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Attribution of Solar Energy Yield Gaps due to Transboundary Particulate Matter Pollution Associated with Trade across Northeast Asia

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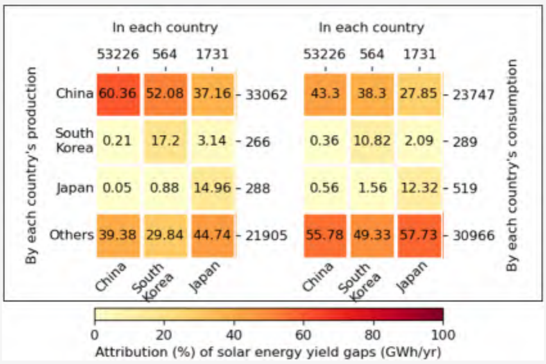
ABSTRACT: The differences between the actual ability to generate solar energy from photovoltaic (PV) panels and the potential ability are denoted as the solar energy yield gap (SEYG). The role of atmospheric particulate matter (PM) and PM deposited on PV panels, associated with domestic and international trade, in attenuating sunlight and influencing SEYGs remains largely unexplored, although their investigation could help mitigate SEYGs. We integrate well-evaluated models of trade, atmospheric composition, and solar PV performance to quantify and attribute the SEYGs that occur in Northeast Asia (NEA) (including China, South Korea, and Japan) to the production and consumption of goods and services within these countries and globally. For utility-scale solar PV facilities, we estimate an SEYG of 33.6 TWh/yr due to the production of goods and services across NEA in 2015. In contrast, the SEYG linked to the consumption of goods and services is lower at 24.6 TWh/yr, with the 9 TWh/yr difference accounting for the net exports outside NEA. Imports have only avoided an SEYG of 1.4 TWh/yr across NEA. Addressing regional SEYGs requires a coordinated response from the producers and consumers of goods and services.



KEYWORDS: *particulate matter, photovoltaics, international trade, satellite, Northeast Asia*

INTRODUCTION

Rapidly transitioning from conventional to renewable energy sources is key to addressing the linked challenges of air pollution and climate change, but it is increasingly recognized that air pollution and climate change affect the supply and demand of renewable energy.[1−4] Whether we continue this vicious cycle or transform it into a virtuous cycle depends on the speed at which we transition away from carbon-based energy sources to meet the growing energy needs of the world's population.

In this study, we examine the impacts of particulate matter (PM) on the functioning of solar photovoltaic (PV) panels. Atmospheric PM significantly impacts solar energy generation by attenuating incoming light intercepted by the panels.[5] PM can also be deposited onto the PV panels, which also attenuates the incoming solar energy needed to excite the electrons in the PV semiconductor material.[6,7] Billions of dollars are lost every year in the solar energy industry due to these PM impacts.[8,9] Previous studies have focused on mitigating the solar energy generation losses by reducing PM emissions from anthropogenic sectors,[10−13] recognizing that natural sources of PM are more difficult to control. These anthropogenic PM emissions originate from producers of goods and services that respond to changes in domestic and international consumer demands.[14] From a production perspective, all emissions generated within a country are considered as its own responsibility regardless of where the associated goods and services are ultimately consumed. In contrast, a consumption perspective attributes all emissions induced by a country's consumption to that country, irrespective of where the emissions are produced. Quantifying and contrasting PM emissions and the resulting solar energy generation losses attributable to both domestic and international producers and consumers would aid in their mitigation, but relevant studies remain scarce.

Northeast Asia (NEA), including China, South Korea, and Japan, is one of the most densely populated regions in the world. As of 2023, it is home to ~1.6 billion people, representing ~20% of the global population.[15] It includes some of the world's largest economies, with its combined GDP in 2023 accounting for ~24% of global GDP, totaling ~$39.59 trillion (at 2021 prices),[16] of which ~42% is related to trade

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(exports and imports of goods and services).[17] Driven in part by rapid economic growth, NEA has long been one of the most polluted hotspot regions globally, leading to significant environmental conflicts among China, South Korea, and Japan.[18] To meet the region's energy demands while mitigating pollution and advancing carbon neutrality goals, NEA is actively developing clean energy technologies, particularly solar energy. As of 2023, the region's total installed solar PV capacity reached ~724.04 GW, contributing to ~51% of the global installed solar PV capacity.[19] All of these unique features (high population density, economic prominence, severe PM pollution, and a leading solar energy industry) make NEA an ideal case for attribution analysis of solar energy generation losses due to transboundary PM pollution associated with trade, paving the way for a broader subsequent global analysis.

To estimate and attribute the regional solar energy yield gap (SEYG) across NEA due to PM emissions, we integrate models that describe regional trade fluxes that can be translated in PM emissions;[20] atmospheric chemistry and transport that describe how PM evolves in space and time;[21] radiative transfer that describes how atmospheric and deposited PM attenuate incoming sunlight;[7,11,22] and a solar PV performance model[23] that describes how attenuated light from atmospheric and deposited PM affects SEYGs. We quantify SEYGs using the difference between actual and potential maximum values, if excluding PM impacts, based on the solar PV electricity generation. The solar PV electricity generation is determined by combining solar PV efficiency described by capacity factors (CFs)—defined as the ratio of a PV panel's actual power output to its maximum possible output[7,8,11]—outputted from the integrated model with satellite-derived solar PV installations data.[24] We distinguish between the roles of atmospheric and deposited PM, which we denote as PM dimming and soiling, respectively.

