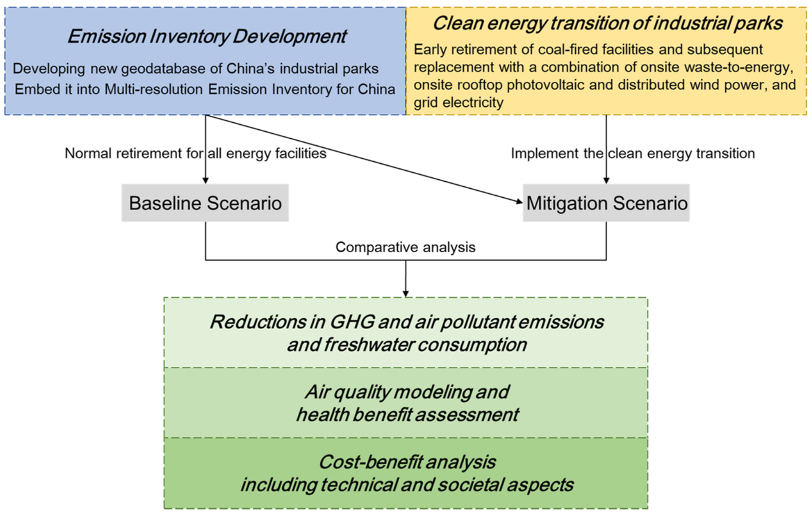

Figure 2. Integrated analysis framework.

retirement of coal-fired facilities and subsequent replacement with a combination of onsite municipal solid waste (MSW)-to-energy, onsite rooftop photovoltaic (PV) and distributed wind turbines, and electricity from the power grid. These measures are chosen because small, highly polluting, and inefficient coal-fired facilities are being phased out in industrial parks.[6] This practice is consistent with national planning for the coal power sector[15] with a shortened 20-year lifetime found to allow full recovery of power plant capital costs and to facilitate China's carbon targets.[16,17] Second, industrial symbiosis practices, especially waste-to-energy, enable industrial parks to convert MSW, they and surrounding communities generate, into energy.[6] China's near-term plans also highlight MSW incineration, rather than landfilling, as a mainstream treatment approach to address land scarcity and provide efficient energy recovery.[18,19] Third, renewable energy-driven facilities in industrial parks accounted for only 1% of total power capacity in 2014, and national guidelines for eco-industrial parks emphasize the onsite deployment of distributed solar and wind power facilities in industrial parks.[20] Finally, China plans to decarbonize the power sector with above 1.2 TW of wind and solar power by 2030.[21] Thus, utilizing power from the grid as it decarbonizes will reduce GHG emissions of the industrial sector.

2. METHODS

Our methodological framework is presented in Figure 2. We first develop a geodatabase of point-source emissions of GHG, SO_2, NO_x, $PM_{2.5}$, PM_{10}, and volatile organic compounds (VOC) from the energy systems of 850 industrial parks in

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Table 1. Baseline and Mitigation Scenario Criteria for Industrial Parks[a]

energy supply		2014	2030 baseline scenario (BS)	2030 mitigation scenario (MS)
coal-fired power/heat/CHP units (GW)	≥100 MW	404	324	106
	<100 MW	45	32	0
MSW-to-energy (GW)		2.4	2.4	35
photovoltaic facilities (GW)		1.4	1.4	111
wind power (GW)		0.3	0.3	17
natural gas-fired units (GW)		42	38	62
other energy infrastructure (GW)		19	17	17
total (GW)		515	415	347

[a]Note: CHP, combined heat and power; MSW, municipal solid waste.

2014 based on our previous work.[10] We then embed this database into the Multi-resolution Emission Inventory for China (MEIC) for 2014[22−24] by locating industrial parks in MEIC grid cells at a 0.25° resolution. Second, we configure 2030 Baseline and Mitigation Scenarios (MS) for the energy supply of industrial parks and identify their differences to quantify reduction potential for GHG and air pollutant emissions and freshwater consumption using a life-cycle assessment. The Baseline Scenario (BS) employs a normal retirement timeline between 2014 and 2030 for existing energy infrastructure units in industrial parks. The Mitigation Scenario early retires coal-fired units after 20 years of operation. Electricity supply gaps resulting from the early retirement are filled with onsite renewables, waste-to-energy, and grid electricity; heat supply gaps are filled with waste-to-energy and natural gas. Thus, the total energy supply in both scenarios remains the same. Third, we apply a regional atmospheric chemistry model to simulate air quality in both scenarios and estimate human health benefits from air quality improvements across China. Finally, we conduct a cost−benefit analysis incorporating technical costs of equipment and energy use as well as social benefits of reduced premature mortalities and carbon mitigation.

2.1. Scenario Setup. Energy infrastructure in the 850 China's industrial parks had a total capacity of 515 GW in 2014, including 449 GW of coal-fired units, 42 GW of natural gas-fired units, and 24 GW of other energy sources-driven units. Coal-fired units accounted for 87% of total capacity, while renewables-driven units (solar, wind, hydro, bioenergy and geothermal) accounted for only 1% of the total. The energy infrastructure collectively supplied 2200 TWh of electricity and 3800 PJ of heat in 2014. Such heavy coal dependence in China's industrial parks necessitates a clean energy transition that diversifies energy sources and phases down coal-fired units. Detailed data of energy infrastructure units are provided in the Supporting Information, Dataset.

Scenario configurations are summarized in Table 1. In the Baseline Scenario, coal-fired units operate based on a 30-year lifetime.[25] In the Mitigation Scenario, the clean energy transition is organized in the following steps (Figure S1). First, we classify coal-fired units [including power, heating, and combined heat and power (CHP) units] into ≥100 and <100 MW. Coal-fired units < 100 MW are widely employed (61% of the capacity and 64% of the number) as CHP in industrial parks, serving as primary heat sources.[10] According to unit vintage years (year of initial operation), we retire units < 100 MW immediately and retire units ≥ 100 MW when they reach a 20-year lifetime, which is the minimum duration to be break-even economically.[16] We assume non-coal energy infrastructure units retain their typical lifetimes in both scenarios.

