Cleaner Energy Systems 15 (2026) 100282

Contents lists available at ScienceDirect

Cleaner Energy Systems

journal homepage: www.elsevier.com/locate/cles

Co-benefits of residential heat electrification through interstate grid interconnections in Northeast Asia

Haein Kim [a,*], Tracey Holloway [b,c], Peter Rafaj [d], Zbigniew Klimont [d], Gregor Kiesewetter [d], Jonathan A. Patz [b,e]

[a] Center for International Studies, Program for Integrated Assessment Modeling, Yonsei University, Seoul, South Korea
[b] Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI, USA
[c] Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI, USA
[d] International Institute for Applied Systems Analysis, Laxenburg, Austria
[e] Department of Population Health and Sciences, University of Wisconsin-Madison, Madison, WI, USA

ARTICLE INFO

Keywords:
Heating electrification
Grid interconnections
Low carbon transitions
Air quality
Public health

ABSTRACT

This study examines the potential ambient air quality and associated human health co-benefits of residential heating electrification powered by the Asia Supergrid, which connects the China-North, Korea, and Japan-West regions. By linking a bottom-up power sector optimization model and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, we assessed the impacts of the complete removal of fossil fuels from residential heating by 2050, replaced by clean electricity supply through carbon pricing and cross-border electricity transmission. Our results show that the locations of clean energy transitions and health benefits do not necessarily coincide. Power trade redistributes generation and associated emissions between exporting and importing regions, resulting in heterogeneous transboundary air quality and health outcomes that can be obscured by national or regional averages. Combined residential and power sector decarbonization prevents 1600–15,500 premature deaths depending on the electricity generation mix. We found that renewable electricity generation is important in maximizing the co-benefits of end-use electrification, yielding higher health benefits than a carbon-neutral electricity supply based on carbon capture and sequestration and hydrogen. These findings highlight the importance of considering the spatial distribution of health co-benefits in designing regional energy cooperation and coordinated decarbonization strategies.

1. Introduction

Globally, residential heating relies on fossil fuel combustion in stoves and boilers, which results in health-relevant air emissions and climate-relevant carbon dioxide (CO_2). The combustion of coal, oil, and natural gas is used for residential heating, emitting nitrogen oxides (NO_x), sulfur dioxide (SO_2, mainly from coal), particulate matter (PM, mainly from coal and oil), and other health- and climate-relevant compounds (Xue et al., 2016). Despite a relatively small contribution to national energy consumption, the high emission factors in the residential sector have a large potential for health benefits from electrification (Shen et al., 2019).

Over the past decade, air quality in East Asia has significantly improved owing to air pollution control policies. In China, initiatives such as the Air Pollution Prevention and Control Action Plan (2013–2017) and the Blue-Sky Protection Campaign have reduced the national average $PM_{2.5}$, by >40% since 2013 (Q. Zhang et al., 2019), while Korea and Japan have also implemented emission standards and seasonal fine dust management programs (Ito et al., 2021; Yeo et al., 2025). Despite this progress, achieving further improvements in air quality requires more targeted efforts (Zhao et al., 2024). Unlike large-scale power plants or industrial facilities, where pollution controls can be directly installed, residential heating cannot be controlled using emission control technologies. Rather, broader changes to the energy system are required, with electrification offering a pathway to move distributed fuel combustion toward centralized, controlled, and/or non-emitting energy sources.

Residential heating is a significant and challenging source of air pollution in East Asia. As of 2021, coal accounted for approximately 20% of the heating needs in China, with solid biomass in rural areas (Du et al., 2023; OECD and International Energy Agency, 2022; Sarigiannis

* Corresponding author.
E-mail address: haein.kim@yonsei.ac.kr (H. Kim).

https://doi.org/10.1016/j.cles.2026.100282
Received 9 June 2026; Received in revised form 24 August 2026; Accepted 19 September 2026
Available online 20 September 2026
2772-7831/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Nomenclature

CCS	carbon capture and sequestration
CN—N	China-North
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
JP-W	Japan-West
KR	Korea
NEA	Northeast Asia
NNT0	Baseline scenario
$PM_{2.5}$	Fine particulate matter with aerodynamic diameter $\leq$2.5 μm
STEPS	Stated Policies Scenario
NO_x	Nitrogen oxides
SO_2	Sulfur dioxide
CO_2	Carbon dioxide

et al., 2014). Studies identify the residential sector as the main contributor to air pollution in Northern China (Kuerban et al., 2020; Liu et al., 2016; Peng et al., 2018), prompting the adoption of electrification policies aimed at replacing coal-based heating. These include large-scale programs covering Beijing, Tianjin, and 26 other cities with pilot projects targeting the substitution of up to 60% of household coal with clean fuels and electricity by 2021 (Yang et al., 2023). Natural gas and oil comprise approximately 50% of the energy mix for residential space heating in Japan and Korea, with high rates of electrification and heat pump adoption. Although heat pumps are installed in approximately 90% of households, nearly half are mainly used for cooling, with gas boilers remaining the primary heating source owing to high electricity prices (Maeyama, 2020). China, Japan, and South Korea are major manufacturers in the heat pump industry, with a higher potential for domestic sales to meet heating needs than North America and the European Union (OECD and International Energy Agency, 2022).

The air quality and health benefits of sectoral electrification have been found to depend on the characteristics of the electricity system (Guo et al., 2024; Mac Kinnon et al., 2021; Peng et al., 2018). In this study, we evaluate the potential role of grid interconnections in supporting cleaner electricity. In Northeast Asia (NEA), defined here as China, South Korea, and Japan, >60% of electricity is produced from fossil fuels (International Energy Agency, 2020). Grid interconnections can increase generation efficiency and support more ambitious renewable energy deployment by enabling a cross-border electricity trade that mitigates variability and reduces curtailment (Kim, 2023; Kim and Jung, 2023). Evidence from Europe, where the world's largest interconnected grid facilitates a cost-effective transition to a clean power system (Cremona, 2023), suggests that energy cooperation through inter-regional power trade in Northeast Asia could similarly accelerate decarbonization across interconnected systems.

Few studies have investigated the health impacts of heating electrification in NEA. Existing studies have focused predominantly on China's heating transition, with large uncertainties in the magnitude of future benefits depending on the study design, baseline assumptions, and other factors. Peng et al. (2018) compared different levels of decarbonization in electricity generation for residential heating electrification in 2030 and found that a 30% coal removal in residential heating in the North China Plain region leads to air quality improvement by 6–8 μg/m3 (8–11%). Ma et al. (2023) found that carbon neutrality in rural cooking and heating would reduce $PM_{2.5}$ concentrations by 1.9–5.4 $\mu g/m^3$ in northern China by 2050, in a study that used the Greenhouse gases and Air pollution Interactions and Synergies (GAINS) model (Ma et al., 2023).

At the regional scale, transboundary transport produces shared and asymmetric benefits: China's emission reductions improve air quality in Korea and Japan, whereas its own benefits depend mainly on domestic action (OECD and IIASA, 2022), and the Chinese contribution to ambient $PM_{2.5}$ in South Korea is substantial and strongly seasonal, peaking in winter (Kumar et al., 2021). Although relative contributions have likely declined with recent air quality gains, these changing dynamics remain important for assessing the incremental co-benefits of coordinated regional decarbonization.

This study frames grid interconnection and carbon pricing as instruments of cleaner production in the power sector, reducing fossil generation while expanding renewable capacity, and examines the public health synergies that arise when residential heating is electrified through this cleaner electricity supply. The framing rests on a central distinction. Evaluated solely by climate outcomes, technologies such as carbon capture and sequestration (CCS) constitute viable transition options in transitioning into carbon neutrality; once health effects are considered, however, carbon-neutral and clean-air pathways are therefore not interchangeable. While residual combustion under CCS continues to emit health-relevant air pollutants, we quantify the conditions under which cross-sectoral coupling yields additional air quality improvements rather than carbon neutrality alone or a spatial redistribution of emissions.

The primary objective of this study is to quantify how residential heating electrification and cross-border grid interconnection jointly affect air quality and public health in Northeast Asia, and how these co-benefits depend on the decarbonization pathway of the electricity supply. We examine China-North, Korea, and Japan-West under alternative heat-electrification, power trade, and carbon pricing scenarios for 2030 and 2050.

To address the questions, we soft-linked a bottom-up power sector optimization model with the GAINS air quality model. The power system model represents hourly and monthly variations in electricity demand using 288 representative hourly time slices (24 h for a representative day in each month), derived from observed hourly load profiles. This temporal representation captures both intra-day load dynamics and month-to-month variations in heating demand, including winter peak loads and the associated generation responses. Power and residential sector fuel use changes are subsequently transferred to GAINS at the subregional level to quantify changes in ambient $PM_{2.5}$ concentrations and associated premature mortality. This integrated framework therefore links the temporal dynamics of heating electrification and power system operation with the spatial distribution of air quality and health impacts, allowing us to identify whether regional electricity cooperation creates uneven local health benefits that may be masked by national or regional averages. The remainder of this paper is organized as follows. Section 2 describes our modeling approach for linking the power system and air quality analysis models. Section 3 elaborates on the short- and long-term sectoral contributions to emission reductions of SO_2, NO_X, and $PM_{2.5}$ with different decarbonization strategies and their air quality and health impacts. Finally, Section 4 presents the conclusions of this study.

