Co-Benefit Environmental and Health Impact Assessment of Carbon Border Adjustments

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Abstract

Environmental leakage caused by varying carbon prices of different jurisdictions applied to the commonly shared transmission grid can negatively affect carbon emission reduction, air pollution exposure, and health implications for communities. Carbon border adjustment, as a set of constraints imposed on security-constrained economic dispatch, aims to address the environmental leakage by adjusting the dispatch outcomes. This paper presents a framework to assess the changes in air quality and health impacts of carbon prices and border adjustment once applied to the power systems. This is done by calculating the spatial distribution of pollutants based on the output of power system operations and linking it with the air diffusion and epidemiological modeling and mapping tool. We focus on three border adjustment schemes: non-border, one-way, and two-way models currently studied by various RTOs. The results are conducted on a grid with 10,0000 buses geographically encompassing the Western U.S. considering detailed data of generation emission and local socioeconomic conditions at county levels. Results show that individual communities can be impacted differently, even unfairly due to environmental leakage but the intensities can be reduced by appropriate employment of border adjustment. Thus, it is still important to complement carbon border adjustment with renewable energy investment for effective decarbonization and reducing inequity in air pollution exposure.

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***Keywords*—Carbon prices, carbon border adjustments, environmental leakage, air quality, and health impact assessment.**

NOMENCLATURE

Set and indices

$\mathcal{G}$, g	Set and indices of generators
$\mathcal{I}, i$	Set and indices of transmission buses
$\mathcal{L}, \ell$	Set and indices of transmission lines
$\mathcal{C}, \mathcal{NC}$	Carbon-priced and noncarbon-priced regions

Parameters

b_g	Marginal costs of generator g $[\$/MWh]$
π	Price per ton of carbon emissions $[\$/ton]$
D_i	Power demand at bus i $[MW]$
$\rho_g^{\text{CO}_2}$	CO_2 emission rate of generator g $[ton/MWh]$
x_ℓ	Reactance of line ℓ $[p.u.]$
$\underline{P}_g, \overline{P}_g$	Minimum/Maximum capacity of power dispatches of generator g $[MW]$
$\overline{F}_\ell$	Transmission line thermal limit ℓ $[MW]$

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Variables

δ_i	Voltage phase angle of bus i
F_ℓ	Active power flowing in line ℓ $[MW]$
P_g	Physical power dispatch of generator g $[MW]$
P_g^π, P_g^o	Power dispatch portions of generator g with and without carbon price included $[MW]$
η	The locational marginal price of carbon allocation constraint in border adjustment $[\$/MWh]$
λ_i	The shadow price of the nodal balance constraint at bus i $[\$/MWh]$

Air quality and health impact notations

m	Pollutant index, $m \in \{\text{CO}_2, \text{SO}_2, \text{NO}_x\}$
ρ_g^m	Emission rate of generator for pollutant m
e_g^m	Emission of pollutant m by generator g
h	Indexes of adverse health effects (cardiovascular, heart attacks, asthma, ..., etc).
c, s	Indexes of counties in the study
$\Delta e_c^m, \Delta z_c$	changes in emission of pollutant m and equivalent changes in $PM_{2.5}$ in county c.
$T_{s,c}^m$	Transfer coefficient (sec/m^3) for pollutant m from county s to county c
Δy_c^h	Changes in the impact of adverse health effect h in county c.
$Cases^{h,c}_{\text{Avoided}}$	Expected number of cases avoided for an adverse health effect h in county c.
$Benefits_c$	Monetized health impact benefit of emission reduction in county c

I. INTRODUCTION

THE electric power sector is currently one of the leading emitters of carbon dioxides (CO_2) and other criteria pollutants such as NOx, SOx, and $PM_{2.5}$ as byproducts of burning fossil fuels for electricity generation [1]. Exposure to air pollution can lead to harmful health effects, imposing additional costs on customers and society at large [2]. Research suggests that monetized benefits of reducing carbon emissions in the power sector are high for air quality improvements, especially relevant and tangible at the local community level [3]. Carbon pricing is considered an effective approach for power grid decarbonization [4]. Pricing carbon emissions from power plants captures the cost of climate impacts, promotes clean energy sources [5]–[7], and reduces the emissions of harmful pollutants to improve air quality and public health [3]. The obtained tax revenue can be then recycled to subsidize consumers and reinvest in grid assets to enhance grid reliability and resiliency [8]. However, each state in the U.S. individually determines its carbon pricing policy within its jurisdiction [9].