Early retirement of coal-fired units results in energy supply gaps. By investigating 213 national-level industrial parks in China, we found 100% of heat demand and 87% of electricity demand in industrial parks in 2015 were satisfied by their own energy infrastructure.[9] In the Mitigation Scenario, we fill the energy supply gaps with onsite PV, wind power, MSW, natural gas, and grid electricity. We optimize the priorities of these alternatives to maximize decarbonization opportunities within the constraints of resource availability. Our previous study found that MSW-to-energy facilities in industrial parks accounted for 55% of China's total MSW-to-energy capacity, and new MSW-to-energy facilities tend to be deployed in industrial parks. Industrial parks are favored for MSW-to-energy deployment to avoid public concerns about potential smells and toxicity.[26] Industrial parks install waste incinerators with stringent end-of-pipe controls to replace coal-based heat generation with heat from waste combustion thus decreasing carbon emissions—a win−win opportunity.[26] To reduce the costs of deploying MSW-to-energy, the turbines and generators of early-retired small-capacity coal-fired units can be utilized and only MSW incinerators need to be constructed. We detail the estimation of such costs in Tables S5 and S6. We model the additional capacity as well as electricity and heat generation of MSW-to-energy using replaced capacity of coal-fired units < 100 MW and available MSW quantities from surrounding communities for incineration (detailed in Supporting Information, Note 1). We model the additional capacity as well as electricity generation of onsite rooftop PV and distributed wind turbines using solar and wind resources of industrial parks, their available land area to deploy renewables, and technical parameters of PV panels and wind turbines (see estimations in Supporting Information, Notes 2−3 and detailed results in the Supporting Information, Dataset). We use a conservative 2030 grid electricity mix[27] that includes 57% of electricity from coal (currently 63% in 2020), 26% from renewables (hydro, 14%; solar, 5%; wind, 7%), 8% from nuclear, 7% from gas, and 2% from other (Supporting Information, Note 4).

We first apply MSW-to-energy and onsite renewables to replace the electricity supply gaps, and then use grid electricity if there are still gaps. We first fill the heat supply gaps with MSW and then use natural gas if there are still gaps. We perform a sensitivity analysis to examine the impacts of changing critical parameters (such as shortened coal power lifetimes, grid electricity mixes, and available land area for onsite renewables) on the model results in Supporting Information, Note 5. Moreover, upstream air pollutant emissions of energy-related processes are attributed to provinces where they physically occur for air quality simulations (Supporting Information, Note 6).

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2.2. Emission Inventory Development. We use a bottom-up geodatabase of energy infrastructure of China's industrial parks that collected and integrated multiple data sources for 1604 of China's industrial parks in 2014.[10] Among them, 850 industrial parks have energy supply systems, which are the research sample in this study. Indices include capacities, technologies, vintages, efficiencies, fuel inputs, energy outputs, and freshwater consumption of energy infrastructure units in industrial parks.[10] Here we further collect data on boiler types, ash contents of coal, PM removal techniques and efficiencies, and VOC emission factors of the energy infrastructure units.[28−32] Using these factors, we calculate CO_2, CH_4, N_2O, SO_2, NO_x, $PM_{2.5}$, PM_{10}, VOC emissions, and freshwater consumption from energy supply of each industrial park. Point-source emissions from industrial parks are then embedded into grid cells of MEIC 2014 (see Supporting Information, Note 7). GHG and air pollutant emissions and freshwater consumption in both scenarios can be calculated based on the database of industrial parks and their energy facilities in the Supporting Information, Dataset as well as environmental impact factors and upstream impact allocation approaches in the Supporting Information. We focus on the supply side and do not analyze changes in the demand side. We address only the benefits of decarbonizing the energy supply systems in industrial parks. Energy use data are not necessary for this analysis. Energy use data for the 850 industrial parks are also unavailable at this stage as no statistics exist on China's industrial park energy use.

2.3. Air Quality Simulations and Health Impact Assessment. To analyze changes in concentrations of $PM_{2.5}$, O_3, SO_2, and NO_2, we conduct simulations for January, April, July, and October of the Baseline and Mitigation Scenarios using Weather Research and Forecasting model with Chemistry (WRF-Chem) v3.6.1, developed by US National Center for Atmospheric Research.[33] We average the 4-month simulations to obtain annual average concentrations of $PM_{2.5}$, SO_2, and NO_2. The maximum daily 8 h average (MDA8) O_3 concentrations in July are used as a proxy for summer O_3 concentrations. The resolution employed is 27 km × 27 km (∼0.25° × 0.25°), with a domain covering China and parts of surrounding Asian countries (9−58°N, 60−156°E). Meteorological data on initial and boundary conditions are from the National Centers for Environmental Prediction FNL Operational Global Analyses[34] at 1° × 1° resolution. Chemical initial and boundary conditions are derived by the Community Atmosphere Model with Chemistry.[35] Our previous work describes the model configurations for physical and chemical schemes as well as calculations for biogenic emissions and natural dust emissions.[36,37] We simulate air pollutant concentrations for 2014 as a base year and evaluate the performance of WRF-Chem by comparing the simulated concentrations with observations in 2014, as described in Supporting Information, Note 7.

We adopt a counterfactual method to evaluate the air quality improvements and resulting health benefits of decarbonizing China's industrial parks. We use 2014 air pollutant emissions as our base case. For the 2030 Baseline and Mitigation Scenarios, we only change emissions from industrial parks and additional grid electricity used for industrial parks, and we keep emissions from the other sectors the same as in 2014. The counterfactual method is widely used for impact comparison between scenarios with and without policy interventions,[38] and is suitable to identify the environmental benefits that directly result from decarbonizing industrial parks. In the Baseline Scenario, industrial park emissions slightly decrease relative to 2014 due to the normal retirement of energy infrastructure. In the Mitigation Scenario, industrial park emissions are substantially reduced but additional grid electricity used by industrial parks results in a slight increase in the power sector emissions. We then simulate the air quality for each scenario and identify the differences in air pollutant concentrations as the air quality improvements of decarbonizing industrial parks.