Our experimental design allows us to examine the: (1) geographical distribution of solar PV efficiency and how it is influenced by PM associated with trade; (2) country-level attribution of SEYGs across NEA due to domestic and international production and consumption of goods and services; and (3) sensitivity of the SEYG estimates and attributions to the cleaning of PV panels, either by rainfall or manual labor.

MATERIALS AND METHODS

We take four steps to estimate SEYGs due to transboundary PM pollution associated with trade across the NEA (Figure S1). First, we use a multiregional input−output model[20] to track the flow of goods and services among China, South Korea, and Japan, and thereby the associated emissions responsible for transboundary PM pollution. Second, we use the GEOS−Chem chemical transport model[21] to simulate the PM levels in the atmosphere and on solar panels, the latter of which is further modulated by rainfall and panel cleaning practices. The built-in radiative transfer module in GEOS−Chem,[22] alongside a custom approach governing how solar radiation is reduced by PM accumulation on solar panels,[7,11] allows us to estimate the final solar radiation that reaches the solar cells. Third, we use the PVLIB−Python model[23] to estimate the solar PV efficiency of three widely used solar panel configurations: horizontal fixed (Flat), fixed with optimal tilt (Tilt), and one−axis tracking (OAT). Finally, we integrate the modeled solar PV efficiency with satellite-derived solar PV installation data[24] to estimate the solar PV electricity generation and its losses (aka SEYGs) due to transboundary PM pollution associated with trade across NEA. We give detailed descriptions of these steps in the Supporting Methods.

Our previous work[11] has extensively evaluated the performance of the integrated model against a range of *in situ* measurements of various PM-related variables, and we provide in the Supporting Methods an expanded evaluation of the model's performance in relation to *in situ* measurements of these variables across NEA, reflecting updates to emission inputs and the inclusion of additional observational data. We find that the integrated model performs reasonably well, though there remain areas for improvement. However, these areas for improvement do not impact the accuracy of quantifying source−receptor relationships for SEYGs across NEA in terms of self- and mutual percentage contributions, as discussed in the Supporting Methods.

We design a total of 16 major scenarios (Table S1), each with three subscenarios (Table S2), to attribute losses in solar PV efficiency (referred to as ΔCFs)—and consequently, solar PV electricity generation (referred to as SEYGs)—to transboundary PM pollution associated with trade across NEA. For each major scenario, its three subscenarios help isolate ΔCFs and SEYGs associated with PM dimming (e.g., $\Delta\text{CF}_{\text{Dimming}} = \text{CF}_{\text{NODimming}}^{\text{NOSoiling}} - \text{CF}_{\text{Dimming}}^{\text{NOSoiling}}$), soiling (e.g., $\Delta\text{CF}_{\text{Soiling}} = \text{CF}_{\text{Dimming}}^{\text{NOSoiling}} - \text{CF}_{\text{Dimming}}^{\text{Soiling}}$), and a combination of the two (e.g., $\Delta\text{CF}_{\text{Dimming+Soiling}} = \Delta\text{CF}_{\text{Dimming}} + \Delta\text{CF}_{\text{Soiling}} = \text{CF}_{\text{NODimming}}^{\text{NOSoiling}} - \text{CF}_{\text{Dimming}}^{\text{Soiling}}$). Using a zero-out approach,[25] scenarios 2−4 decompose ΔCFs and SEYGs into components associated with emissions produced in China, South Korea, Japan, and elsewhere, e.g., $\Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1}} = \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S2}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S3}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S4}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{Remaining}}$. Similarly, scenarios 5−7 decompose ΔCFs and SEYGs into components associated with emissions induced by consumption in China, South Korea, Japan, and elsewhere, e.g., $\Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1}} = \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S5}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S6}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S7}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{Remaining}}$. Further, scenarios 8−10 decompose ΔCFs and SEYGs due to emissions produced in China into components associated with emissions induced by consumption in China, South Korea, Japan, and elsewhere, e.g., $\Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S2}} = \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S8}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S9}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S10}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{Remaining}}$. Likewise, scenarios 11−13 and 14−16 decompose ΔCFs and SEYGs due to emissions produced in South Korea and Japan, respectively, into components associated with emissions induced by consumption in China, South Korea, Japan, and elsewhere, e.g., $\Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S3}} = \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S11}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S12}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S13}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{Remaining}}$, and $\Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S4}} = \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S14}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S15}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{S1−S16}} + \Delta\text{CF}_{\text{Dimming + Soiling}}^{\text{Remaining}}$. In short, scenarios 2−7 provide a comprehensive production− and consumption-based accounting of ΔCFs and SEYGs due to transboundary PM pollution associated with trade across NEA. We also apply a two-tailed paired *t*-test to assess the statistical significance of the differences between these two sets of results. Additionally, scenarios 8−16 offer a detailed breakdown of the production-based ΔCFs and SEYGs obtained in scenarios 2−4. By contrasting these with the consumption-based SEYGs from scenarios 5−7, we gain insights into the SEYGs associated with exports versus imports across NEA.