2. Methods

2.1. Method and scenarios

We adopted an integrated approach to assess the air quality and health impacts of cross-sectoral clean heat transitions by linking the power supply and air quality models (see Fig. 1 for the input-output flow of the integration framework). To assess the fuel use changes in the power and residential sectors with clean heat transitions, we first estimated the additional electricity demand associated with the electrification of residential heating. This incremental demand was then distributed over the historical load curve of residential heating activities. Building on the bottom-up optimization model by Kim (2023), which identifies the least-cost combination of generation technologies for an hourly power supply under various technology-specific and system-level constraints, we extended the analysis to incorporate future

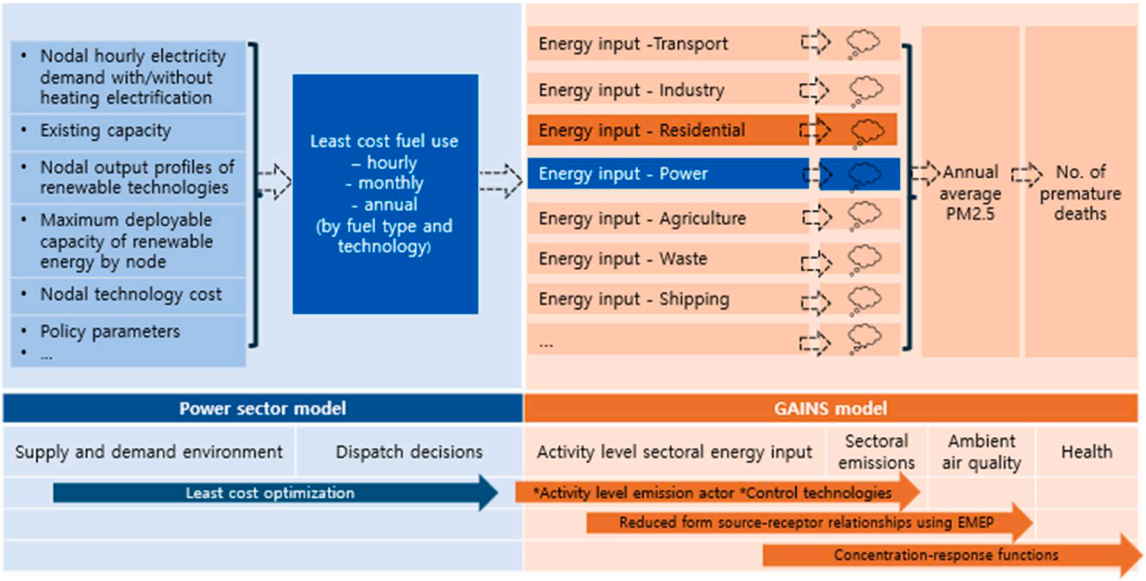


Fig. 1. Input–output flow of the multi-model integration framework. Schematic overview of the integrated modeling framework linking a bottom-up power sector optimization model with the GAINS air quality model. The power sector determines least-cost electricity generation and fuel use under heating electrification scenarios, which are translated into sectoral energy inputs for GAINS to estimate emissions, ambient $PM_{2.5}$ concentrations, and associated premature deaths.

demand scenarios with end-use electrification.

The power sector model uses regional energy information—such as existing system capacity, technology costs, maximum allowable renewable capacity, and hourly renewable output profiles—to determine the least-cost combination of power generation and storage technologies subject to technical constraints that reflect system operations and policy regulations. Fuel consumption estimated by the power-sector model, based on trends from the IEA Stated Policies Scenario (STEPS), is then fed into the GAINS model. Considering future changes in activities and associated emission factors (that change due to continued improvement of energy efficiency and introduction of further abatement measures to comply with national legislation), the GAINS model projects emissions of air pollutants and calculates the annual average concentration of $PM_{2.5}$ and the number of premature deaths for the corresponding GAINS regions (Amann et al., 2008).

To evaluate the contribution of the residential and power sectors to regional air quality and public health, we developed 12 scenarios (see Table 1). The scenarios vary by region-specific transition pathways in the residential heating sector and power supply mode (power trade vs. independent supply) at three carbon price levels.

Residential heating transitions are represented by full electrification of the remaining fossil fuel based heating demand via heat pump adoption, replacing the remaining fossil fuel use in residential heating embedded in the STEPS baseline for each year between 2025 and 2050. For power sectors, we expected carbon pricing to reflect increasingly stringent climate policies and influence the relative cost competitiveness of electricity generation technologies. We applied 0, 100, and 200 USD/tCO_2, which spanned the conservative to moderately stringent policy conditions (AMRO, 2023; IEEFA, 2025). These values allowed us to explore how increasing emission penalties affect the relative cost competitiveness of generation technologies and power trade dynamics among three countries and redistribute the associated air quality and health co-benefits. The combination of inter-regional power transmission with carbon pricing is expected to further contribute to regional air quality improvement by encouraging clean energy investments, making renewable electricity generation cheaper and available to regions where renewables are more expensive and/or unreliable. We report results for 2030 and 2050 to distinguish near-term transition effects from long-term decarbonization outcomes. The 2030 results capture system and health responses while substantial fossil-fuel use remains in both residential heating and electricity generation, whereas 2050 represents the endpoint of the assumed full electrification of remaining fossil-fuel-based residential heating and coincides with the carbon neutrality target year for Korea and Japan in the power sector model.

The STEPS assumptions used in our scenarios reflect the energy policies and policy proposals of 2021, including heat pump adoption rates and measures supporting their implementation (International

Table 1
Scenario formulations.

Final energy consumptions	Air pollution policies	Residential		Power		Scenarios
		Heat transitions	Region	Power supply	Carbon price	
IEA STEPS	Current legislations	Heat pump adoptions	All NEA (A)	Trade (T)	0	AT0
					100	AT1
					200	AT2
				No trade (NT)	0	ANT0
					100	ANT1
					200	ANT2
		No transition	All NEA (N)	Trade (T)	0	NT0
					100	NT1
					200	NT2
				No trade (NT)	0	NNT0 (baseline)
					100	NNT1
					200	NNT2

Energy Agency, 2022). For air pollution policies, we assumed full compliance with current national legislation, including emission limit values for power and industrial plants, as well as road vehicles and non-road machinery standards. For GAINS modeling, STEPS assumptions on energy input were spatially downscaled and applied to adjust the activity levels in all other emitting sectors. In GAINS, historical country data are disaggregated into provinces or subregions based on provincial statistics and the official statistical yearbooks of each country. The evolution of sub-regional shares in national totals over time was derived from earlier country-specific modeling studies. For power sector modeling, STEPS projections of annual electricity demand from 2015 to 2050 were used to endogenously determine the least-cost technology mixes in system capacity and power generation. In the heat transition scenarios, we included the additional electricity demand required to fully replace the remaining fossil fuel use in residential heating under the STEPS baseline. Solid biomass is represented in the underlying GAINS/STEPS residential energy baseline and follows its baseline trajectory over time. We do not impose an additional transition on biomass use. Accordingly, the estimated incremental air-quality and health effects reflect the replacement of fossil fuel heating relative to a baseline that already incorporates projected changes in biomass and other residential energy uses. Accordingly, STEPS serves as the policy baseline and the policy scenarios evaluated in this study measure the incremental effects of additional residential electrification, carbon pricing, and cross-country power trade beyond the energy and air pollution policy embedded in the baseline.

2.2. Power sector modeling

We adapted the bottom-up linear optimization model of Kim (2023) to compute fuel consumption in power generation under the electrification and grid-interconnection assumptions of each scenario. The model represents three nodes—the China-North grid, South Korea, and Japan-West—covering power supply, demand, and inter-regional transmission via ultra-high-voltage direct current. China's power market is divided into six subnational grids and Japan's into two, each balancing independently, while Korea operates as a single integrated market. The three interconnected grids are geographically close and contain key economic hubs, so they jointly represent substantial electricity and heating demand while sharing the air quality impacts of sectoral emissions.

The model captures node-specific energy-system characteristics using datasets at varying granularities. Hourly solar and wind output profiles, drawn from utility data and the literature (Korea Southeast Power, 2018; Korea Southern Power, 2019; Otsuki et al., 2016), simulate renewable generation at each node, subject to a node-specific maximum deployable capacity. Existing system capacity, derived from plant-level location data (Power Plant Tracker, 2018), determines capacity additions and fuel use over the study horizon. The model considers 24 generation technologies—including five CCS technologies and two storage options (pumped hydro and batteries)—with node-specific costs based on international datasets and the literature (Bogdanov and Breyer, 2016; De Vita, 2018; N. International Energy Agency, 2020).

The objective function minimizes total system cost—capital investment, fixed and variable O&M for generation, storage, and transmission, fuel cost, and a CO_2 emission penalty—subject to technical and policy constraints (Full formulation and variable definition in Kim, 2023; key information in SI section S1). We applied a uniform CO_2 price of 0, 100, or 200 USD/tCO2 across the three countries to test how emission penalties reshape technology cost-competitiveness, generation mixes, and trade dynamics. Key constraints follow Kim (2023) and include hourly supply–demand balance, generation and storage capacity limits, node-specific renewable potential and hourly profiles, thermal ramping limits, a 20% reserve margin, no new nuclear in Korea and Japan (only restart of suspended units), net-zero CO_2 by 2050 (KR, JP-W) and 2060 (CN—N), and a maximum interstate trade flow of 15% of hourly regional demand. These policy-relevant parameters reflect existing national plans or comparable interconnection targets such as the EU's (European Commission, 2017). The horizon spans 2015–2065 in 10-year steps, with 288 time slices (24 h × 12 months) per period to retain the temporal flexibility needed to resolve monthly and time-zone variation in residential activity (IEA, 2019).

To construct hourly load profiles, we used 8760 hourly demand records for 2019—the best available national data for the three countries (Harvard Dataverse, 2020; Korea Power Exchange, 2020; TEPCO, 2020)—and disaggregated them by sector following Castillo et al. (2022), whose SSP2 projections incorporate biophysical parameters such as temperature and irradiance to capture regional load variation. The resulting sector-specific hourly profiles (see S1 for detailed rationale and figure) were used to allocate the additional demand from electrifying the remaining fossil-fuel-based heating demand onto historical residential load shapes. We adopted a static allocation, holding the activity-level load shape fixed over time while inflating the residential heating load, given the limited availability of projections for future hourly demand-response behavior. This end-use representation lets the model reflect shifts in peak-demand hours and seasonal variation in hourly demand. Inter-regional transmission then enables more efficient low-carbon investment by exploiting cross-regional differences in resource availability and technology cost, reducing fuel consumption and emission penalties (Kim and Jung, 2023).