The uneven setting of state-determined carbon prices over the commonly shared and federally regulated transmission network can lead to environmental leakage where carbon emissions and air pollutants induced by dispatches from fuel sources shift from carbon-priced to noncarbon-priced regions. Thus, although the total carbon emission and air pollution can be reduced, the received benefits of individuals can vary due to the local nature of air pollution exposure [10]. Jurisdictions with low-income and disadvantaged communities typically have less restrictive regulations and are more vulnerable to air pollution as they lack financial means and medical access [11].

The Federal Energy Regulatory Commission, as discussed with several RTOs, affirmed the support of integrating state-determined carbon prices in wholesale electricity markets in which environmental leakages must be addressed [12]. The regulation policy that accounts for variance in carbon pricing policies across different jurisdictions to mitigate environmental leakage is carbon border adjustment [1]. It involves import charges and potential rebates on carbon-related products from areas without regulations [13], [14]. When applied to an electric transmission grid, the border adjustment becomes a set of additional constraints imposed on the security-constrained economic dispatch (SCED) to adjust the SCED optimal solution such that the migration of emission-associated power dispatch is mitigated [15]–[18]. However, there is a lack of frameworks and studies for assessing the effectiveness of revising power system operations with the carbon price and border adjustment, especially on air quality and public heaths.

Existing literature in carbon pricing studies generally considers regular physical and economic quantities as design objectives and evaluation metrics (e.g., total emission target [5], renewable energy investment cost [6], clean energy generation mix [7]), assuming a system-wide decarbonization policy applied to the whole power grid. Recently, RTOs and policymakers have conducted several conceptual works on border adjustments and environmental leakage [15]–[18]. CAISO implemented the one-way border adjustment in which emissions associated with electricity imported to California are charged [15]. PJM studied the two-way border adjustment concept that includes charges on imported to and rebates on export from the carbon-priced region and compared it with the one-way design using an illustrative two-node grid example [16]–[18]. However, these works only evaluate physical quantities such as total emission reduction/leakage and carbon tax revenue. Air quality and public health driven by carbon price and border adjustments are not studied. Also, the employed networks, which either aggregated generators/loads over a geographically large region [15] or is artificial [18], cannot model the variation of social-economic status in local communities in CAISO and PJM. Conversely, the works [19], [20] analyze environmental and public health impacts using stylized emission scenarios instead of the outputs of power system models. Thus, they cannot capture the drivers and impacts of the carbon pricing integration model on emission change and human health. The work [3] employs a detailed power grid model, i.e., US-REGEN [21], to quantify air quality but does not show the consequences on public health. It also assumes universal decarbonization policies applied to the whole U.S. national grid, ignoring variation in state-determined carbon pricing policies. The work [22] evaluates the health benefits of carbon emission reduction from planning the PJM system. The energy exchange constraints over the transmission networks are simplified as commodities in the transportation network where each PJM state is aggregated as a single node. The paper also assumes a system-wide carbon price while PJM, in reality, consists of both carbon-priced and noncarbon-priced regions [18]. Thus, the model might not capture emission-associated power dispatch highly subject to power flow constraints and the variation of health impacts on PJM communities diverse in demographics and economics.