We estimate the health benefits of the Mitigation Scenario relative to the Baseline Scenario using the relative risk of premature mortalities due to $PM_{2.5}$ and O_3 exposure.[39,40] $PM_{2.5}$-associated causes of death include noncommunicable diseases (mainly including chronic obstructive pulmonary disease, lung cancer, ischemic heart disease, and stroke) and lower respiratory infections.[41] O_3-associated premature mortalities also result from the respiratory and circulatory diseases mentioned above.[42] Health impact assessment for $PM_{2.5}$ and O_3 exposure has been well developed in existing studies[40−42] and we detail the approaches in Supporting Information, Note 8.

2.4. Cost−Benefit Analysis. We conduct a comprehensive cost−benefit analysis including changes in technical costs and social benefits in the Mitigation Scenario relative to the Baseline Scenario. Total net benefits of the clean energy transition result from changes in costs for equipment, fuel, electricity, and heat, and monetized social benefits for human health and carbon emission reductions, as formulated in eq 1.

$$\begin{cases} \text{total net benefit} = \Delta\text{social benefit} - \Delta\text{technical cost} \\ \Delta\text{technical cost} = \Delta\text{equipment cost} + \Delta\text{fuel cost} \\ \qquad\qquad + \Delta\text{electricity cost} + \Delta\text{heat cost} \\ \Delta\text{social benefit} = \Delta\text{health benefit} \\ \qquad\qquad + \Delta\text{carbon reduction benefit} \end{cases} \tag{1}$$

Equipment cost changes cover expenditures of additional MSW incinerators, rooftop PV panels, distributed wind turbines, and their auxiliaries and installations. These capital costs are amortized over the service lifetime of these facilities. Fuel cost changes include coal cost savings resulting from the early retirement of coal-fired units, subsidies from the governments for MSW treatment, and natural gas cost additions. Early retirement of coal power results in an electricity supply gap, of which a portion must be filled by grid electricity, resulting in additional electricity costs. We estimate the cost changes and adjust them in 2015 values. Associated parameters are listed in the Supporting Information, Table S6.

We apply the value of a statistical life (VSL, a measure of people's willingness to pay to reduce mortality risk)[43] for the monetization of health benefits. Estimates for VSL are significantly dependent on countries, age groups and income groups.[43] A recent study estimated the VSL in China by investigating six representative cities, and obtained a central estimate of US$0.79 million (in 2019 values) with low and high estimates of US$0.58 million and US$0.98 million.[44] We use price indices to adjust the numbers to 2015 values of US $0.72 million (US$0.54−0.90 million). We also quantify the monetary benefits of GHG mitigation using the social cost of carbon (SCC, the marginal global societal cost of emitting an additional ton of CO_2).[45] The central value for SCC used by the Obama administration was US$50 per tonne of CO_2,

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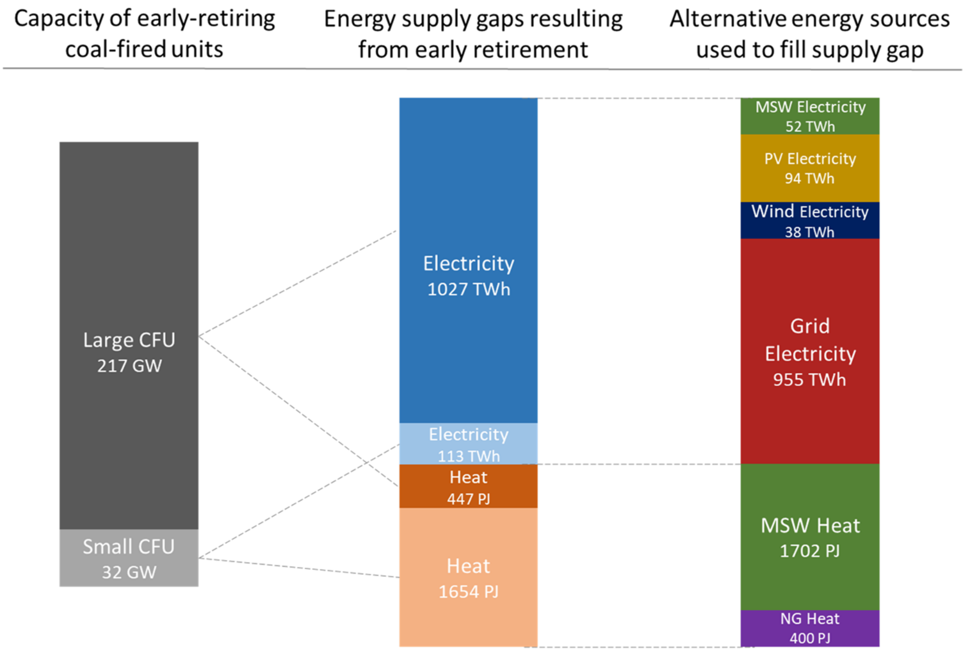

Figure 3. Energy supply transition in the Mitigation Scenario relative to the Baseline Scenario. CFU, coal-fired units; MSW, municipal solid waste; PV, photovoltaic; and NG, natural gas.

Table 2. GHG and Air Pollutant Emission Changes in the Mitigation Scenario (MS) Relative to the Baseline Scenario (BS)[a]

indicator	BS onsite emissions (Mt)	MS onsite emissions (Mt)	(MS-BS) onsite emissions (Mt)	(MS-BS) upstream emissions (Mt)	(MS-BS) total emissions (Mt)	(BS-MS)/BS mitigation (%)
GHG	1856	734	−1121	353	−768	41
SO_2	1.845	0.709	−1.136	0.378	−0.758	41
NO_x	2.357	1.105	−1.252	0.490	−0.762	32
$PM_{2.5}$	0.332	0.121	−0.211	0.069	−0.142	43
PM_{10}	0.387	0.145	−0.242	0.122	−0.120	31
VOC	0.027	0.019	−0.0081	0.0078	−0.00032	1.2

[a]Note: (MS-BS) denotes the difference between the Mitigation and Baseline Scenarios. The greenhouse gas (GHG) metric is million ton CO_2 equivalent that converts CH_4 and N_2O into CO_2 equivalents using 100-year global warming potentials of 28 and 265, respectively, according to the Intergovernmental Panel on Climate Change report Climate Change 2013: The Physical Science Basis. VOC = volatile organic compounds.

which may be modified significantly upwards to US$100−200 based on a more comprehensive evaluation of climate damages.[46] We therefore consider a range of SCC values to evaluate the uncertainty underlying the SCC monetization.[47] We apply low and high estimates (in 2020 values) of SCC from the US Interagency Working Group 2021 official guidelines,[48] using the average (US$51) and 95th percentile (US$152) of SCC with a discount rate of 3%. We use price indices to convert them to 2015 values of US$47−139 with a median of US$93.