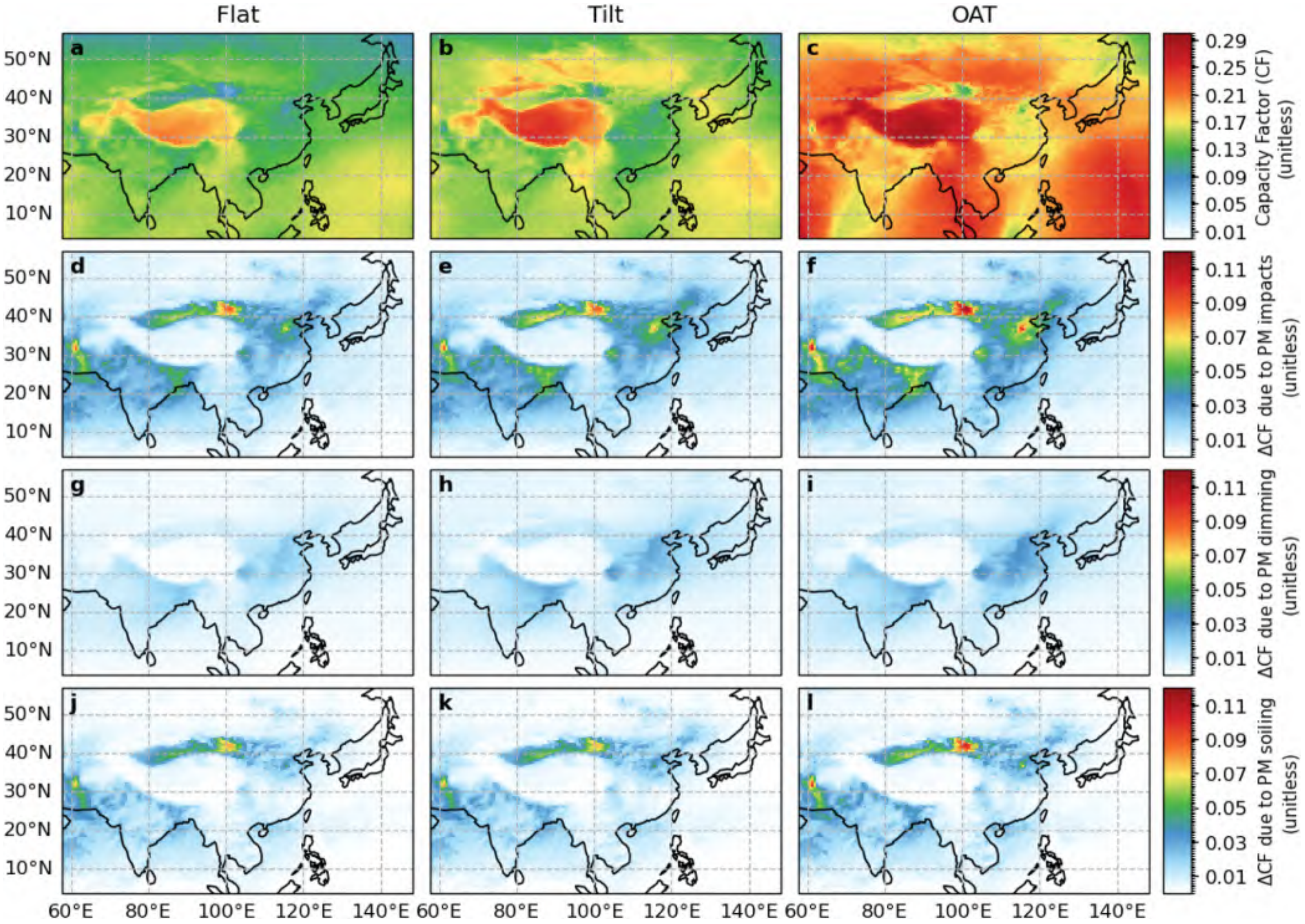

Figure 1. Geographical distribution of annual mean solar PV efficiency (a−c) described by capacity factors (CFs) and its losses (ΔCFs) due to PM pollution (d−f), including PM dimming (g−i) and soiling (j−l), for flat (a, d, g, j), tilt (b, e, h, k), and one-axis tracking (c, f, i, l) panels over Northeast Asia in 2015. Scales are different for the first and subsequent rows.