2.3. Air quality and health assessment

For air quality modeling, we used the GAINS model developed by the International Institute of Applied Systems Analysis (IIASA) (Amann et al., 2011). The model computes the emissions of SO_2, NO_X, carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (VOCs), $PM_{2.5}$ (including black carbon (BC) and organic carbon (OC)), and greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (Liu et al., 2019). To estimate ambient $PM_{2.5}$, GAINS applies a source-receptor relationship from the European Monitoring and Evaluation Program (EMEP) chemistry-transport model using a spatially explicit and sector-resolved emission inventory. The concentration fields incorporate contributions from primary anthropogenic $PM_{2.5}$, secondary inorganic aerosol formation from SO_2, NO_X and NH_3 emissions, and natural PM sources such as dust, sea salt, and biogenic emissions.

GAINS considers the activity levels (fuel consumption) of sectoral activities, emission factors, control technology options, and the implementation rate of emission controls for calculating emission projections by 2050 in 5-year steps (Höglund-Isaksson et al., 2020). To capture the concentration level of ambient $PM_{2.5}$ from anthropogenic emissions, grid concentrations were calculated separately for the urban and rural areas of each grid cell. While our focus was on ambient air quality rather than explicitly modeling indoor air pollution, we assumed that emissions from indoor residential combustion are directly emitted into ambient air, contributing to outdoor air pollution (Chafe et al., 2014; Du et al., 2023; Sarigiannis et al., 2014). GAINS has been widely applied in air quality analysis and has undergone extensive validation in previous studies (Kiesewetter et al., 2024). For our study, it is important to note that atmospheric calculations in GAINS rely on fixed 2015 meteorology; reported concentrations represent population-weighted means over the full administrative region, and short-term emission reductions associated with the COVID 19 lockdown in 2020 are not explicitly incorporated. Together, these factors limit the model's ability to reproduce absolute concentration levels in anomalous years such as 2020. Because the same meteorological assumptions are applied across scenarios, this limitation is more consequential for absolute health estimates than for relative comparisons across policy scenarios.

The soft link between the power sector model and the GAINS model was established by feeding the fuel consumption results from the heat

transitions and power sector modeling into the GAINS power/residential sector activity data. In our study, this process required downscaling the power sector modeling results into GAINS subregions and fuel categories. For example, the China-North grid includes six GAINS regions/provinces, including Beijing, Hebei, Tianjin, Inner Mongolia, Shanxi, and Shandong; Korea is divided into four subregions, including Seoul, Busan, North, and South; and the Japan West grid includes Kinki, Chubu, Chugoku-Shikoku, and Kyushu-Okinawa. We used the existing spatial (sub-regional) activity patterns in GAINS to calculate the provincial distribution of fuel and technology (emitting activity). After matching each generation technology within the power sector model with the GAINS power sector technology and fuel type, we distributed the fuel input for each GAINS activity category according to the distribution ratio.

For residential sectors, the GAINS model distinguishes the energy input for each fuel type and specific end-use residential activities to evaluate emissions and control measures for reducing air pollution. For residential heating and cooking, the GAINS model classifies sources into fireplaces, stoves, single-house boilers, and medium-sized boilers, each with distinct emission characteristics, and categorizes fuels into solid (wood, agricultural residues, dung, and coal), liquid (kerosene and fuel oil), and gaseous (LPG and natural gas) types. Given the limited availability of detailed statistical data, the GAINS model integrates a mix of sources and expert assessments to derive specific activity data from national- or sector-level data (Klimont et al., 2017). To calculate the heating demand in residential buildings, we relied on the WEO regional data from the IEA STEPS scenario downscaled in GAINS to provincial projections of fuel consumption in each sector, year, and region. We calculated the ratio of the heating energy input (space heating and water heating) to the sectoral total to estimate the residential energy input for heating purposes and subtracted the corresponding portion from the baseline in the electrification cases.

The GAINS model computes the number of premature deaths of adults (aged 25 years and older) associated with long-term exposure to $PM_{2.5}$, one of the leading causes of early mortality associated with air pollution, (Dedoussi et al., 2020) to assess the human health effects of ambient air quality changes. Utilizing mortality data tailored to the demographics of the countries, the model established fundamental survival rates for each demographic group over time (Amann et al., 2008). The process of estimating attributable deaths involves applying disease- and age-specific fractions to the total deaths related to specific illnesses, known as the population-attributable fraction (PAF). The PAF calculation in GAINS considers six causes of death: ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory infections (LRI), and type 2 diabetes (T2D), utilizing a Bayesian, regularized, trimmed model based on the Global Burden of Disease (GBD) 2019 study (Vos et al., 2020). For future population assumptions, we followed projections of population size and structure from recent updates of World Population Prospects by the United Nations Department of Economic and Social Affairs (United Nations Department of Economic and Social Affairs, 2011).

3. Results and discussion

3.1. Emissions

3.1.1. Heating sector

We focused on changes in the emissions of three key air pollutants (NO_x, SO_2, and $PM_{2.5}$) in the residential and power sectors in 2050 relative to the baseline (see S2 for detailed information on the 2020 baseline emissions). The baseline was simulated based on the IEA's STEPS, which incorporates a broad range of government announcements as of 2021, including Nationally Determined Contributions for the Paris Agreement, electrification plans, and energy efficiency improvement, as well as updated air pollution control options for power plants (International Energy Agency, 2023). Building on the baseline, we developed scenarios to capture the incremental impacts of residential heating electrification and power sector decarbonization under different levels of power trade and carbon pricing.

Table 2 shows substantial baseline (NNT0) emission reductions over time from existing and planned policies; for China-North (CN—N), SO_2 falls by 86% between 2020 and 2050. Heating-sector transitions (ANT0–AT2) add further reductions beyond the baseline—lowering CN—N SO2 by a further 20% in 2050—and provide the largest incremental gains for NO_x and SO_2 in Korea (KR) and Japan-West (JP-W), at 51–66% and 40–46% relative to the 2050 baseline, respectively. The smaller $PM_{2.5}$ reductions reflect the continued role of biomass in the STEPS-based residential baseline.

Comparing heat pump adoption in 2030 and 2050, residential decarbonization reduces NOx more than SO2 or $PM_{2.5}$ over the long term. Complete residential heating decarbonization yields comparable NO_x reductions relative to the respective baselines in 2030 and 2050—about 30%, 49%, and 25% in 2030 versus 29%, 50%, and 24% in 2050 for CN—N, KR, and JP-W—whereas continuing current plans (NNT0) leaves less room for SO_2 and $PM_{2.5}$ reductions by 2050, roughly half those achievable in 2030, because the baseline assumes sustained natural gas use. Current residential energy policies therefore warrant particular attention to long-run NO_x control. Baseline $PM_{2.5}$ in KR and JP-W rises slightly by 2050 from increasing fuelwood use in medium boilers, cooking, and heating stoves, though heat transitions limit this increase.

3.1.2. Power generation sector

Next, we examined the power sector's contributions to the same pollutant emissions by comparing scenarios with and without power trade for heat transition cases at different carbon price levels. Before examining the emissions results, it is worth discussing the grid-scale responses to heating electrification. From the power sector analysis, we found that incorporating heating electrification increased the daily power demand by a maximum of 8.46%, 9.6%, and 3.31% in January in CN—N, KR, and JP-W, respectively, and also hourly demand by a maximum of 15%, 11%, and 3.8% in three respective regions (January 8, A.M.) (Kim et al., 2024). Responding to the demand changes, optimization results show grid interconnections with higher carbon pricing will achieve more renewable-based electricity generation in 2050, while zero carbon pricing is associated with higher dependence on CCS to meet carbon neutrality in Korea and Japan because of resource limitations and cost competitiveness of renewable electricity generation.

Fig. 2 compares the projected power sector emissions of SO_2, NO_x, and $PM_{2.5}$ across scenarios (NNT0, ANT0, AT0-AT2) for 2030 and 2050 in three regions (China North in red, Korea in blue, and Japan West in green). Each bar represents the total annual emissions (in kt) under various heat pump adoption and carbon price assumptions. (see S3 for NEA power generation mixes computed from power sector modeling, and S4 for regional emission results in absolute numbers).

We found two dimensions of variation: 1) a temporal decline in emissions and 2) scenario-based differences within the same year across carbon prices and power-trade assumptions. Emissions generally declined from NNT0 to AT2, indicating that higher carbon prices and regional power trades substantially reduce pollutant emissions. Aggregated across the three regions, power sector emissions in 2050 are substantially lower than the 2020 baseline, especially NO_x and SO_2, reflecting the combined effect of stringent air pollution policies and deep decarbonization of power generation to meet carbon neutrality targets (binding in 2050 in Korea and Japan and 2060 in China).

Heating electrification without carbon pricing and power trade (ANT0) increases pollutant emissions compared with NNT0, indicating that the additional power demand is met by emission-intensive generation (fossil fuels, CCS, and biomass). Comparing trade and no-trade cases under heating electrification (ANT0 vs. AT0), interregional power trade at a zero-carbon price reduces emissions in Korea and Japan

Table 2
2030 and 2050 residential emissions [kt] before (NNT0) and after (ANT0, AT0, AT1, AT2) heat transitions by pollutant; the results for heat transition cases are shown as % change in emissions compared to the NNT0 scenario.