3. RESULTS

3.1. GHG and Air Pollutant Emission Reductions. In the Mitigation Scenario, we customize early-retirement schedules for onsite large- and small-capacity coal-fired units based on their vintage years and remaining lifetimes, and parameterize the deployment of MSW-to-energy and renewable energy in 850 industrial parks considering industrial park locations, maximum available MSW quantities, and solar and wind resources. In the Mitigation Scenario, early retirement of coal-fired power/heat/CHP units results in a significant gap in energy supply, equal to 62 and 72% of total electricity and heat supplied in the Baseline Scenario (detailed in Supporting Information, Dataset). Alternative energy sources include MSW, solar and wind power, natural gas, and grid electricity (Figure 3). We optimize the priorities of these alternatives to maximize GHG mitigation opportunities, that MSW-to-energy and renewable energy are first used to fill the gap with supplements of grid electricity and natural gas-based heat. The installed capacity of MSW-to-energy, PV, and wind power increases from 2.4, 1.4, and 0.3 GW in 2014 to 35, 111, and 17 GW in the 2030 Mitigation Scenario, respectively (Table 1). MSW-to-energy, PV, and wind power annually supply 52, 94, and 38 TWh, respectively, of electricity in the Mitigation Scenario (Figure 3). Specifically, Shandong, Jiangsu, Inner Mongolia, and Zhejiang account for 14, 10, 8, and 7%, respectively, of total coal power capacity that is retired early, and they collectively need to deploy 51, 43, and 51% of total additional capacity of MSW-to-energy, PV and wind power, respectively (detailed in Table S1 and Supporting Information, Dataset). 84% of the electricity generation gap is filled by grid electricity with onsite use of MSW, PV, and wind responsible for 16%. We use a conservative 2030 grid electricity mix[27] including 57% of electricity from coal (currently 63% in 2020) and 26% from renewables (hydro, 14%; solar, 5%; wind, 7%). For comparison, solar and wind power account for 3.4 and 6%, respectively, of the 2020 grid electricity mix; thus, the 2030 grid electricity mix we use is highly achievable.[14] The heat

MS - BS	Onsite emission			Upstream emission				
	MSW incineration	NG combustion	Coal combustion	PV power	Wind power	Grid power	NG production	Coal production
GHG (Mt)	96 (5.2%)	24 (1.3%)	-1241 (-67%)	6.3 (0.3%)	1.1 (0.1%)	581 (31%)	8.7 (0.5%)	-244 (-13%)
SO_2 (kt)	151 (8.2%)	0.8 (0.04%)	-1288 (-70%)	37 (2.0%)	4.2 (0.2%)	687 (37%)	10 (0.5%)	-360 (-20%)
NO_x (kt)	437 (19%)	19 (0.8%)	-1708 (-72%)	18 (0.7%)	3.3 (0.1%)	704 (30%)	10 (0.4%)	-244 (-10%)
$PM_{2.5}$ (kt)	23 (6.9%)	0.3 (0.1%)	-234 (-71%)	4.7 (1.4%)	1.0 (0.3%)	88 (27%)	0.9 (0.3%)	-26 (-7.8%)

-1708 704

Figure 4. GHG and air pollutant emission changes in the Mitigation Scenario (MS) relative to the Baseline Scenario (BS) by energy sources. (MS-BS) denotes the difference between the Mitigation and Baseline Scenarios. Numbers in parentheses indicate % changes relative to onsite emissions of each species in the Baseline Scenario.

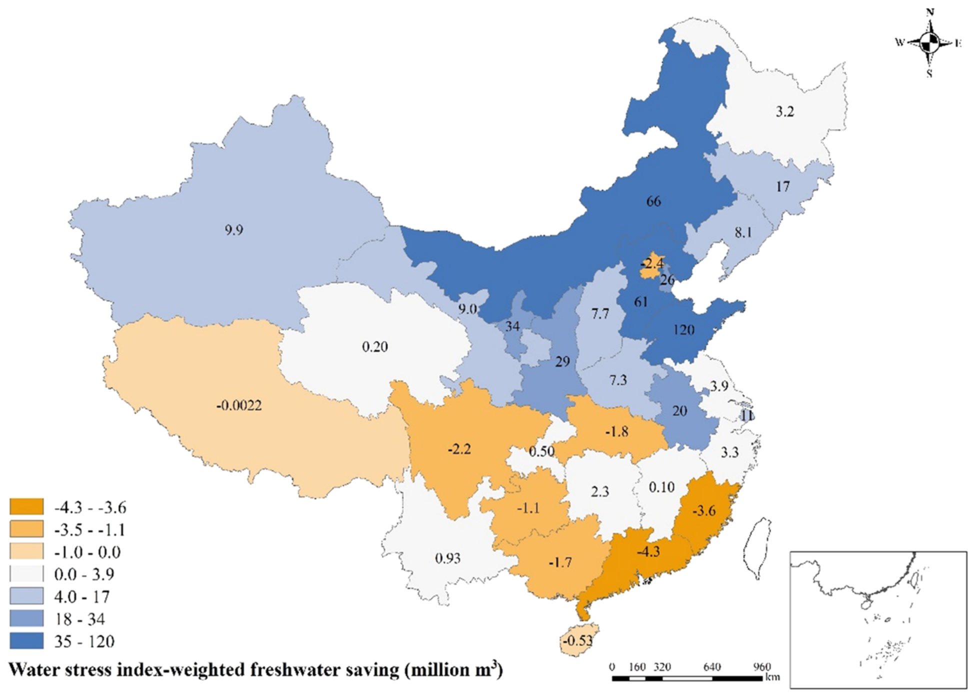

Figure 5. Water stress index-weighted freshwater consumption reductions in the Mitigation Scenario compared to the Baseline Scenario. The water stress index (WSI = local freshwater withdrawal/renewable freshwater availability) is a weighting factor to incorporate the heterogeneity of water scarcity across provinces.[51] Orange/blue indicates increased/decreased freshwater consumption.

supply gap is primarily filled by MSW-driven incinerators (81%) complemented by NG-fired boilers (19%).