RESULTS AND DISCUSSION

Solar PV Efficiency and Its Modulation by PM Associated with Trade. Figure 1 shows solar PV efficiency (CFs) and its losses (ΔCFs) due to PM dimming and soiling for flat, tilt, and one-axis tracking panels across NEA, building on our previous work.[11] Compared to the flat panels, tilt panels show increased solar PV efficiency in northern high latitudes, and OAT panels show increased solar PV efficiency across the entire study domain. In contrast, losses in solar PV efficiency due to PM dimming and soiling exhibit more consistent spatial patterns across the three types of panels, with the magnitude of losses increasing progressively from flat to tilted and then to OAT panels. PM dimming primarily affects northern and eastern China, China's Sichuan Basin, and over the eastern Indo-Gangetic Plain[26] including Bangladesh, while PM soiling mainly impacts the Gobi Desert. PM soiling in magnitude is comparable to PM dimming, except over the Gobi Desert, where it exceeds double the maximum PM dimming observed in eastern China (0.11 versus 0.05). Given the similar spatial patterns of solar PV efficiency losses due to PM pollution across the three types of panels and their attribution to domestic and international production and consumption of goods and services across NEA (in work not shown), we onward focus on OAT panels for the discussion of the results. These panels offer superior performance and closely align with the satellite-derived solar PV installations data[24] used in this work.

Figure 2 illustrates the grid-level attribution of solar PV efficiency losses in OAT panels to domestic and international production and consumption of goods and services across NEA. Generally, we find that PM emissions, irrespective of whether they are associated with the production or consumption of goods and services, lead to the largest reductions in solar PV efficiency in the country where the production or consumption occurs, with smaller impacts over the immediately adjacent countries. PM emissions from the production of goods and services in one country reduce solar PV efficiency in another country exclusively by atmospheric transport, while solar PV efficiency losses in one country due to PM emissions from the consumption of goods and services in another country involve atmospheric transport of PM and international trade. Figure 2, along with Figure S2, shows that losses in solar PV efficiency are smaller from a consumption-centric, rather than a production-centric, viewpoint, both for the three countries individually and for the upwind−downwind relationships among them, including those from China to South Korea and Japan, and from South Korea to Japan. An opposite pattern is observed for the "Others" category and for the downwind−upwind relationships among the three countries, including those from Japan to South Korea and China, and from South Korea to China. This contrast suggests