To make carbon pricing work, it is critical to quantify the resulting air quality, public health, and their variation among individual communities under different carbon pricing integration [23]. This paper aims to fill this gap in the literature by developing an integrated model assessing air quality and health impacts on communities under state-determined carbon prices and RTO-imposed border adjustment. Mathematically, carbon price and border adjustment alternate the SCED optimal solutions, i.e., changing dispatches and locational marginal prices (LMPs). These SCED solutions are inputs for environmental and societal processes that simulate air quality and health impacts on communities following their demographic and economic conditions. Based on this observation, we convert the generation dispatch into spatial emission of pollutants (NOx, SOx, and $PM_{2.5}$) following the generators' emission rates and locations [24]. We simulate pollutant diffusion to capture air pollutant exposure at the U.S. county level by using the source-receptor model embedded in the Co-Benefits Risk Assessment (COBRA) of the U.S. Environmental Protection Agency (EPA) [25]. The air pollution exposure is then monetized into equivalent medical costs based on individual counties' socioeconomic conditions. We conduct our analysis on a large-scale WECC 10k synthetic transmission node system covering 14 states in the Western U.S. [26] considering three types of carbon border adjustment constraint, non-border adjustment, one-way adjustment as one designed in CAISO [15], and two-way border adjustment as proposed by PJM [18]. We show that the socioeconomic and environmental impacts of power grid operations & planning can be measured in detail, implying the feasibility of integrating these metrics into the decision-making processes of the power grid for an equitable and smooth clean energy transition. While this paper focuses on carbon pricing, our developed framework can assess air quality and health resulting from power system operations under different decarbonization policies, e.g., renewable energy portfolio standards and transportation electrification.

The rest of this paper is organized as follows. Section II reviews the SCED formulation. Section III presents three border adjustment schemes: non-border, one-way, and two-way designs. We discuss how the imposed constraints address the environmental leakage and their designed limitation by adjusting SCED outcomes against the undesirable changes caused by state-determined carbon prices. Section IV discusses how to assess economic, environmental, and health impacts resulting from power system operations. Section V presents numerical results followed by the conclusion in Section VI.

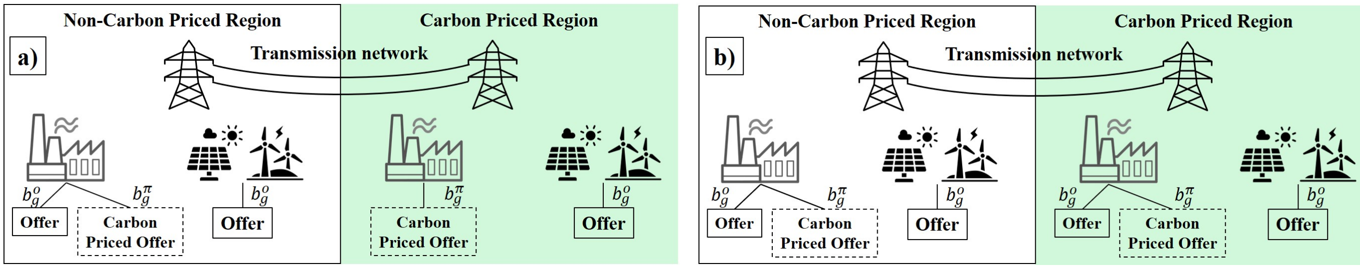

Fig. 1: Border adjustments: (a) One-way, currently used in CAISO [15], and (b) two-way, recently proposed by PJM [18].

II. Security Constrained Economic Dispatch

The original SCED represents the generation and delivery of electricity over the transmission network to serve demand in the least cost manner subject to system constraints:

$$\min_{P_g,\delta_i,F_\ell} \quad \sum_{g\in\mathcal{G}} b_g P_g \tag{1a}$$

$$\text{s.t.} \quad F_\ell = \frac{1}{x_\ell}(\delta_i - \delta_j), \quad \forall \ell = (i \to j) \in \mathcal{L}, \tag{1b}$$

$$\sum_{g\in\mathcal{G}_i} P_g + \sum_{k:k\to i} F_{ki} - \sum_{j:i\to j} F_{ij} = D_i, \ [\lambda_i], \quad \forall i \in \mathcal{I}, \tag{1c}$$

$$-\overline{F}_\ell \le F_\ell \le \overline{F}_\ell, \quad \forall \ell \in \mathcal{L}, \tag{1d}$$

$$\underline{P}_g \le P_g \le \overline{P}_g, \quad \forall g \in \mathcal{G}, \tag{1e}$$