Pollutant	Regions	2020 Baseline	2030		2050	
			Baseline (NNT0)	Transition scenarios (ANT0-AT2) %Δ vs NNT0	Baseline (NNT0)	Transition scenarios (ANT0-AT2) %Δ vs NNT0
NO_X	CN—N	164.83	104.02	−30%	61.15	−29%
	KR	49.48	45.18	−49%	33.45	−50%
	JP-W	53.82	49.19	−25%	37.83	−24%
SO_2	CN-N	547.58	204.78	−35%	75.71	−20%
	KR	27.90	20.90	−36%	14.38	−25%
	JP-W	11.37	8.48	−5%	7.00	−4%
$PM_{2.5}$	CN-N	517.31	282.21	−16%	119.69	−9%
	KR	7.83	7.77	−3%	10.25	−1%
	JP-W	2.15	4.64	−1%	8.98	−0%

Note: NNT0: Baseline with current policies and policy proposals. ANT0, AT0, AT1,AT2: Heat transition scenarios (with/without power trade, at different CO_2 prices). Values in % are relative reductions compared to the NNT0 baseline in the same year. Regions: CN—N (China North grid), KR (Korea), JP-W (Japan West grid).

but increases them in China North, where low-cost thermal generation expands to meet export demand. This leads to the total aggregated emissions in AT0 exceeding those in ANT0.

The introduction of carbon pricing reduces the emissions across all pollutants and scenarios (ANT1, AT1, ANT2, and AT2). At each carbon price level, allowing power trade further enhances emissions reduction, as trade facilitates renewable energy investment. Compared with residential decarbonization, accelerating the power sector transition yields larger and more persistent air quality benefits. In 2050, renewable generation shares rise from 69.1% to 71.5% between ANT1 and AT1, and from 78.7% to 83.1% between ANT2 and AT2, whereas reliance on CCS and hydrogen-based generation declines. This shows that regional grid integration promotes renewable energy deployment in resource-abundant areas and reduces pollutant emissions across Northeast Asia (Bogdanov and Breyer, 2016; Kim and Jung, 2023).

3.2. Concentrations of $PM_{2.5}$

For air quality impact, we examined the simulated concentration of ambient $PM_{2.5}$ at the sub-regional level, which revealed more detailed information regarding actual sectoral activities (residential heating and power generation) impacted by clean heat transitions at finer resolutions (Fig. 3). Comparing trade cases (AT0, AT1, and AT2) with no-trade cases (NNT0 and ANT0), the regional analysis shows that each region requires different sectoral efforts to improve air quality. For example, in CN—N, we find that residential decarbonization has a larger impact in Beijing than power sector contributions for both 2030 and 2050. However, power sector decarbonization (or renewable transitions) was found to have a greater impact on air quality improvement in Shandong. The 2050 decarbonization of the power sector is especially important for Shandong, with a 0.9 point (2%) decrease from ANT0 to AT2 in 2030 and a 2.7 point (8%) decrease in 2050.

By 2050, a low-carbon/renewable power supply is found to be more impactful than residential decarbonization for regional ambient air quality in all subregions of the KR and JP-W. This implies the substantial potential for air quality co-benefits existing in current energy policies and proposals (baseline scenario) in the power sector. While net CO_2 emissions in 2050 are constrained to less than zero for the power sectors in the two regions based on their carbon neutrality targets, the results imply that a carbon-neutral power generation system does not ensure safe local air quality if it is dependent on CCS and negative carbon-emission technologies that still involve pollutant emissions. Policy considerations for more stringent renewable development (as seen in the high carbon price cases in AT1 and AT2) and emissions control technologies are necessary for further air quality improvement.

This is also relevant to the 2050 air quality improvement observed in Shandong under AT2. The power sector's contribution increases over time with low-carbon transitions and is maximized with renewable transitions. With CN—N serving as a net exporter in the electricity trade utilizing grid interconnections for its low-cost electricity system, Shandong is subject to greater air quality benefits with policy support to ensure renewable transitions in the region.

3.3. Health impacts

As found in the air quality impact, heating electrification without further power sector measures for decarbonization contributes to public health improvement, but the magnitude of the impact is limited compared to cross-sectoral decarbonization cases with a renewable electricity supply. This distinction reflects a fundamental difference in how each pathway treats the emitting source: a renewable-based supply removes combustion altogether, whereas capture- or offset-based carbon neutrality does not. Even where CCS achieves net-zero CO_2, the underlying combustion continues to emit health-relevant pollutants such as NOx and PM, so the local pollutant burden—and the associated health impact—largely persists.

First, at the NEA level, the 2050 NNT0 case yields an increase in the absolute number of premature deaths compared to the 2020 baseline for various reasons, such as population growth and an aging society, etc. (Rafaj et al., 2021). This is consistent with an earlier study using the GAINS model (Rafaj et al., 2021) that analyzed the impact of socio-demographic drivers on ambient air pollution-related premature mortality in China, Japan, and the Republic of Korea by 2050. The results show that population aging and urbanization trends largely offset the positive health impacts of decarbonization and emission controls because of the higher vulnerability of the exposed population. Population (de)growth by 2050, however, acts in the opposite direction in all three countries, most notably Japan. The demographic factors used here are the same as those in the aforementioned study; therefore, their role in relative terms remains valid in our analysis.

Focusing on 2050, power trade with zero-carbon pricing (AT0) contributes to reducing the number of premature deaths in KR and JP-W, but not in CN—N, yielding smaller benefits compared to the no-trade scenario (ANT0) by 336 lives (Fig. 4). However, the regional distribution of health benefits from power trade shows that the impact of power trade falls disproportionately at the subnational level. Power trade at zero carbon price (AT0), compared to ANT0, brings an especially large health burden to Shandong (from 53 increased premature deaths to 649). Nevertheless, renewable energy transition in the power sector brings substantial health benefits to the region, with AT2 reducing premature deaths by 5.4% relative to baseline. We also noticed that the contribution of the power sector to public health in AT2 is larger in 2050 than in 2030, especially in Shandong. This implies that the region plays an important role in the power supply, owing to its cheap thermal sources. Allowing inter-regional power trade without policy support to ensure clean power generation threatens local health by pressuring the region to burn more fossil fuels for least-cost power generation. These results emphasize the need to integrate health and equity considerations

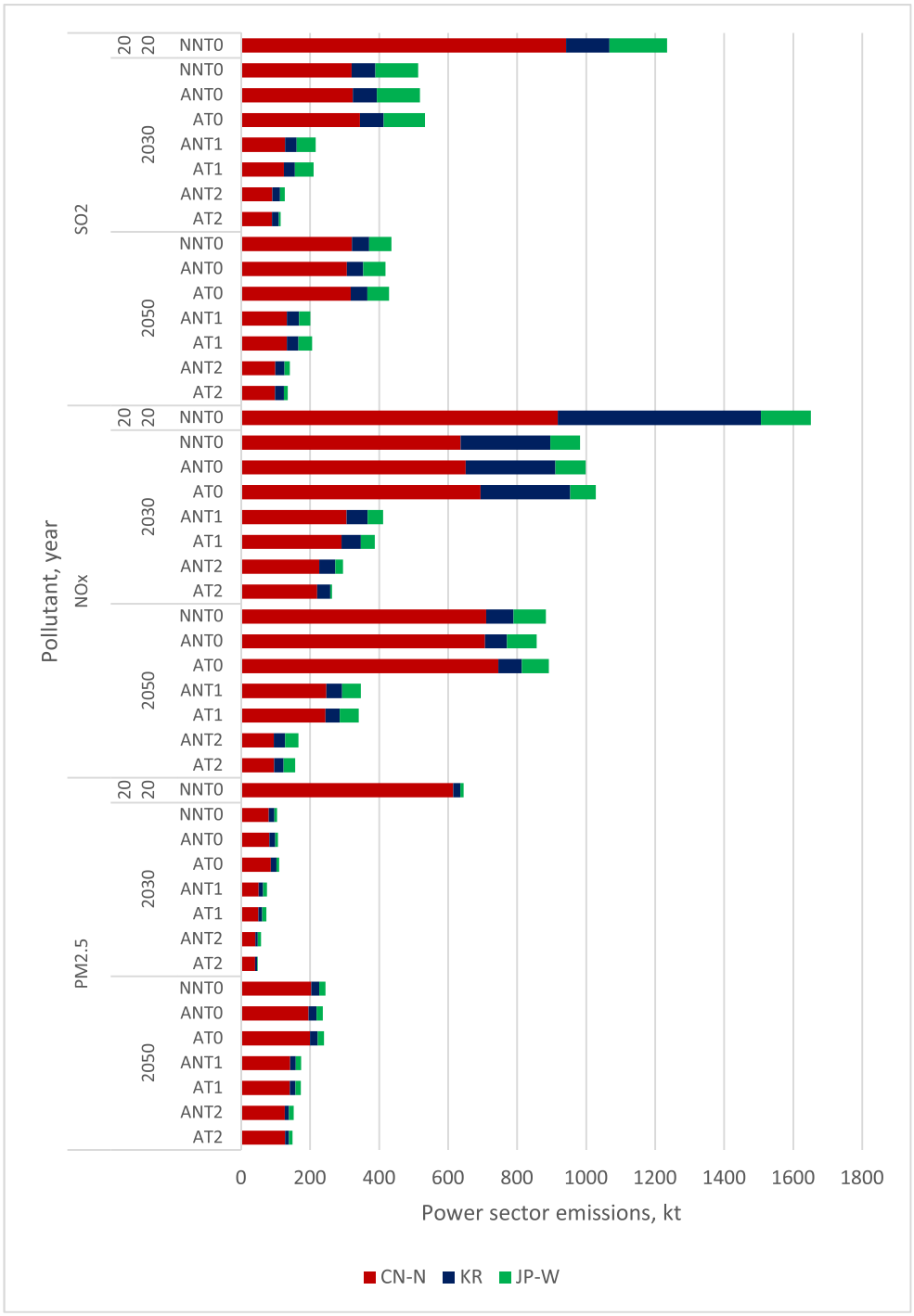
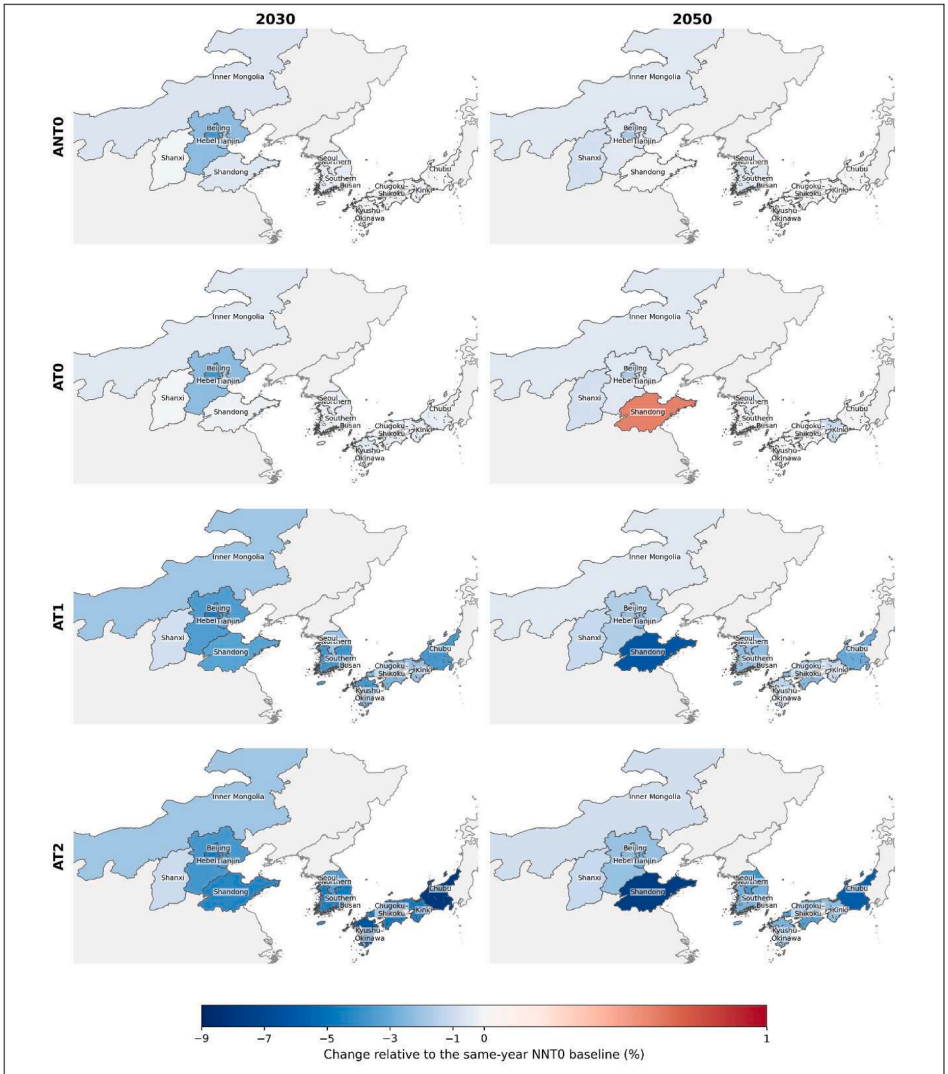


