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Assessing co-benefits incentivizes climate-mitigation action

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To lessen the myriad impacts of climate change, the world faces the daunting task of transitioning away from fossil-fuel-based infrastructure. In this issue of *One Earth*, Peng et al. demonstrate that such a transition in China's transportation and power-generation sectors could additionally provide substantial health and economic benefits, further incentivizing sustainable development pathways.

Emission and accumulation of greenhouse gases in Earth's atmosphere has increased radiative forcing, led to global climatic change, and altered both the frequency and intensity of extreme meteorological events.[1] A quick scan of global headlines on almost any given day reveals record-breaking and often unprecedented meteorological conditions and attendant human suffering. Projections indicate that the coming decades could be worse—without deep decarbonization, the frequency, severity, and/or duration of heat waves, drought, deluge, and other meteorological calamities are likely to increase. To forestall and/or lessen future climate change, decarbonization is key.

Although carbon-intensive technologies currently power many of the necessities and conveniences that comprise our expected standards of living, low-carbon, carbon-neutral, and negative-carbon alternatives are fast developing and becoming more affordable. Innovation is needed because essential services like transportation and power generation account for a substantial fraction of energy-related global carbon emissions, around 23% and 40% respectively.[2] A key strategy in the decarbonization transition is the aim to *electrify everything*, with the idea that the electric grid—currently composed of a mix of combustion, renewable, and nuclear-generation units—will become cleaner and greener over time, as will any electric device, appliance, or vehicle that plugs into it.

Despite the established links between carbon emissions and past and future meteorological calamity, barriers to decarbonization are substantial. In a comprehensive report,[3] the International Energy Agency (IEA) detailed the substantial costs, requisite leaps in innovation, and institutional and regulatory changes needed to attain net-zero emissions by 2050. Although the task is formidable, reports like those from the IEA suggest it is also achievable. Among the most compelling and therefore viable carbon-reduction measures proposed are those with socio-economic and/or public health co-benefits.[4] In this issue of *One Earth*, Peng et al.[5] use a co-benefits analysis framework to make the case for coupled decarbonization of China's transportation and power-generation sectors. Their analysis focuses on the impending transition to alternative-energy vehicles (AEVs, the majority of which are electric vehicles) and their potential to not only reduce carbon emissions but also improve air quality. Peng et al.[5] simulate 11 different AEV penetration/power-generation scenarios with a chemical transport model that is capable of constraining spatiotemporal changes in both primary (e.g., PM, CO, NO_x, SO_x, and VOCs) and secondary pollutants (e.g., O_3 and secondary organic aerosols). Their article highlights the tremendous economic and public-health benefits of AEV adoption when conducted in concert with grid decarbonization; for example, if all of China's vehicles are replaced by AEVs, coupled with a 91% non-fossil-fuel energy system, about 329,000 air-pollution-associated premature deaths could be avoided annually. However, their results also indicate that AEV adoption without expansion of renewable power generation could offset transportation-sector gains and have undesirable health outcomes.

Constraining the co-benefits and potential tradeoffs of the adoption of sustainable climate solutions is non-trivial.[6] For carbon dioxide, a well-mixed greenhouse gas, changes in its emission can be directly related to changes in its atmospheric abundance, even if the location of the emission is displaced by hundreds of kilometers, for example, from the tailpipe of an internal-combustion-engine vehicle to the smokestack of the power plant that is providing the energy to charge the battery of an electric vehicle. However, the fate of the emissions of many air pollutants and their precursors depends on additional factors. Poor air quality forms in the near-surface environment when meteorological conditions allow emissions and other air pollutants to accumulate and/or form. Emission changes from the adoption of sustainable climate solutions, like electric vehicles or heat pumps, are spatiotemporally heterogeneous, and the potential for these altered emissions to produce hazardous air quality depends on numerous complicating and potentially nonlinear factors such as the background chemical regime (e.g., NO_x versus VOC limited for ozone or NH_3 rich versus NH_3 poor for particulate matter); the relative rates at which co-pollutants are emitted; the proximity to, type, and magnitude of other nearby emissions sources; and even the season and time of day during which emissions occur. In addition, feedbacks between atmospheric chemistry and meteorological conditions can play a substantial role in the formation of hazardous conditions.

Because of these dynamic and interlinked interactions, when considering the air quality co-benefits and tradeoffs of sustainable climate solutions, such as decarbonizing the energy system or electrifying various sectors, it is essential to examine adoption outcomes with coupled tools that assess feedbacks between emissions, atmospheric chemistry, and meteorology. Earth system models, chemistry climate models, and chemical transport models can each serve a purpose in these investigations. In the case of Peng et al.,[5] and other topically similar studies,[7–9] transport-to-grid emission remapping tools were developed and coupled to chemical transport models, providing a robust platform on which to simulate scenario-based AEV remediation initiatives. Experiments using such coupled tools can provide critical insights and reveal unexpected outcomes. For example, Fang et al.[8] identified the spillover effect wherein electrification schemes inequitably shift the burden of pollution from power-hungry urban environments to rural populations with nearby power-generation facilities. Likewise, Peters et al.[9] identified a "permanent" ozone weekend effect in some urban centers when NO_x-emitting and O_3-titrating internal-combustion-engine vehicles were replaced by non-emitting electric vehicles.

Future advances in climate-solution-focused Earth-system science will need to weigh the advantages and tradeoffs of explicitly modeling increasingly complex and interconnected infrastructure systems with more traditional Earth-system-modeling concerns like higher spatial resolutions, signal-to-noise ratios, and computational costs.[10] In the case of constraining air quality co-benefits, an argument could be made for prioritizing simulations that attempt to capture emissions and pollutant changes at neighborhood-scale resolutions. Fine-scale simulations are more likely to resolve local meteorological processes, emission sources, and their interactions and are therefore more likely to capture chemical gradients and accumulation hotspots and identify inequitably impacted communities. Indeed, evidence suggests that quantifying co-beneficial air-quality outcomes of climate-mitigation actions is appealing to citizens and political leaders alike because air-quality improvements tend to be local, near term, and easily recognizable, unlike carbon-mitigation efforts whose benefits tend to have longer time horizons and less easily discernable local benefits.[11]

Widespread electrification of combustion-dominant sectors, as well as increased efficiencies within sectors that are currently electric dominant, offers the potential to both reduce carbon emissions and improve air quality. The extent to which these benefits are realized, as demonstrated by Peng et al.,[5] is largely dependent on the scale of the transition to electrified technologies and the source of electricity generation used to power them. Combustion-generation sources— and therefore greenhouse gas and air-pollutant emission sources—currently comprise ~63% of the world's electric generation. Given the longevity of combustion-generation facilities,[12] near-term air-quality-focused co-beneficial analyses of sustainable climate solutions need to consider the net effect of altered grid demand, emission profiles, and atmospheric chemistry. Novel couplings of energy and Earth system models can help constrain remediation initiative outcomes, whereas economic and health-focused contextualization of co-benefits over a variety of sectors has the potential to make the decarbonization transition more palatable, if not desirable.

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