where $\mathcal{G}$, $\mathcal{L}$, $\mathcal{I}$ are sets of generators, transmission lines, and buses indexed by g, ℓ, i, respectively, and ℓ=(i→j) denotes the line connecting bus i to bus j. Parameters include the generator marginal costs, b_g, minimum/maximum generation dispatches, $\underline{P}_g$, $\overline{P}_g$, transmission line reactances, x_ℓ, line thermal limits, $\overline{F}_\ell$, and nodal power demand, D_i. Optimization variables include power dispatches of generators P_g nodal voltage phase angles δ_i and transmission line flows F_ℓ. The objective (1a) represents the total electricity generation cost to be minimized. Constraint (1b) represents transmission flow on line ℓ using the DC power flow formulation. Constraint (1c) captures the nodal power balance. Specifically, the total power generated from all generators located in bus i, $\sum_{g\in\mathcal{G}_i} P_g$, plus the total power bus i receives from other buses, $\sum_{k:k\to i} F_{ki}$, minus the total power outflowing from bus i to other buses, $\sum_{j:i\to j} F_{ij}$, must equal the power demand D_i. The associated dual variable λ_i represents the LMP of bus i. The limits of transmission line flow and generation dispatch are captured in (1d)-(1e) respectively.

III. Carbon Border Adjustment

State-determined carbon prices mathematically alternate the outcomes of SCED (1), and some consequences are undesirable. In terms of regulatory actions, we need to impose additional constraints on the SCED to readjust the SCED optimal solution (i.e. changes in power dispatches, emissions, and LMPs) such that environmental leakages are mitigated, the impacts on ratepayers are minimized, and emissions associated with power exchanges among states are charged according to the variations in carbon prices. In this section, we first present the SCED model without border adjustments. and subsequently examine two distinct schemes: the one-way and the two-way border adjustments, depicted in Figure 1. The one-way model, adopted in CAISO [15], imposes a carbon price on imports from the noncarbon-priced region into the carbon-priced region. In contrast, the two-way border adjustment, studied by PJM [18], involves pricing imports and rebates on exports of electricity exchanged between the two regions.

A. Non-border Adjustment Model

The generator's marginal cost b_g in the original SCED (1) is mainly its operational cost b_g^o. A generator producing electricity from fuels will also emit an amount of carbon emission as $e_g = \rho_g^{CO_2} P_g$ where $\rho_g^{CO_2}$ is its carbon emission rate. Implementing carbon pricing will alter the generator's marginal cost. Specifically, when the carbon price π is applied to the emission e_g, the generator's marginal cost b_g is now the sum of the original operational cost and the carbon emission cost, expressed as $b_g^\pi = b_g^o + \pi\rho_g^{CO_2}$.

Without border adjustment, the carbon price π is directly incorporated into the marginal cost of generators if they are located in the carbon-priced region:

$$b_g = \begin{cases} b_g^o & \text{if } g \in \mathcal{NC} \\ b_g^\pi = b_g^o + \pi\rho_g^{CO_2} & \text{if } g \in \mathcal{C} \end{cases} \tag{2}$$

where $\mathcal{NC}$ denotes the noncarbon-priced region and $\mathcal{C}$ denotes the carbon-priced region. Mathematically, we run the original SCED (1) with the generation marginal costs b_g defined in (2). Unfortunately, directly including state-determined carbon prices in generation marginal cost as in (2) without appropriate regulatory constraints can lead to environmental leakages. Generators in the noncarbon-priced region will have advantages in the market-clearing process, while offers from generators in the carbon-priced region are less likely to be cleared, leading to a shift (*leakage*) in electricity production and carbon emissions from the carbon-priced region to the non-carbon priced region. Thus, while the carbon-priced region has carbon emissions reduced and air quality improved, communities in the noncarbon-priced region can be affected due to increasing air pollution exposure. Also, the increase in LMPs triggered by the carbon price can negatively impact ratepayers.