Fig. 2. NEA regional NOx, SO_2, $PM_{2.5}$ emissions from the power sector in 2030 and 2050 (kt). NNT0: No heat pump adoption with no power trade at carbon price 0, ANT0/1/2: All regions heat pump adoptions with no power trade at carbon price 0100, 200 USD/tCO_2, AT0/1/2: all regions heat pump adoption with power trade at carbon price 0100,200 USD/tCO_2 respectively.

into regional power planning, ensuring that interregional trade supports clean generation and delivers co-benefits, rather than shifting burdens to fossil-dependent regions.

The magnitude of the health benefits from the power trade is not necessarily proportional to the carbon price levels. With the adoption of carbon pricing ranging from 0 to 100, CN—N benefits the most. AT1 yields a further saving of 2539 lives in CN—N compared to ANT0 (8375 compared to the baseline), with the largest benefits found in the Hebei region. However, the transition from AT1 to AT2 yields only modest additional savings of 227 lives. JP-W shows a relatively large benefit increase with more ambitious carbon pricing. When comparing AT0, AT1, and AT2, the reduction in premature deaths relative to the baseline increases from 0.9 to 3.5 and 6.4%, respectively. This reveals the different energy environments in the power sectors of the three regions. CN—N's power sector responds to a relatively low carbon price in clean electricity generation, leading to increased health benefits, whereas a higher level of carbon pricing is required to incentivize clean electricity transitions in JP-W.

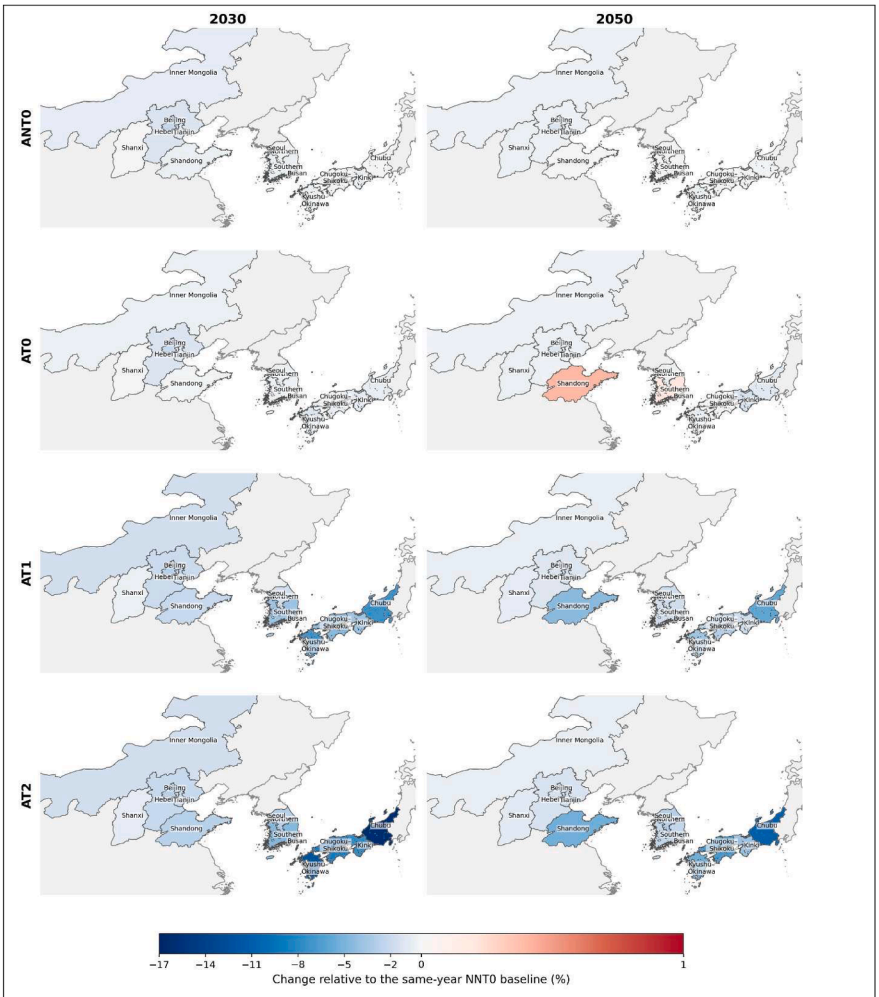
Higher carbon pricing in power generation with grid interconnections brings especially large health benefits to JP-W and KR in



	Regions	2020	2030					2050				
			NNT0	ANT0	AT0	AT1	AT2	NNT0	ANT0	AT0	AT1	AT2
CN-N	Beijing	54.0	45.5	-3.7	-3.7	-4.7	-4.7	38.8	-1.8	-1.8	-2.1	-2.3
	Hebei	55.7	49.4	-2.3	-2.3	-3.5	-3.6	43.3	-0.5	-0.5	-1.6	-2.1
	Inner Mongolia	26.0	22.0	-0.7	-0.5	-1.9	-1.9	21.1	-0.5	-0.5	-0.5	-0.9
	Shanxi	42.7	36.4	-0.1	-0.1	-0.8	-1.0	37.7	-0.8	-0.8	-1.1	-1.1
	Shandong	45.2	39.8	-0.6	-0.2	-3.2	-4.3	35.5	0.0	0.6	-6.2	-7.6
	Tianjin	55.4	51.4	-1.8	-1.6	-3.4	-3.7	44.7	-0.7	-0.4	-2.7	-3.1
KR	Northern	28.7	27.4	-0.3	-0.4	-2.0	-3.5	27.0	-0.4	-0.4	-2.2	-3.7
	Busan	20.3	17.3	-2.1	-2.1	-6.0	-8.1	15.9	0.0	0.0	-3.1	-3.8
	Seoul	33.3	31.4	-0.3	-0.3	-2.3	-4.3	30.5	-0.3	-0.3	-2.6	-3.6
	Southern	20.6	19.0	-0.4	-0.3	-3.7	-4.6	18.3	-0.5	0.0	-2.2	-2.7
JP-W	Chugoku-Shikoku	9.3	8.9	-0.1	-0.4	-2.6	-4.9	8.5	0.0	0.0	-2.4	-3.5
	Chubu	8.1	7.4	0.0	-0.3	-3.6	-7.9	6.9	0.0	0.0	-2.9	-5.8
	Kinki	10.2	9.2	-0.2	-0.4	-2.1	-4.7	9.0	0.0	-1.1	-1.1	-2.2
	Kyushu-Okinawa	8.4	8.0	-0.2	-0.6	-3.7	-6.3	7.5	0.0	0.0	-1.3	-2.7

**NNT0 in μg/m³; ANT0, AT0, AT1, AT2 in % change from NNT0*

Fig. 3. Percent change in annual average ambient $PM_{2.5}$ concentration by subregion in 2030 and 2050 relative to the same-year NNT0 baseline. ANT0 represents residential heating electrification without power trade or carbon pricing; AT0–AT2 represent heating electrification with power trade under carbon prices of 0, 100, and 200 USD/tCO_2, respectively. Negative values indicate reductions relative to baseline.