The Mitigation Scenario reduces total life-cycle emissions of GHG, SO_2, NO_x, $PM_{2.5}$, and PM_{10} by 31−43%, compared with the Baseline Scenario. Specifically, the Mitigation Scenario decreases onsite emissions of the above species from onsite fuel combustion by 53−64% relative to the Baseline Scenario, while increasing offsite emissions resulting from changes in energy-related upstream processes, equal to 19−32% of the baseline onsite emissions (Table 2). Total net GHG emission reductions of decarbonizing industrial parks are equivalent to ~7% of China's GHG emissions in 2014.[49] As we employ the 2030 grid electricity mix that is still relying substantially on coal, reductions in GHG and air pollutant emissions derived in the Mitigation Scenario may be conservative. Shandong, Jiangsu, Zhejiang, and Inner Mongolia account for ~50% of total GHG mitigation occurring in the Mitigation Scenario relative to the Baseline Scenario (17, 13, 8, and 8%, respectively, for each province). Thus, these four provinces are desirable early candidates for a clean energy transition of industrial parks to achieve the majority of carbon mitigation benefits. See detailed results in Table S1 and Supporting Information, Dataset.

We further analyze emission changes of GHG, SO_2, NO_x, and $PM_{2.5}$ based on energy sources as shown in Figure 4. The Mitigation Scenario reduces onsite coal combustion and as a result, onsite emissions of the species by ~70% compared to the Baseline Scenario. Additional consumption of MSW and NG increases onsite emissions of the species by 6−19% of the baseline onsite emissions. For upstream emissions, however, the Mitigation Scenario increases the use of grid electricity and thus leads to additional emissions from the power sector of 27−37% of the baseline onsite emissions. Upstream emissions from manufacturing and installation of PV and wind power as well as NG production also increase by 1−3% of the baseline onsite emissions, while upstream emissions from coal

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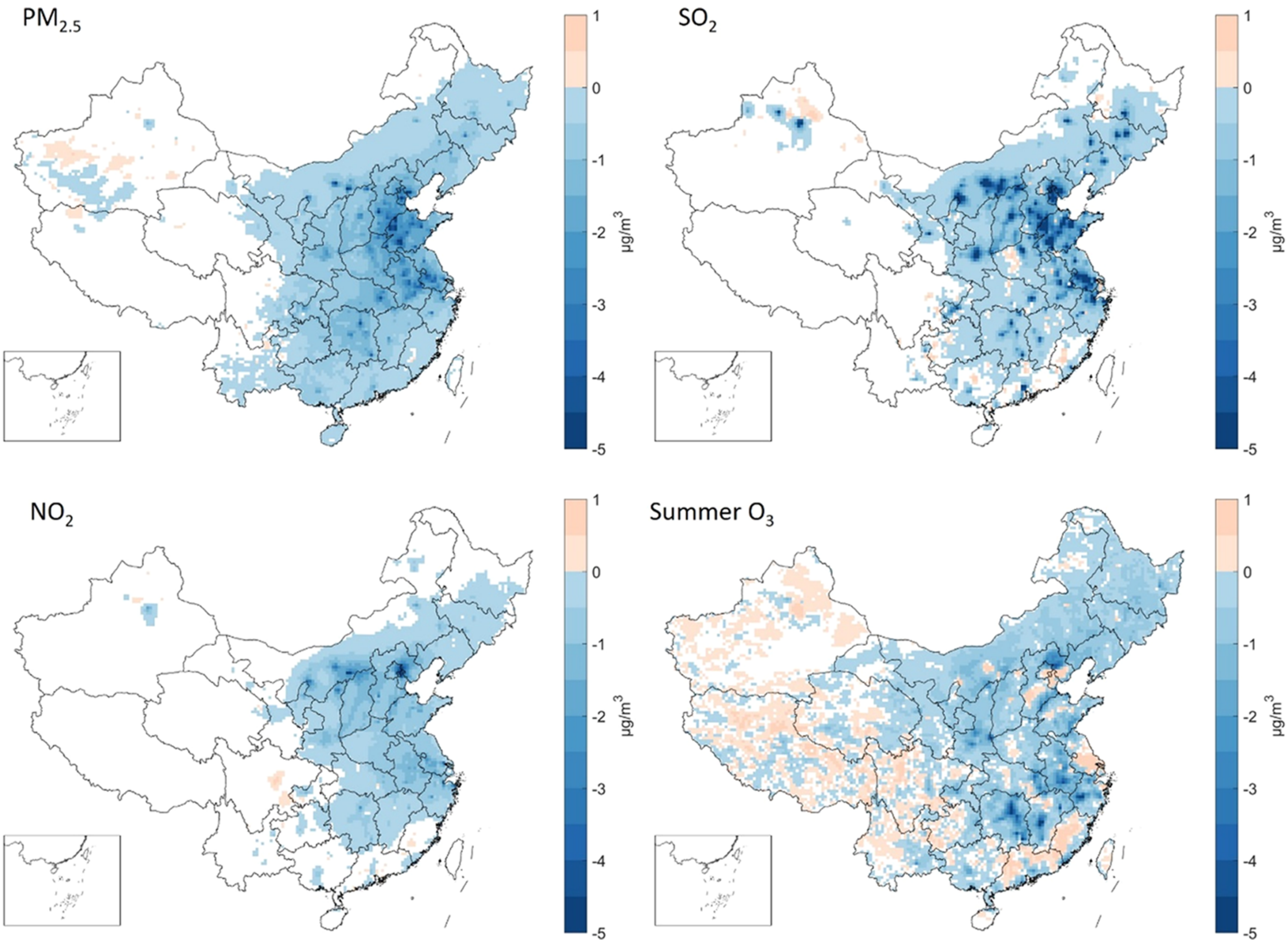

Figure 6. Air pollutant concentration changes in the Mitigation Scenario relative to the Baseline Scenario. Annual $PM_{2.5}$, SO_2, and NO_2 concentration changes are the average of those in January, April, July, and October. Summer O_3 concentration changes are represented by the July simulations. Changes within (−0.1, 0.1) $\mu g/m^3$ are shown as white.

production drop by 8−20%. Detailed results of the energy supply transition and emission changes are presented in the Supporting Information, Dataset.