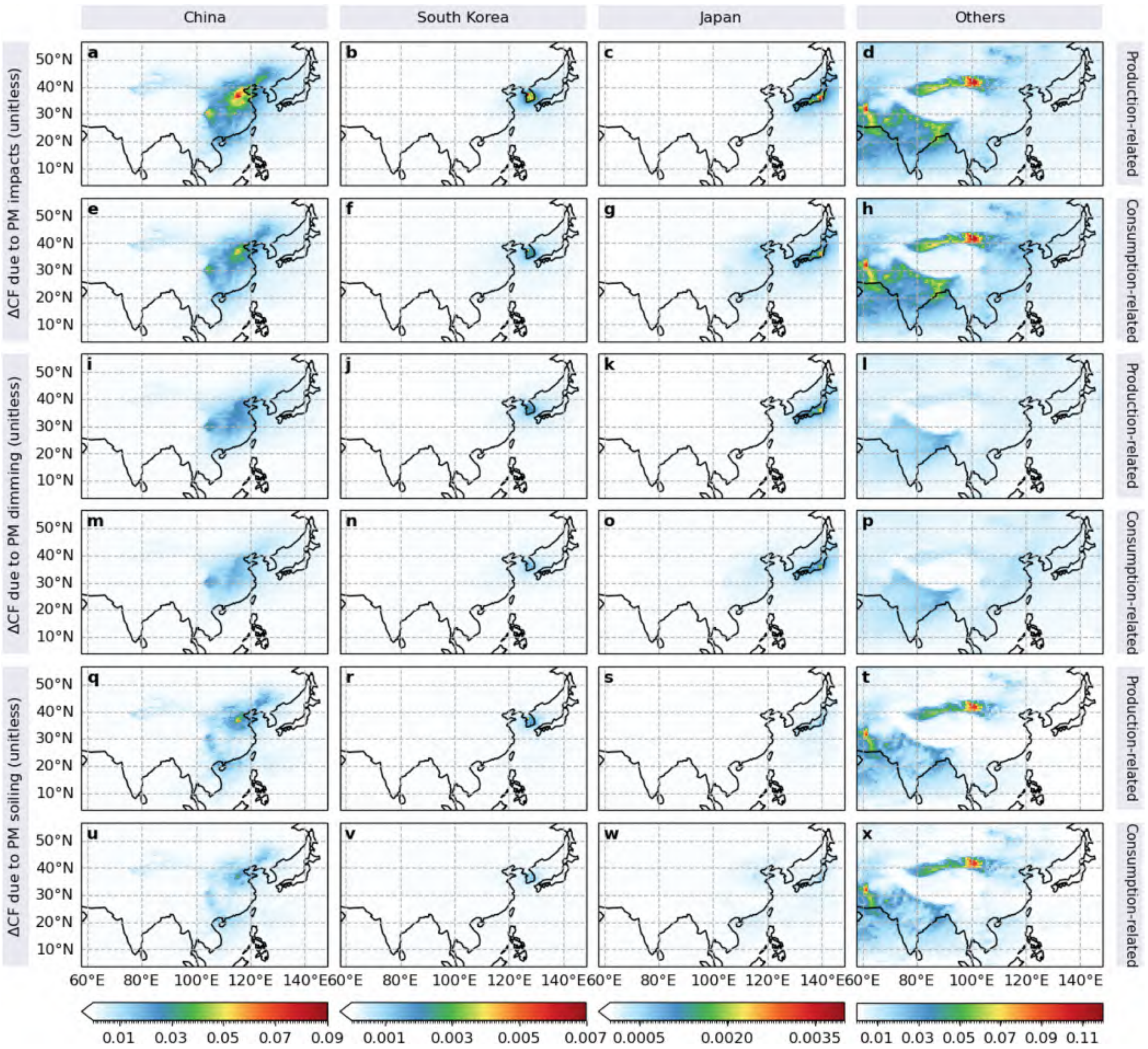

Figure 2. Geographical distribution of annual mean solar PV efficiency losses (ΔCFs) in OAT panels due to PM pollution (a−h), including PM dimming (i−p) and soiling (q−x), associated with emissions produced in (a−d, i−l, q−t) or induced by consumption (e−h, m−p, u−x) in China (a, e, i, m, q, u), South Korea (b, f, j, n, r, v), Japan (c, g, k, o, s, w), and "Others" (d, h, l, p, t, x) over Northeast Asia in 2015. Note that "Others" encompasses contributions from other countries and other natural sources of PM, but the latter cancels out when subtracting production-based results from consumption-based results, leaving only the contributions from net exports outside Northeast Asia. Scales are different for each column.

narrower gaps in mutual contributions to solar PV efficiency losses from a consumption-centric, rather than a production-centric, perspective among China, South Korea, and Japan, which are all significantly influenced by the net exports of goods and services outside NEA. The differences between losses in solar PV efficiency due to PM dimming and soiling are generally small (Figure S3), except over the Gobi Desert, where natural sources of PM result in significant levels of PM soiling that are not correlated with either the production or consumption of goods and services.

Attribution of PM-Related SEYGs to the Production and Consumption of Goods and Services. Figure 3 shows a numerical breakdown of the country-level SEYG due to transboundary PM pollution in terms of the production and consumption of goods and services across NEA. As we have seen in the analyses of solar PV efficiency losses, we find that consumption-based SEYG values are smaller than production-based values, both for the three countries individually and for the upwind−downwind relationships among them, including those from China to South Korea and Japan, and from South Korea to Japan. This is reflected by the negative differences shown in the diagonal and upper triangular parts of the heatmaps in Figure 3g−i. Conversely, a reversed pattern is observed for the "Others" category and for the downwind−upwind relationships among the three countries, including those from Japan to South Korea and China, and from South Korea to China. This is reflected by the positive differences shown in the lower triangular parts of the heatmaps in Figure