Regions		2020	2030					2050				
		NNT0	NNT0	ANT0	AT0	AT1	AT2	NNT0	ANT0	AT0	AT1	AT2
CN-N	Beijing	30,465	38,876	-2.2	-2.1	-2.7	-2.7	55,444	-1.1	-1.1	-1.3	-1.4
	Hebei	91,639	105,629	-1.2	-1.2	-1.9	-2.0	136,206	-0.3	-0.3	-1.1	-1.4
	Inner Mongolia	19,145	21,180	-0.7	-0.5	-1.7	-1.7	28,826	-0.3	-0.3	-0.6	-0.6
	Shanxi	39,544	40,732	-0.1	-0.1	-0.5	-0.7	61,132	-0.4	-0.4	-0.7	-0.8
	Shandong	114,955	134,162	-0.4	-0.2	-2.0	-2.7	177,526	0.0	0.4	-4.5	-5.4
	Tianjin	19,904	26,401	-0.9	-0.8	-1.9	-2.0	38,004	-0.3	-0.2	-1.6	-1.8
	Total	315,652	366,980	-0.8	-0.7	-1.8	-2.2	497,138	-0.3	-0.2	-2.3	-2.7
KR	Northern	8,156	10,637	-0.2	-0.4	-1.6	-2.8	16,916	-0.2	-0.3	-1.8	-2.8
	Busan	958	1,113	-2.2	-2.2	-6.4	-8.5	1,803	0.0	0.0	-3.4	-4.0
	Seoul	5,728	7,530	-0.2	-0.2	-1.6	-3.1	13,133	-0.4	-0.4	-2.0	-2.9
	Southern	5,944	7,411	-0.4	-0.3	-3.8	-4.6	11,114	0.0	0.2	-1.7	-2.3
	Total	20,786	26,691	-0.3	-0.4	-2.4	-3.6	42,966	-0.2	-0.2	-1.9	-2.7
JP-W	Chugoku-Shikoku	1,374	1,416	-0.1	-0.6	-4.4	-8.8	1,251	0.0	-0.1	-2.9	-7.0
	Chubu	3,780	3,570	0.0	-0.6	-7.5	-16.2	3,095	-0.2	-0.8	-5.9	-11.0
	Kinki	4,625	4,491	-0.4	-0.7	-3.7	-7.9	4,491	0.0	-1.4	-1.8	-3.8
	Kyushu-Okinawa	3,072	3,152	-0.3	-1.1	-7.2	-12.1	2,745	-0.5	-0.6	-3.6	-5.4
	Total	12,851	12,629	-0.2	-0.7	-5.7	-11.4	11,582	-0.2	-0.9	-3.5	-6.4
NEA total		349,289	406,300	-0.7	-0.7	-2.0	-2.6	551,686	-0.3	-0.2	-2.3	-2.8

Fig. 4. Percent change in premature deaths associated with ambient $PM_{2.5}$ by subregion in 2030 and 2050 relative to the same-year NNT0 baseline. ANT0 represents residential heating electrification without power trade or carbon pricing; AT0–AT2 represent heating electrification with power trade under carbon prices of 0, 100, and 200 USD/tCO_2, respectively. Negative values indicate reductions in premature mortality relative to baseline.

terms of the percentage change from the baseline. We observe that a clean power supply for heating electrification (AT2) has a large positive impact in the short term, with a reduced number of premature deaths of 8.5% and 12.1% in the Busan, KR, and Kyushu-Okinawa, JP-W regions, respectively. This is because KR and JP-W's power sectors avoid fossil fuel combustion, which is replaced with electricity imported from CN—N and domestic low-carbon electricity generation. While the same decarbonization impact (AT2) seems smaller in 2050, the reduced impact is associated with a baseline assumption that models carbon-neutral power generation by 2050 in the two regions.

3.3.1. *Inter-regional benefit transfer with heat transition*

Finally, we assess the inter-regional benefit transfer with heating sector transitions by comparing the benefits in the all-countries' action case (ANT0) and single-country cases (CNT0, KNT0, and JNT0) relative to NNT0. The GAINS model considers transboundary air pollution across all regions by applying transfer coefficients (REF). We assume that the positive difference in reduced premature deaths between a single country and all countries' action cases is associated with the benefit transferred from outside. For example, if we assume that a region expects more premature deaths to be averted in the NEA-level action case compared to the country's single-transition case, with baseline assumptions applied to other regions, the increase in health benefits is due to emission reductions outside the region.

Comparing the cases, we find that CN—N's decarbonization has the largest impact on regional public health outcomes compared to KR and JP-W's heat transitions, whereas the action scenario of all regions yields the largest health benefits compared to single-region transition scenarios. Fig. 5 shows the composition of the reduced number of premature deaths in ANT0 in 2050 for each modeled region compared to the NNT0 case. The sum of single and transfer cases is the total number of reduced premature deaths in ANT0 (light and dark blue), and the light-blue segment is the number of single-action cases: CNT0/KNT0/JNT0 for CN—N, KR, and JP-W, respectively. With a relatively small transfer contribution found for CN—N, most of the health benefits in the CN—N subregions stem from their own heat transitions, whereas we expect a benefit transfer within CN—N. We find that CN—N's domestic heat transitions bring a reduction of 634 premature deaths in Beijing, with no changes with NEA heat transitions; meanwhile Shanxi sees a further reduction of 15 lives, in addition to 251 lives from domestic action. Shandong is an interesting region where its own heat pump adoption increases the threat to public health because of its role in additional power supply at P0, and the NEA heat transition also burdens regional health at the same carbon price.

Northern Korea and Japan's Kyushu and Okinawa regions benefit more from NEA-level heat transitions than from their own heat transitions. The modeling results show that heat transition in Japan has limited health impacts in the Kyushu and Okinawa regions, but NEA heat transitions can reduce premature deaths by 14 in the region. The northern region of Korea is found to be susceptible to NEA heat transitions, with 28 of 31 saved lives stemming from NEA-level heat transitions. While the magnitude of health improvement seems smaller than that in China, the result implies that a slowdown of transitions would lead to continued elevated exposure and potentially increase the death toll. Considering that we focused on health impacts from ambient PM exposure only, quantification of other impacts, such as ozone, could

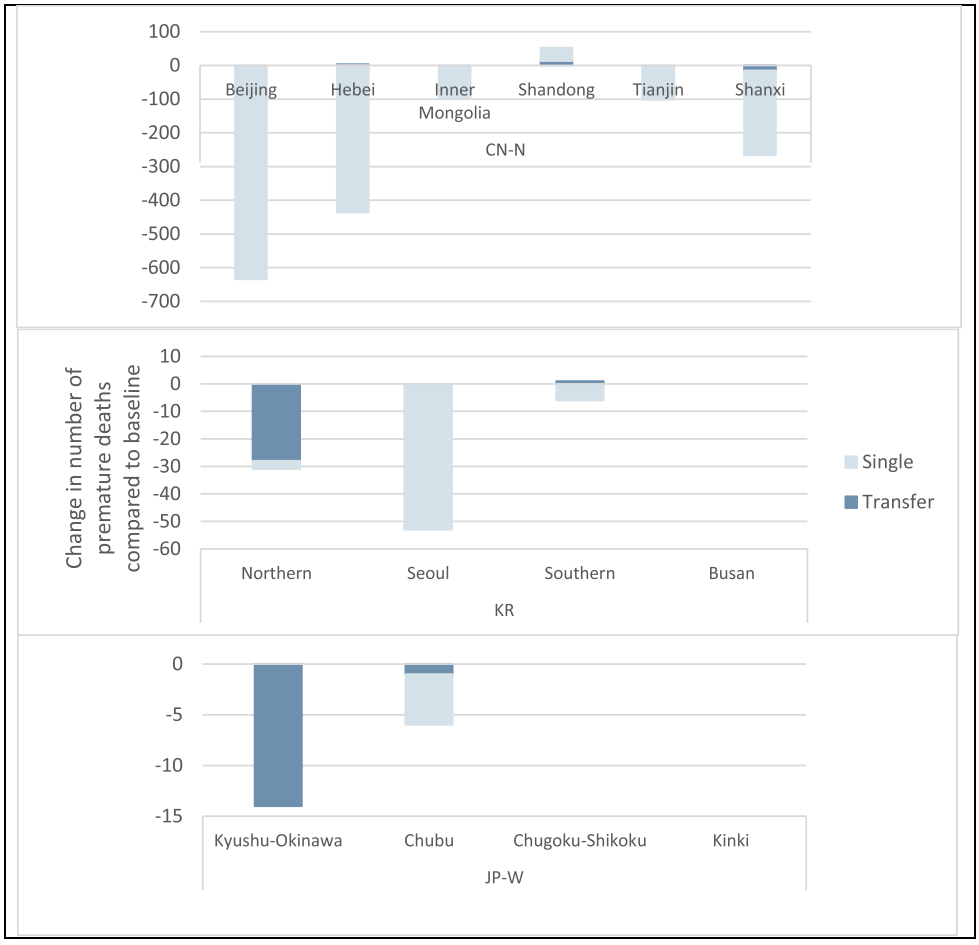


Fig. 5. Composition of regional/inter-regional health benefits in ANT0 relative to baseline in 2050. Light blue denotes single-region heat pump adoption cases, and darker blue denotes further reductions in premature deaths with all-regions' heat pump adoption.

capture additional health effects from heat transitions in these regions.

4. Conclusions

The techno-economic feasibility of grid interconnections in Asia has been validated extensively (Bogdanov and Breyer, 2016; Kim, 2023; Kim and Jung, 2023; Otsuki et al., 2016; Yamaguchi, 2018). Beyond such system-level analyses, this study quantifies the air quality and public health co-benefits of regional power-sector cooperation, demonstrating that inter-regional transmission in Northeast Asia shapes the health outcomes of residential heat electrification, with several implications.

First, the cross-sectoral synergy of clean heat transitions depends on a clean power supply. Grid interconnections reduce fossil fuel consumption and incentivize renewable growth at the regional level, but only under ambitious carbon pricing. Without it, interconnection can raise fossil-based generation in exporting regions to meet import demand. High carbon pricing is therefore essential to lift renewable penetration at all participating nodes.