3.2. Freshwater Conservation. The clean energy transition for industrial parks brings large co-benefits in freshwater conservation as replacement of coal-fired units substantially reduces freshwater consumption (the portion of freshwater withdrawal that is not returned to the original water source). The Mitigation Scenario requires 1210 million m^3 less onsite freshwater consumption than the Baseline Scenario. However, upstream freshwater consumption increases by 670 million m^3 mainly due to increased reliance on grid electricity. Thus, the Mitigation Scenario delivers total life-cycle freshwater savings of 540 million m^3 (20%) compared to the Baseline Scenario.

We locate freshwater consumption changes from upstream energy processes in the Mitigation Scenario to provinces where freshwater consumption physically occurs, according to provincial production levels[13] of coal, NG, thermal power, and PV panels (see Table S2). Upstream freshwater consumption required for wind power is attributed to provinces where additional wind turbines are deployed. As a result of high transport costs and resulting limited transport distances of equipment (such as nacelles) and building materials (such as concrete and steel), environmental impacts related to wind turbine manufacturing are primarily located in provinces where wind power is deployed.[50]

In the Mitigation Scenario, most northern provinces reduce their freshwater consumption with the largest reductions in Shandong (−28%), Inner Mongolia (−16%), and Hebei (−14%) contributing ∼60% of total water stress index (WSI)-weighted water savings (Figure 5). Additionally, Shanxi and Inner Mongolia dramatically reduce their provincial freshwater consumption for industrial parks by 82 and 46%, respectively, in the Mitigation Scenario compared with the Baseline Scenario. Water-rich provinces generally increase their provincial freshwater consumption for industrial parks, especially in Sichuan (+101%), Hainan (+53%), Fujian (+44%), and Guizhou (+40%). Such geographic distribution of freshwater conservation matches the availability of water resources.

For a given province, reductions in onsite freshwater consumption (primarily for cooling) depend on the capacity of early-retired coal-fired units in the industrial parks of the province. Variations in upstream freshwater consumption depend on increases in thermal power generation for grid electricity versus decreases in coal mining and processing in the province. Northern provinces host a slightly higher share (54 and 56%) of total early-retired coal power and total added thermal power generation, respectively, than southern

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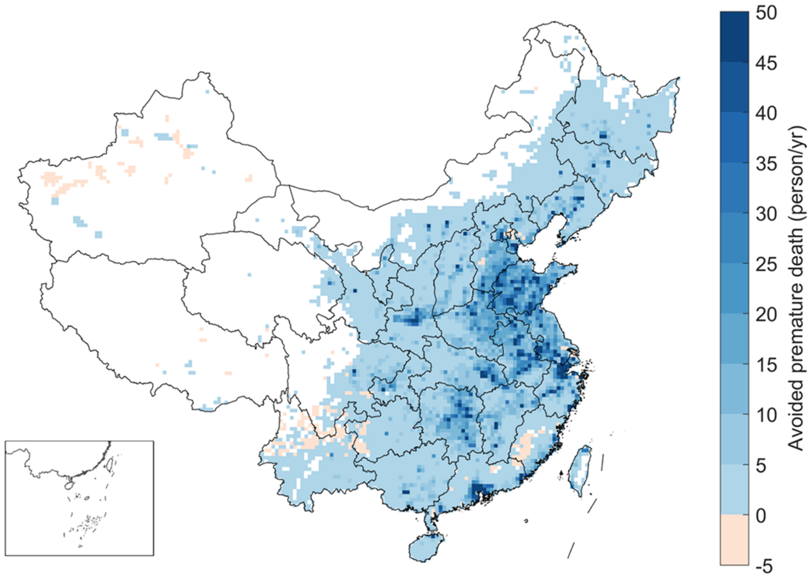

Figure 7. Avoided premature deaths attributable to reductions in $PM_{2.5}$ and O_3 concentrations in the Mitigation Scenario relative to the Baseline Scenario. Changes within (−0.1, 0.1) are shown as white.

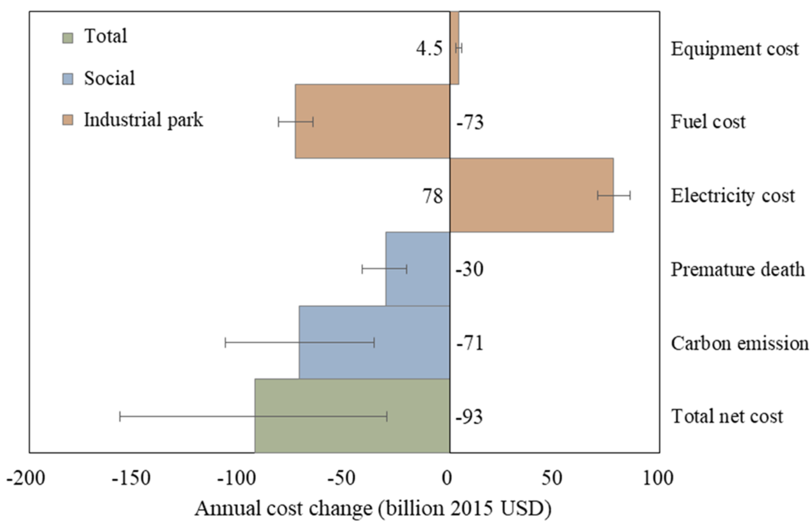

Figure 8. Annual cost changes of Mitigation Scenario relative to Baseline Scenario.

provinces (46 and 44%) due to older coal-fired units and larger coal power capacity in the north. Meanwhile, northern provinces have a much higher share (85%) of total decrease in coal production than southern provinces (15%), with Shanxi (26%), Inner Mongolia (24%), and Shaanxi (14%) each accounting for a substantial fraction of the total decrease. Thus, northern provinces have slightly larger onsite freshwater consumption reductions and much larger upstream freshwater consumption reductions than southern provinces, resulting in greater total water savings in the north than the south. Given that northern provinces suffer more from water scarcity than southern provinces, this is particularly advantageous.