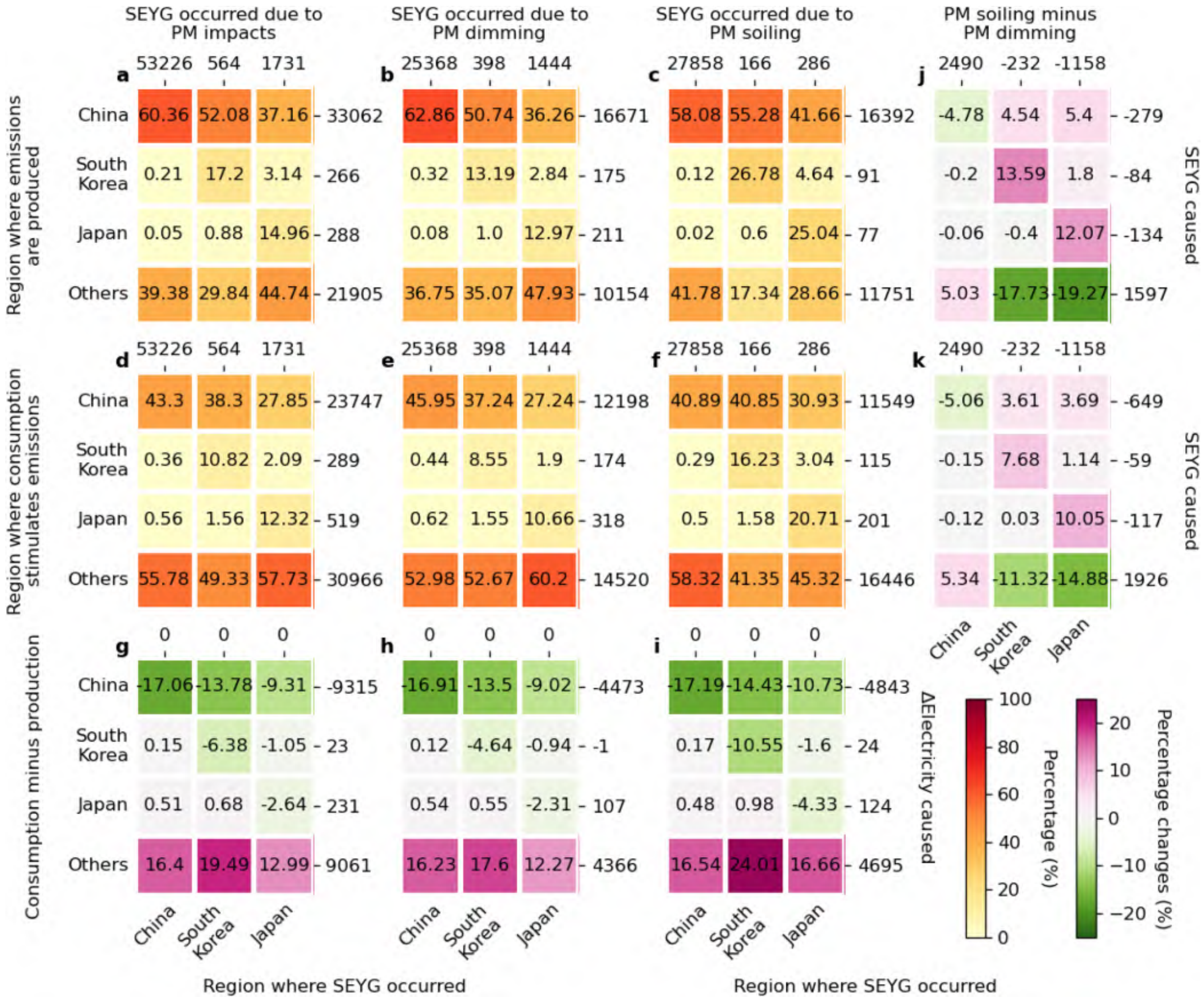

Figure 3. Contributions from source countrys' production-related (a–c) and consumption-related (d–f) emissions to receptor countrys' solar energy yield gaps (SEYGs) attributable to PM pollution (a, d), including PM dimming (b, e) and soiling (c, f). Each cell in the grid shows the proportion of SEYGs that occurred in the country indicated by the column due to emissions produced in or induced by consumption in the country indicated by the row, wherein consumption stimulates emissions domestically and elsewhere. The diagonal thus reflects the proportion of SEYGs in a country due to emissions produced in or induced by consumption within the same country. At the top, the total SEYGs (GWh/yr) that occurred in each country are presented, while on the right, the total SEYGs (GWh/yr) in the three countries (aka Northeast Asia) caused by emissions produced in or induced by consumption in each country are outlined. Notably, the sum of the numbers at the top equals the sum on the right. (g–i) Differences between consumption- and production-related results. (j, k) Differences between PM soiling and dimming.

3g–i. The differences between the consumption-based and production-based SEYG values are statistically significant (Figure S4), highlighting closer interdependence among China, South Korea, and Japan in their mutual contributions to solar PV efficiency losses from a consumption-centric, rather than a production-centric, standpoint, as well as the important role of net exports of goods and services outside NEA in determining the SEYG values across the region. Although we continue to observe similar contrasting patterns between PM dimming and soiling in consumption- and production-based SEYG values (Figure 3j,k), these patterns become slightly more noticeable as a result of aggregation. Nonetheless, our immediate focus is on reducing their combined impacts rather than on addressing them individually.

Figure 3a–c further illustrates that China plays the largest role in determining production-based SEYGs in China, South Korea, and Japan (for PM soiling only). In contrast, Figure 3d-f reveals that consumption-based SEYGs are primarily driven by the "Others" category in these three countries. Additionally, China causes more production- than consumption-based SEYGs in NEA, whereas the opposite is true for South Korea, Japan, and the "Others" category (Figure 3g–i). Of the total 33.6 TWh/yr SEYG in NEA resulting from the production of goods and services across the region, about 3.4% (1.1 TWh/yr) is related to the production of goods and services in a different NEA country from where the SEYG occurred. In contrast, of the total 24.6 TWh/yr SEYG in NEA due to consumption of goods and services across the region, about 5.0% (1.2 TWh/yr) is related to the consumption of goods and services in a different NEA country from where the SEYG occurred. All of these findings indicate that, when considering trade, the responsibility for SEYGs in NEA is more