Second, renewable penetration—rather than carbon-neutrality per se—is the key driver of air quality improvement. Although the Korean and Japanese power sectors reached net-zero CO_2 across all scenarios, pathways relying heavily on CCS did not deliver the largest health benefits, consistent with recent evidence on the air pollution impacts of decarbonization technologies (Li et al., 2022; Wei et al., 2024). Where coal-fired fleets are long-lived, pairing end-of-pipe controls with residual CCS can be deployed quickly as an interim measure to secure near-term health benefits during the transition. This role is strictly transitional, however; the durable air quality and health gains depend on an eventual shift toward renewable generation, which should remain the ultimate objective.

Third, the co-benefits are distributed unevenly across and within countries, revealing localized health benefits and burdens that can be obscured by national-level averages. The locations of clean-energy transitions do not necessarily coincide with the locations of health gains. Clean heat transitions in China-North confer health benefits on Korea and Japan, with particularly pronounced gains in northern Korea and Kyushu-Okinawa region, whereas China-North's own benefits arise mainly from its domestic transitions. Without policies ensuring renewable generation, however, least-cost dispatch can shift generation-related emission burdens onto exporting regions such as Shandong. These results underscore the need to incorporate spatial equity into regional power planning so that interregional trade delivers co-benefits rather than displacing them.

From a cleaner production perspective, these findings reframe residential heat electrification as a route to replace distributed, uncontrollable combustion sources with centralized, controllable, and increasingly non-emitting electricity—provided the upstream power supply itself decarbonizes through renewables rather than offset-based neutrality. Realizing this potential requires coordinated regional governance that couples cross-border transmission with aligned carbon pricing, renewable deployment mandates, and emission standards across the three countries. Treating interconnection as a shared clean-energy infrastructure, rather than a least-cost balancing mechanism alone, would allow Northeast Asia to convert decarbonization commitments into equitably distributed public health gains.

Finally, our framework relies on simplifying assumptions: it captures annual ambient $PM_{2.5}$but not ozone, indoor pollution, or wintertime transboundary transport, which are outside the scope of the present assessment. Future work extending the framework to broader health endpoints, systematic sensitivity analyses, and policy-feasibility assessment would strengthen these conclusions.

By comparing single-region heat transition cases and all regions' transitions, we found that the heating electrification of CN—N contributes to regional health benefits in KR and JP-W, whereas CN—N's health benefits are mostly impacted by its own clean transitions. This benefit transfer is similar to the findings of IIASA (2022) (OECD and IIASA, 2022). In particular, northern Korea and the Kyushu–Okinawa region in Japan were found to be susceptible to CN—N's clean heating transition, with most health benefits in all NEA heat transition cases not realized in its single-region transition cases.

While this study focuses on the annual concentration of $PM_{2.5}$ to capture air quality improvement, temporal air quality patterns and transboundary transport of air pollutants in East Asia may further enhance the benefits of clean heat transitions. Studies have shown higher concentrations of $PM_{2.5}$ in winter months, especially in the China North region, where the residential sector has been identified as a major contributor to local air pollution (Liu et al., 2016; Peng et al., 2018). In addition, in terms of the transboundary transport of air pollutants, international sources contribute 60–70% of ambient $PM_{2.5}$ in Korea in the winter, compared to 20% in the summer months (Kumar et al., 2021; Yim et al., 2019). With the high heating demand in winter, we expect that electrification through renewable electricity will yield larger public health benefits than those captured in our model.

These estimates are larger than our projections based on the assumption of 100% coal removal in residential heating by 2050 relative to STEPS. We interpret that the difference in estimates stems mainly from the baseline assumptions. ECLIPSE V5a incorporates China's 12th Energy Plan (Westervelt et al., 2019) before clean heating policies were implemented in northern China regions (X. Zhang et al., 2019) and SSP2 assumes a slow decrease in fossil fuel consumption without technological breakthroughs (O'Neill et al., 2017). While this study finds relatively smaller sectoral decarbonization impacts than the baseline, this does not necessarily mean that sectoral decarbonization has a small overall health impact. Our results capture the policy progress embedded in the baseline in realizing the potential health benefits that previous studies have assessed and show the evolving dynamics.

Our modeling framework relies on a set of assumptions that affect the magnitude and scope of the estimated health benefits. GAINS uses fixed 2015 meteorology and focuses on annual ambient PM2.5, excluding future changes in atmospheric conditions and ozone impacts, which might underestimate the total health benefits. While the use of common meteorological assumptions across scenarios supports relative comparisons, these limitations affect the interpretation of absolute health estimates. Another important assumption concerns renewable deployment potentials. The node-specific renewable ceilings used in the model reflect technical and geographic constraints, but estimates of deployable potential can vary depending on how spatial and policy constraints such as land availability and siting restrictions are represented (Koutsandreas et al., 2026). Alternative potential estimates could affect the substitution among low-carbon generation options in the power system and thus associated air quality and health benefits. Future work could also extend the framework to electrification in other end-use sectors, including transport, where sector-specific temporal and seasonal demand profiles may induce different power-system responses (Amann et al., 2022). Examining how these load patterns affect clean power deployment, generation and emissions would provide a broader assessment of the air-quality and health implications of economy-wide electrification. Future work can also build on this framework by extending it to a broader set of health outcomes, systematic sensitivity analyses, and a detailed assessment of policy implementation pathways and feasibility.

CRediT authorship contribution statement

Haein Kim: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Tracey Holloway:** Writing – review & editing, Supervision. **Peter Rafaj:** Writing – review & editing, Software, Methodology. **Zbigniew Klimont:** Software, Methodology. **Gregor Kiesewetter:** Writing – review & editing, Software, Methodology. **Jonathan A. Patz:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

HK acknowledges a gift from Sarah and David Epstein to the University of Wisconsin–Madison to support the Planetary Health post-doctoral fellow program.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cles.2026.100282.

Data availability

Data will be made available on request.

References

Amann, M., Bertok, I., Borken, J., Chambers, A., Cofala, J., Dentener, F., Heyes, C., Hoglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schöpp, W., Texeira, E., Toth, G., Wagner, F., Winiwarter, W., 2008. GAINS Asia: a tool to combat air pollution and climate change simultanously. Methodology.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model. Softw. 26, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012.

Amann, G., Escobedo Bermúdez, V.R., Boskov-Kovacs, E., Gallego Amores, S., Giannelos, S., Iliceto, A., Ilo, A., Chavarro, J.R., Samovich, N., Schmitt, L., Souza e Silva, N., Strbac, G., Tomsic, Z., Zengin, E., 2022. E-mobility Deployment and Impact on grids: Impact of Electric Vehicle and Charging Infrastructure on European Transmission and Distribution grids: Innovation Needs. Publications Office of the European Union. https://doi.org/10.2833/937755.

AMRO, 2023. ASEAN+3 regional economic outlook: on the road to Net zero.

Bogdanov, D., Breyer, C., 2016. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers. Manag. 112, 176–190. https://doi.org/10.1016/j.enconman.2016.01.019.

Castillo, V.Z., De Boer, Muñoz, R.M., Gernaat, D.E., Benders, R., Van Vuuren, D., 2022. Future global electricity demand load curves. Energy 258, 124741.

Chafe, Z.A., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., Riahi, K., Dentener, F., Smith, K.R., 2014. Household cooking with solid fuels contributes to ambient $PM_{2.5}$ air pollution and the burden of disease. Environ. Health Perspect. 122, 1314–1320. https://doi.org/10.1289/ehp.1206340.

Cremona, E., 2023. Power in Unity: Doubling electricity interconnection can boost Europe's green transition and strengthen security of supply. Ember. In collaboration with the European Environmental Bureau and Renewables Grid Initiative. https://eeb.org/en/library/power-in-unity-doubling-electricity-interconnection-can-boost-europes-green-transition/.

De V., 2018. ASSET study on technology pathways in decarbonisation scenarios.

Dedoussi, I., Eastham, S., Monier, E., Barrett, S., 2020. Premature mortality related to United States cross-state air pollution. Nature 578, 261–265. https://doi.org/10.1038/s41586-020-1983-8. -+.

Du, W., Wang, J., Feng, Y., Duan, W., Wang, Z., Chen, Y., Zhang, P., Pan, B., 2023. Biomass as residential energy in China: current status and future perspectives. Renew. Sustain. Energy Rev. 186, 113657. https://doi.org/10.1016/j.rser.2023.113657.

European Commission, 2017. Communication on achieving the 15% electricity interconnection target - Making Europe's electricity grid fit for 2030, COM(2017) 718 final. Brussels: European Commission. Available at: europa.eu.

Guo, M., Hamm, N.A.S., Chen, B., 2024. Understanding air pollution reduction from the perspective of synergy with carbon mitigation in China from 2008 to 2017. J. Environ. Manage. 367, 122017. https://doi.org/10.1016/j.jenvman.2024.122017.

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., Schöpp, W., 2020. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. Environ. Res. Commun. 2, 025004. https://doi.org/10.1088/2515-7620/ab7457.

IEEFA, 2025. Carbon pricing in Asia.

International Energy Agency, 2023. Global energy and climate model documentation 2023.

International Energy Agency, 2020a. Country report.

International Energy Agency, 2022 Iea steps.

International Energy Agency, N., 2020b. Projected costs of generating electricity 2020 edition.

Ito, A., Wakamatsu, S., Morikawa, T., Kobayashi, S., 2021. 30 Years of air quality trends in Japan. Atmosphere 12, 1072. https://doi.org/10.3390/atmos12081072.

Kiesewetter, G., Zhang, S., Liu, J., 2024. Health benefits of decarbonization and clean air policies in Beijing and China. Environ. Res. Lett. 19, 124051. https://doi.org/10.1088/1748-9326/ad8c65.

Kim, H., 2023. Grid interconnections and decarbonization pathways for carbon neutrality of Northeast Asia. Renew. Energy 219, 119358. https://doi.org/10.1016/j.renene.2023.119358.