3.3. Air Quality Improvements and Health Benefits. The Mitigation Scenario provides air quality improvements and health benefits compared to the Baseline Scenario (Figures 6 and 7). Population-weighted $PM_{2.5}$, SO_2, and NO_2 concentrations decrease by 1.13 ± 0.44 (2%), 1.52 ± 0.62 (4%), and 0.50 ± 0.31 $\mu g/m^3$ (2%) in the Mitigation Scenario relative to the Baseline Scenario. Geographically, several densely populated and industry-intensive provinces contribute disproportionately to the air quality improvements, as population-weighted $PM_{2.5}$ concentrations in the Mitigation Scenario decrease more than average in Tianjin (−3.60 $\mu g/m^3$; −3%), Shandong (−2.41 $\mu g/m^3$; −3%), Hebei (−2.23 $\mu g/m^3$; −2%), Anhui (−2.09 $\mu g/m^3$; −3%), and Jiangsu (−1.86 $\mu g/m^3$; −3%). These five provinces have 24% of national population and 30% of industrial parks while including only 6% of national land area.[52] Reductions in population-weighted SO_2 concentrations are larger than $PM_{2.5}$ concentration reductions and the Mitigation Scenario reduces population-weighted SO_2 concentrations by more than 5% in 10 provinces, e.g., Zhejiang (−11%), Inner Mongolia (−9%), Jilin (−8%), Tianjin (−8%), and Jiangsu (−8%). Reductions in NO_2 concentrations are less than SO_2 reductions at the provincial level. Meanwhile, the reduction in population-weighted summer O_3 concentrations is 0.31 $\mu g/m^3$ (0.2%). Changes in summer O_3 concentrations vary across provinces (from −1 to 1%) and exhibit a slight overall decline, partly due

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to increased O_3 production efficiency resulting from decreased NO_x emissions and partly due to tiny VOC emission reductions from the clean energy transition. Provincial air quality improvements are detailed in Table S3.

We derive avoided premature deaths and years of life lost (YLL) resulting from reduced noncommunicable diseases and lower respiratory infections due to changes in $PM_{2.5}$ and O_3 concentrations. About 42,000 (95% confidence interval (CI): 37,811−46,061) annual premature mortalities are avoided nationally in the Mitigation Scenario relative to the Baseline Scenario. Reductions in $PM_{2.5}$ concentrations bring 87% of avoided premature deaths (36,809; 95% CI: 34,537−38,891), while reductions in O_3 concentrations reduce premature deaths by 13% (5461; 95% CI: 3274−7170). Five key provinces benefit most (42%) from reductions in $PM_{2.5}$-attributable premature mortalities, including Shandong (∼2700 persons), Jiangsu (∼2200), Anhui (∼1600), Henan (∼1500), and Hebei (∼1400). We further estimate ∼320,000 avoided YLL annually resulting from the avoided premature deaths in ages from 25 to 80 years old (95% CI: 288,474−344,123). Provincial health benefits are shown in Table S4. Decarbonizing industrial parks has spatially heterogeneous health benefits with nearby communities benefiting most.

3.4. Cost and Benefit Changes. We quantify the variations in technical costs and social benefits of the Mitigation Scenario compared with the Baseline Scenario (Figure 8 and Table S5). Total net benefits are US$93 (30−156) billion annually. Annual equipment costs of US$3.1−5.9 billion are tiny relative to other costs due to amortization over a long service lifetime. Fuel cost savings of US$65−82 billion mainly resulting from coal consumption reductions accrue to industrial parks and their enterprises. Cost−benefit analyses include additional NG fuel costs for heating and costs of retrofitting coal-fired boilers to burn NG. We also include government subsidies for MSW treatment and costs of constructing new MSW incinerators. Parameterizations are provided in the Methods section and Table S6. However, early retirement of coal-fired facilities within industrial parks results in increased purchase of grid electricity, adding electricity costs by US$70−86 billion. Total costs to industrial parks are US $−8−27 billion annually. This indicates decreasing renewable energy costs will reduce the costs for purchasing grid electricity and deploying PV and wind power, thus making industrial park costs negative. Annual monetized societal benefits include avoided premature mortalities (US$20−41 billion) and carbon mitigation (US$36−107 billion), delivering total societal benefits of US$57−148 billion. Thus, social benefits outweigh industrial park costs by a substantial margin of US$30−156 billion. Given the total GHG mitigation of 768 million tons CO_2 equivalent, the economic benefit per ton of GHG reduction is US$39−204. Including these social benefits in overall cost-effectiveness, the clean energy transition justifies its widespread deployment in China's industrial parks, simultaneously delivering environmental, health, and monetary benefits.

4. DISCUSSION

4.1. Policy Implications. Industrial parks are emerging globally as a way to collectively engage industrial activities, thus becoming hotspots of carbon and air pollutant emissions and freshwater consumption. Few studies have focused on the environmental benefits of decarbonizing industrial parks at either a holistic or high-resolution level.[2,3] Our earlier work primarily explored the effectiveness of efficiency improvement and coal-to-natural gas measures for energy infrastructure in industrial parks.[10,53] This study analyzes the carbon and environmental benefits of deploying onsite waste-to-energy and renewables as well as using grid electricity to decarbonize the energy supply in industrial parks. We use both life-cycle and trans-boundary perspectives to quantify onsite and upstream environmental impacts on carbon emissions, air quality, public health, and freshwater consumption. Air quality-related impacts, in particular, reach beyond industrial parks and are transported to surrounding communities and provinces.

This study provides implications for policy making regarding industrial parks. First, decarbonizing energy supply in industrial parks can reduce more than 40% of GHG emissions by replacing coal-fired units with a variety of alternative energy sources including onsite MSW-to-energy, rooftop PV, distributed wind power, and grid electricity. By doing so, industrial parks can decompose municipal solid waste generated by themselves and surrounding communities; rooftops as well as inner- and inter-factory space can be utilized for distributed renewables. These alternative energy sources can be networked by micro power grids customized for industrial parks. Such direct supplier-consumer linkages enable practical solutions to efficiently meet high-level energy demands in industrial parks.