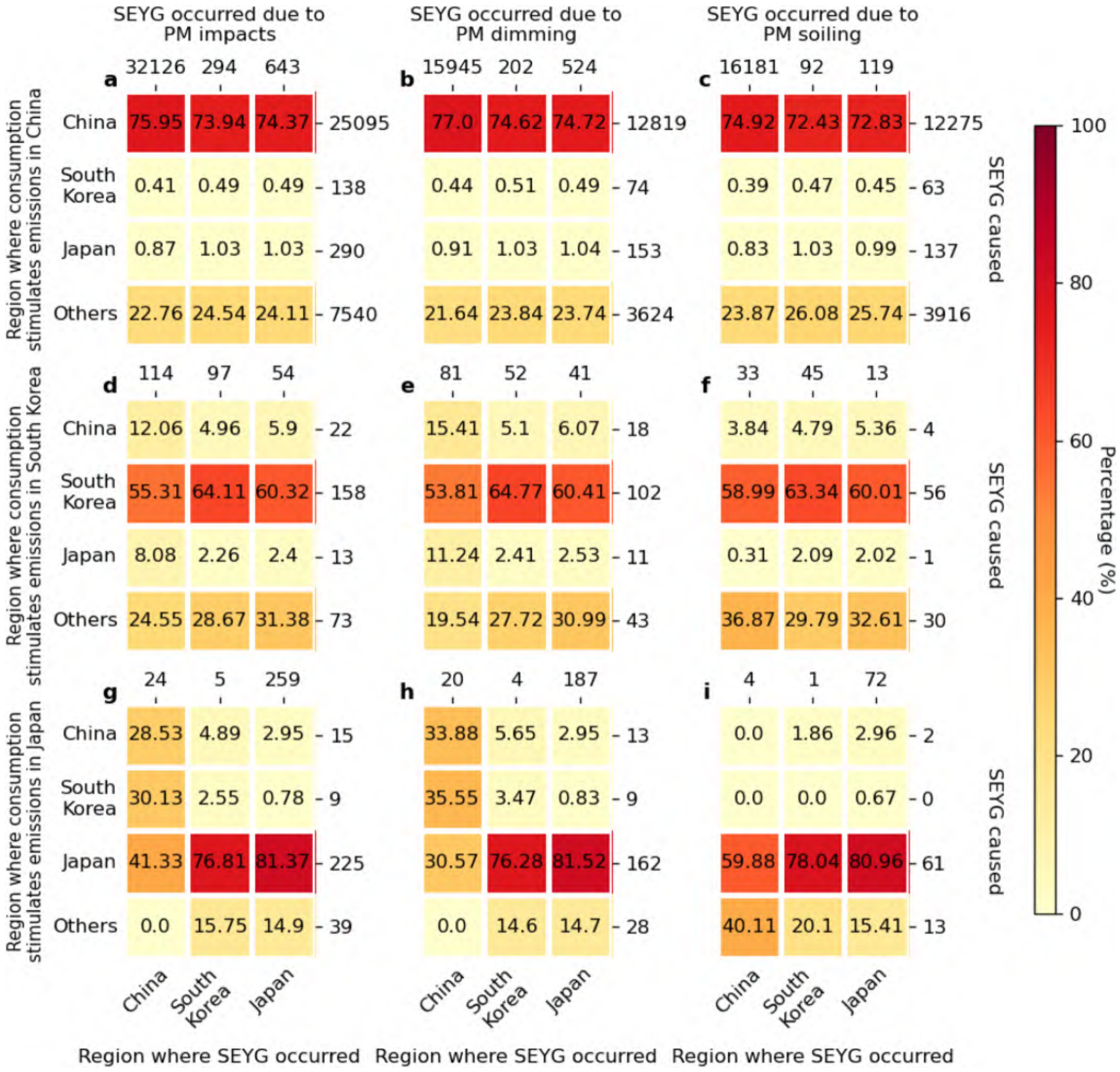

Figure 4. Contributions of production-related emissions from China (a–c), South Korea (d–f), and Japan (g–i) to solar energy yield gaps (SEYGs) in Northeast Asia due to PM pollution (a, d, g), including PM dimming (b, e, h) and soiling (c, f, i), further broken down to components linked to consumption in these countries and elsewhere. Each cell in the grid shows the proportion of SEYGs that occurred in the country indicated by the column due to emissions produced in a Northeast Asian country that are induced by consumption in the country indicated by the row. The diagonal thus reflects the proportion of SEYGs in a country due to emissions produced in a Northeast Asian country and induced by its own consumption. At the top, the total SEYGs (GWh/yr) occurred in each country due to emissions produced in a Northeast Asian country are presented, while on the right, the total SEYGs (GWh/yr) in the three countries caused by emissions produced in a Northeast Asian country that are induced by consumption in each country are outlined. Notably, the sum of the numbers at the top equals the sum at the right.

evenly distributed among China, South Korea, Japan, and other regions.

Figure 4 and our broader analysis (Figures S5–S7) result in the same conclusion: the SEYGs from PM dimming and soiling due to emissions produced in a Northeast Asian country are primarily driven by consumption within that country, followed by consumption outside NEA. Of the total 33.6 TWh/yr SEYG across NEA due to PM dimming and soiling associated with emissions in NEA, about 23% (7.7 TWh/yr) is related to consumption outside NEA. When we disaggregate this regional estimate into country values, we find for China, South Korea, and Japan that 23% (7.3 TWh/yr out of 32.3 TWh/yr), 25% (0.1 TWh/yr out of 0.4 TWh/yr), and 22% (0.21 TWh/yr out of 0.96 TWh/yr), respectively, can be attributed to consumption outside NEA. Figure S8 suggests that countries outside NEA contributing to this consumption likely include the United States, the European Union (e.g., Germany), and other Asian countries (e.g., India), though we have not quantified their specific contributions, as that level of analysis is slightly beyond the scope of this study.

The differences between SEYGs due to emissions linked to goods and services ultimately consumed in a country/region and those linked to goods and services produced in a country/region, as shown in Figure 3g−i, reflect the impact of net imports on a country/region's solar energy generation. Using the SEYGs associated with a country/region's exports, as illustrated in Figure 4, we can easily derive the SEYGs embodied in exports versus imports across NEA, which we summarize in Table 1. Overall, NEA acts primarily as a net exporter, with exports accounting for up to 7.7 TWh/yr of SEYGs in 2015, while imports only offset 1.4 TWh/yr of SEYGs in the same year.