Kim, H., Holloway, T., Meier, P., Rafaj, P., Edwards, M.R., 2024. Powering residential heat electrification through grid interconnections in Northeast Asia.

Kim, H., Jung, T.Y., 2023. Embarking on the Asia Supergrid: trade impact of carbon pricing on regional sustainability in northeast Asia. Renew. Sustain. Energy Rev. 183, 113426. https://doi.org/10.1016/j.rser.2023.113426.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schöpp, W., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmosp. Chem. Phys. 17, 8681–8723. https://doi.org/10.5194/acp-17-8681-2017.

Korea Southeast Power, 2018. Wind output profile.

Korea Southern Power, 2019. Solar output profile.

Koutsandreas, D, Ardehali, A, Giannelos, S, Pudjianto, D, 2026. Quantifying the Trade-Offs Between Clean-Energy Expansion and Land Requirements: Evidence from Greece. Energies 19 (10), 2261. https://doi.org/10.3390/en19102261.

Kuerban, M., Waili, Y., Fan, F., Liu, Y., Qin, W., Dore, A.J., Peng, J., Xu, W., Zhang, F., 2020. Spatio-temporal patterns of air pollution in China from 2015 to 2018 and implications for health risks. Environ. Pollut. 258, 113659. https://doi.org/10.1016/j.envpol.2019.113659.

Kumar, N., Park, R.J., Jeong, J.I., Woo, J.-H., Kim, Y., Johnson, J., Yarwood, G., Kang, S., Chun, S., Knipping, E., 2021. Contributions of international sources to PM2.5 in South Korea. Atmos. Environ. 261, 118542. https://doi.org/10.1016/j.atmosenv.2021.118542.

Li, Y., Yang, C., Li, Y., Kumar, A., Kleeman, M.J., 2022. Future emissions of particles and gases that cause regional air pollution in California under different greenhouse gas mitigation strategies. Atmos. Environ. 273, 118960. https://doi.org/10.1016/j.atmosenv.2022.118960.

Liu, J., Kiesewetter, G., Klimont, Z., Cofala, J., Heyes, C., Schopp, W., Zhu, T., Cao, G., Sanabria, A., Sander, R., Guo, F., Zhang, Q., Nguyen, B., Bertok, I., Rafaj, P., Amann, M., 2019. Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. Environ. Int. 125, 236–244. https://doi.org/10.1016/j.envint.2018.09.059.

Liu, J., Mauzerall, D., Chen, Q., Zhang, Q., Song, Y., Peng, W., Klimont, Z., Qiu, X., Zhang, S., Hu, M., Lin, W., Smith, K., Zhu, T., 2016. Air pollutant emissions from Chinese households: a major and underappreciated ambient pollution source. Proc. Natl. Acad. Sci. U. S. A. 113, 7756–7761. https://doi.org/10.1073/pnas.1604537113.

Ma, T., Zhang, S., Xiao, Y., Liu, X., Wang, M., Wu, K., Shen, G., Huang, C., Fang, Y.R., Xie, Y., 2023. Costs and health benefits of the rural energy transition to carbon neutrality in China. Nat. Commun. 14, 6101. https://doi.org/10.1038/s41467-023-41707-7.

Mac Kinnon, M., Zhu, S., Cervantes, A., Dabdub, D., Samuelsen, G., 2021. Benefits of near-zero freight: the air quality and health impacts of low-NOx compressed natural gas trucks. J. Air Waste Manag. Assoc. 71, 1428–1444. https://doi.org/10.1080/10962247.2021.1957727.

Maeyama, H., 2020. Market report: Japan. Heat Pump Therm. Stor. Technol. Center Japan.

OECD, 2022a. The economic benefits of international co-operation to improve air quality in Northeast Asia: a focus on Japan. Korea and China (OECD Environment Working Papers No. 197). OECD Environment Working Papers. https://doi.org/10.1787/5c5ee1a3-en.

OECD, 2022b. International Energy Agency. The Future of Heat Pumps. OECD. https://doi.org/10.1787/2bd71107-en.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., Van Ruijven, B.J., Van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Otsuki, T., Mohd Isa, A.B., Samuelson, R.D., 2016. Electric power grid interconnections in Northeast Asia: a quantitative analysis of opportunities and challenges. Energy Policy 89, 311–329. https://doi.org/10.1016/j.enpol.2015.11.021.

Peng, W., Yang, J., Lu, X., Mauzerall, D., 2018. Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China. Appl. Energy 218, 511–519. https://doi.org/10.1016/j.apenergy.2018.02.048.

Power Plant Tracker, 2018. Enerdata.

Rafaj, P., Kiesewetter, G., Krey, V., Schoepp, W., Bertram, C., Drouet, L., Fricko, O., Fujimori, S., Harmsen, M., Hilaire, J., Huppmann, D., Klimont, Z., Kolp, P., Reis, L., van Vuuren, D., 2021. Air quality and health implications of 1.5 degrees C-2 degrees C climate pathways under considerations of ageing population: a multi-model scenario analysis. Environ. Res. Lett. 16, 045005. https://doi.org/10.1088/1748-9326/abdf0b.

Sarigiannis, D.A., Karakitsios, S.P., Kermenidou, M., Nikolaki, S., Zikopoulos, D., Semelidis, S., Papagiannakis, A., Tzimou, R., 2014. Total exposure to airborne particulate matter in cities: the effect of biomass combustion. Sci. Total Environ. 493, 795–805. https://doi.org/10.1016/j.scitotenv.2014.06.055.

Shen, G., Ru, M., Du, W., Zhu, X., Zhong, Q., Chen, Y., Shen, H., Yun, X., Meng, W., Liu, J., Cheng, H., Hu, J., Guan, D., Tao, S., 2019. Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. Nat. Commun. 10, 3405. https://doi.org/10.1038/s41467-019-11453-w.

United Nations Department of Economic and Social Affairs, 2011. World Population Prospects: The 2010 Revision. New York.

Vos, T., Lim, S.S., Abbafati, C., Abbas, K.M., Abbasi, M., Abbasifard, M., Abbasi-Kangevari, M., Abbastabar, H., Abd-Allah, F., Abdelalim, A., Abdollahi, M., Abdollahpour, I., Abolhassani, H., Aboyans, V., Abrams, E.M., Abreu, L.G., Abrigo, M.R.M., Abu-Raddad, L.J., Abushouk, A.I., Murray, C.J.L., 2020. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396, 1204–1222. https://doi.org/10.1016/S0140-6736(20)30925-9.

Wei, D., Zhang, Z., Wang, Y., Zhu, Z., Wu, L., Wang, T., Sun, B., 2024. Numerical simulation of hydrogen co-firing distribution on combustion characteristics and NOx release in a 660 MW power plant boiler. Energy 305, 132336. https://doi.org/10.1016/j.energy.2024.132336.

Westervelt, D.M., Ma, C.T., He, M.Z., Fiore, A.M., Kinney, P.L., Kioumourtzoglou, M.-A., Wang, S., Xing, J., Ding, D., Correa, G., 2019. Mid-21st century ozone air quality and health burden in China under emissions scenarios and climate change. Environ. Res. Lett. 14, 074030. https://doi.org/10.1088/1748-9326/ab260b.

Xue, Y., Zhou, Z., Nie, T., Wang, K., Nie, L., Pan, T., Wu, X., Tian, H., Zhong, L., Li, J., Liu, H., Liu, S., Shao, P., 2016. Trends of multiple air pollutants emissions from residential coal combustion in Beijing and its implication on improving air quality for control measures. Atmos. Environ. 142, 303–312. https://doi.org/10.1016/j.atmosenv.2016.08.004.

Yamaguchi, S., 2018. Asian international grid connection and potentiality of DC superconducting power transmission 1.

Yang, T., Shu, Y., Zhang, S., Wang, H., Zhu, J., Wang, F., 2023. Impacts of end-use electrification on air quality and CO2 emissions in China's northern cities in 2030. Energy 278, 127899. https://doi.org/10.1016/j.energy.2023.127899.

Yeo, M.J., Jung, C.H., Kim, Y.P., 2025. Ambient fine particles in Korea: past, present, and future. J. Korean Soc. Atmosp. Environ. 41, 219–253. https://doi.org/10.5572/KOSAE.2025.41.2.219.

Yim, S., Gu, Y., Shapiro, M., Stephens, B., 2019. Air quality and acid deposition impacts of local emissions and transboundary air pollution in Japan and South Korea. Atmos. Chem. Phys. 19, 13309–13323. https://doi.org/10.5194/acp-19-13309-2019.

Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., Xu, X., Wang, J., He, H., Liu, W., Ding, Y., Lei, Y., Li, J., Wang, Z., Zhang, X., Wang, Y., Cheng, J., Liu, Y., Shi, Q., Yan, L., Geng, G., Hong, C., Li, M., Liu, F., Zheng, B., Cao, J., Ding, A., Gao, J., Fu, Q., Huo, J., Liu, B., Liu, Z., Yang, F., He, K., Hao, J., 2019a. Drivers of improved PM2.5 air quality in China from 2013 to 2017. Proc. Natl. Acad. Sci. U. S. A. 116, 24463–24469. https://doi.org/10.1073/pnas.1907956116.

Zhang, X., Jin, Y., Dai, H., Xie, Y., Zhang, S., 2019b. Health and economic benefits of cleaner residential heating in the Beijing–Tianjin–Hebei region in China. Energy Policy 127, 165–178. https://doi.org/10.1016/j.enpol.2018.12.008.

Zhao, B., Wang, S., Hao, J., 2024. Challenges and perspectives of air pollution control in China. Front. Environ. Sci. Eng. 18, 68. https://doi.org/10.1007/s11783-024-1828-z.

Further reading

Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, C., Purohit, P., Borken-Kleefeld, J., Wagner, F., Sander, R., Fagerli, H., Nyiri, A., Cozzi, L., Pavarini, C., 2020. Reducing global air pollution: the scope for further policy interventions. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 378, 20190331. https://doi.org/10.1098/rsta.2019.0331.