Second, we demonstrate that decarbonizing industrial parks induces changes in impact-intensive upstream processes, e.g., decreasing coal mining due to coal consumption reductions in industrial parks, and increasing coal combustion embodied in purchased grid electricity as coal-fired units within industrial parks are retired early. We find that 84% of the electricity supply gaps resulting from the early retirement of coal-fired units needs to be filled by the power grid, while the remaining 16% can be supplied by MSW-to-energy, rooftop PV, and distributed wind power. The heat supply gaps can be filled by onsite MSW-to-energy (81%) and natural gas-based heat (19%). Thus, how rapidly the power grid decarbonizes is crucial in determining the actual decarbonization levels of industrial parks. The clean energy transition provides additional health benefits including reductions in mercury, a health-damaging heavy metal, whose emissions are reduced by phasing out coal. Also, MSW-to-energy reduces heavy-metal emissions relative to coal combustion, and dioxin emissions that result from plastic combustion are stringently limited with end-of-pipe controls.[26] Overall, the clean energy transition delivers substantial environmental co-benefits for air quality, public health, and freshwater conservation, and also brings net economic benefits when social benefits are considered in addition to technical costs.

Third, we find that it costs China's industrial parks US$−8−27 billion annually to implement the clean energy transition considering the amortization of equipment costs and changes in fuel and electricity costs, but results in total societal benefits of US$57−148 billion annually due to avoided premature mortalities and GHG emission reductions. Therefore, incentives and subsidies to industrial parks to defray their clean energy transition costs are necessary to drive the deployment of onsite waste-to-energy and distributed renewables with the gradual coal phase-out. This necessitates policies establishing micro power girds in industrial parks to enable effective and reliable integration of electricity from MSW incineration, rooftop PV, and distributed wind power. As onsite renewables and waste-to-energy take over the role of

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coal power in industrial parks, there will be opportunities to transfer workers from coal power plants to these alternative energy facilities to avoid employment losses. However, coal power phase-out will result in changes in industrial symbiosis networks,[54] such as a reduction in the availability of coal combustion ash for cement production, which at present is widely used across China.[55] Such indirect effects of the clean energy transition require further analysis and quantitative identification of alternatives. Currently, we include changes in upstream emissions such as those resulting from reduced coal and additional NG uses, as described in the Methods section and the Supporting Information. Industrial parks' heat demand does not vary significantly with season, making them year-round consumers of waste-based heat.

Industrial parks can become suitable sites for distributed renewable energy and symbiotic linkages of waste-to-energy to feed their own energy demand. Incentives and policies to support decarbonizing industrial parks will facilitate the achievement of China's climate, air quality, and water targets and will provide social benefits. Industrial parks with a better environmental performance, such as those listed in the national eco-industrial park program,[56] can be pilots to demonstrate the clean energy transition with financial and policy supports from both central government and local administrations.

4.2. Uncertainty Analysis. We examine uncertainties in the reduction potential for GHG and air pollutant emissions (Supporting Information, Note 5). Variations in shortened lifetime of coal-fired units and in the carbon intensity of 2030 grid electricity lead to large uncertainties in emission reductions. Early retirement after 20 years of operation for coal-fired units (rather than a typical 30-year lifetime) within industrial parks allows full payback of capital costs of these units and is thus viewed as economically acceptable.[16,17] We also analyze the effects of using 2014 data (the latest available) rather than more current data (such as 2020). The scenarios target 2030, and early retirement of coal-fired units in the Mitigation Scenario shortens coal power lifetime from 30 to 20 years. That means only coal power units commissioned before 2010 are retired early. As we identify the carbon and air pollutant emission reductions based on the differences between the two scenarios, recently commissioned coal power units do not significantly affect our results.

Using grid electricity allows further decarbonization of industrial parks as the grid greens. This level of decarbonization would not be possible with onsite low-carbon energy transition alone because ∼30% of the 850 industrial parks are not located in places with adequate solar or wind resources to fully replace the early-retired coal power units. The 2030 electricity mix[27] we use includes 26% renewable generation and is considered highly achievable. Increased national efforts can accelerate decarbonization of the grid. Thus the speed of formulating national plans for phasing out coal in industrial parks and decarbonizing the electricity sector will be critical.

Another significant uncertainty arises from monetization in the cost−benefit analysis. As renewable energy costs continuously decrease, the costs for purchasing grid electricity and deploying PV and wind power will decrease accordingly, thus making annual industrial park costs (US$−8−27 billion) negative. In addition, monetary values of avoided premature deaths and carbon mitigation are also highly uncertain, as there are wide ranges of VSL[43] and SCC.[45] Here, we value VSL at US$0.72 (0.54−0.9) million[44] and SCC at US$93 (47−139) per ton of CO_2 equivalent.[48] As the Chinese economy grows, the value of a statistical life will increase, thus increasing the benefits of improving air quality. As understanding of impacts of climate change increases, the value of the social cost of carbon will likely increase as well. Thus, we employ the uncertainty ranges for monetization (Table S5).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c05725.

Parameterizations of MSW-to-energy, rooftop PV, and wind power deployment; characterization of grid electricity mix; sensitivity analyses; spatial allocation of upstream environmental impacts; inventory merging; validation of WRF-Chem simulations; health impact assessment approaches; and supplementary figures and tables (PDF)

Data of all figures and detailed data on China's industrial parks and their energy facilities; the other data used for this study are available from public data sources cited or from the authors upon reasonable request (XLSX)

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Author Contributions

Y.G., L.C., and D.L.M. conceived the research idea and designed the study; Y.G., J.T., and L.C. compiled the industrial park emission inventory and analyzed the clean energy transition; Y.G. estimated the life-cycle emission reductions and freshwater conservation, conducted WRF-Chem simulations, calculated the health benefits, and performed the cost-benefit analyses; M.Z. helped process the emission inventory and facilitated the WRF-Chem simulations and health calculations; L.P. contributed to the health impact assessment; J.Y. contributed to the PV and wind power parameterization; M.L. contributed to the emission inventory processing; and Y.G. and D.L.M. wrote the paper with contributions from all authors.

Notes

The authors declare no competing financial interest.

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