Table 1. Solar Energy Yield Gaps (SEYGs, GWh yr^{-1}) Embodied in Imports Versus Exports across Northeast Asia in 2015[a]

		China	South Korea	Japan	Northeast Asia
SEYGs due to PM pollution associated with	exports	7726.23	34.82	48.26	7652.53
	imports	−1350.71	−1.18	2.56	−1408.92
	net imports	−9076.94	−36.00	−45.70	−9061.45
SEYGs due to PM dimming associated with	exports	3667.56	18.48	34.60	3694.75
	imports	−620.98	0.04	1.29	−671.73
	net imports	−4288.54	−18.44	−33.31	−4366.48
SEYGs due to PM soiling associated with	exports	4058.67	16.34	13.65	3959.39
	imports	−729.73	−1.23	1.26	−735.59
	net imports	−4788.41	−17.56	−12.39	−4694.98

[a] Net imports are derived by contrasting scenarios 5−7 with scenarios 2−4. Exports are derived using scenarios 8−16. Imports are derived from the sum of exports and net imports.

PM-Related SEYGs' Attributions Mostly Insensitive to Rainfall and Panel Cleaning Practices. Previous work has highlighted the significant benefits of rainfall and panel cleaning practices in reducing SEYGs due to PM pollution.[7,11] To investigate the potential impact of these mitigation strategies on the source−receptor relationships of SEYGs across NEA, we rerun all our calculations by excluding the role of rainfall and incorporating the panel cleaning practice at varying frequencies. We then compare the results with those from the baseline run described earlier. We expect, based on previous work, that these changes will affect mostly PM soiling. For brevity, we present only country-level results in Figures S9−S12. We find that the rainfall and the frequency that panels are cleaned result in noticeable reductions in SEYGs, as expected. Nonetheless, we find that the percentage differences between the sets of reruns and the baseline run are typically within ±15% for scenarios 2−7 and ±5% for scenarios 8−16. Consequently, the source−receptor relationships of SEYGs across NEA, determined by changes in meteorology, remain consistent with the baseline calculations. Similarly, the main conclusions reached from the baseline calculations remain unchanged.

Policy Implications and Concluding Remarks. A wide range of environmental[27−38] and social[39−43] impacts embodied in trade have been assessed from a consumption perspective. Our work is the first to extend this perspective to include large SEYGs attributable to PM pollution. Our work is timely because of the rapid expansion of solar energy projects in the region to meet the growing energy demands and to achieve carbon neutrality.

To mitigate SEYGs caused by PM pollution, current policy efforts primarily focus on the timely cleaning of panels to remove deposited PM[7] and on reducing anthropogenic emissions through domestic measures.[11] By further linking SEYGs to international trade, our work highlights additional opportunities for addressing SEYGs from a trade-related perspective. These trade-related policies may include, but are not limited to (1) adjustments of border taxes and tariffs to account for SEYGs, similar to current practices on carbon emissions such as the European Union's Carbon Border Adjustment Mechanism; (2) widening of technical and environmental standards to help reduce domestic and outsourced environmental impacts; (3) transfer of technology to help circumvent avoidable environmental impacts; and (4) interventions aimed at curbing unnecessary, unsustainable consumption.[44] We acknowledge that these policies are necessarily general due to the aggregated nature of our analysis, which limits the granularity required for more targeted policy design. One possible way to overcome this limitation in future work is to develop the adjoint of the integrated model presented in this work. The adjoint model[45] would enable us to efficiently compute the source contributions to SEYGs at detailed sectoral and chemical species levels, across space and time, from both production and consumption perspectives. This improvement would offer more direct and actionable insights for policymakers.

Our work has several limitations that we discuss here and that should be addressed in future research. First, the discrepancies between modeled and observed PM levels may arise from limitations in the emission inventories and the physical and chemical processes represented in the GEOS−Chem model. While we believe that these discrepancies do not affect our findings on the source−receptor relationships of SEYGs across NEA in terms of self- and mutual contributions (Supporting Methods), we acknowledge that improvements in these areas would enhance the accuracy of our results. For absolute SEYGs, we highlight in the Supporting Methods that they are intended as an illustrative yet spatially meaningful demonstration of the worst-case scenarios for the year 2015. This is due to the time mismatch of multisource, imperfect data involved in their calculations that should not be overinterpreted. Second, the source−receptor relationships of SEYGs revealed in this study are for NEA and for the relatively old year 2015, likely limited in reflecting current trade, pollution, and solar energy development. A global analysis focusing on more recent years is thus warranted.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c05935.

> Additional details on model setup, evaluation, and uncertainty analysis; experimental design; mapping between MRIO and EDGARv5 tables; contrasts between production-based and consumption-based accounting of PM emissions and consequently solar PV efficiency losses, as well as between PM dimming and soiling; the role of precipitation and panel cleaning; and the geographical distributions of solar panels across Northeast Asia (PDF)

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Author Contributions

The initial draft was prepared by F.Y., with review and editing by P.I.P. The modeling was performed by F.Y., with additional support from J.L. and H.C. The formal analysis was conducted by F.Y., with further assistance from P.I.P., J.L., and Y.W.

Notes

The authors declare no competing financial interest.

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