B. One-way Border Adjustment Model

The one-way border adjustment [15] depicted in Figure 1a imposes carbon price π on emissions associated with electricity generated within and imported to the carbon-priced region. Emitting generators in the carbon-priced region are mandated to submit single offers with carbon price included, b_g^π. Generators in the noncarbon-priced region submit two offers, one with the carbon price included, b_g^π, and one without the carbon price, b_g^o, respectively representing the dispatch portion exported to the carbon-priced region and consumed in the noncarbon-priced region. Non-emitting resources (e.g. wind and solar) are exempted from carbon prices. To this end, the SCED is reformulated as follows:

$$\min_{P_g, P_g^\pi, P_g^o, F_\ell, \delta_i} \quad \sum_{g\in\mathcal{C}} b_g^\pi P_g + \sum_{g\in\mathcal{NC}} \left(b_g^\pi P_g^\pi + b_g^o P_g^o\right) \tag{3a}$$

$$\text{s.t.} \quad P_g^\pi \geq 0,\ P_g^o \geq 0 \quad \forall g \in \mathcal{NC}, \tag{3b}$$

$$P_g = P_g^o + P_g^\pi, \quad \forall g \in \mathcal{NC}, \tag{3c}$$

$$P_g^\pi = 0, \quad \forall g \in \mathcal{G}: \ \rho_g = 0, \tag{3d}$$

$$\text{constraints (1b)-(1e)}, \qquad [\lambda],$$

$$\sum_{g\in\mathcal{NC}} P_g^o \leq \sum_{i\in\mathcal{NC}} D_i, \qquad [-\eta], \tag{3e}$$

where λ and $-\eta$ are shadow prices of associated constraints.

The objective function (3a) still represents the total electricity generation cost in the network, which includes the cost of the carbon-priced region and the noncarbon-priced region, i.e., $\sum_{g\in\mathcal{C}} b_g^\pi P_g$, and $\sum_{g\in\mathcal{NC}} b_g^o P_g^o + b_g^\pi P_g^\pi$, respectively.

The physical dispatch of a generator in the noncarbon-priced region P_g is decomposed into two nonnegative parts as in (3b). The first part P_g^o is exempt from the carbon price and has marginal cost b_g^o, representing the portion that serves the noncarbon priced region. The second part P_g^π subject to the carbon price π and has marginal cost b_g^π, representing the portion exported to the carbon-priced region. The sum of P_g^o and P_g^π must equal the physical dispatch P_g as in (3c). Dispatches of zero-emitting units, e.g., wind/solar, ($\rho_g = 0$), are exempted from the carbon price, i.e., $P_g^\pi = 0$, as in (3d). All original SCED constraints (1b)-(1e) of physical power dispatch P_g, line flow F_ℓ, nodal voltage phase angle δ_i are included.

Constraint (3e) represents the carbon emission allocation constraint for pricing. Specifically, the total electricity generated in the noncarbon-priced region and exempted from the carbon price $\sum_{g\in\mathcal{NC}} P_g^o$ should not surpass $\sum_{i\in\mathcal{NC}} D_i$, the total load of the noncarbon-priced region. It means net surplus power generated in the noncarbon-priced region and exported to the carbon-priced region will be considered P_g^π and subject to the carbon price π. This discourages emitting units in the noncarbon-priced region from exporting electricity to the carbon-priced region. Although this approach can reduce environmental leakage, it may under-utilize low-emitting units located in the carbon-priced region since they are penalized by carbon emission costs while high-emitting units in the noncarbon-priced region remain unaffected.

C. Two-way Border Adjustment Model

The two-way border adjustment [18] depicted in Figure 1b imposes carbon price π on emissions associated with electricity imports to the carbon-priced region and rebates π on electricity exports from the carbon-priced region. All emitting generators submit two offers, one without the carbon price included for electricity consumed in the noncarbon-priced region, b_g^o, and one with the carbon price for electricity consumed in the carbon-priced region, b_g^π. Meanwhile, offers from zero-emitting units are not subject to the carbon price. To this end, the SCED is re-formulated as follows:

$$\min_{P_g, P_g^\pi, P_g^o, F_\ell, \delta_i} \quad \sum_{g\in\mathcal{G}} \left(b_g^o P_g^o + b_g^\pi P_g^\pi\right) \tag{4a}$$

$$\text{s.t.} \quad P_g^\pi \geq 0, P_g^o \geq 0, \ \forall g \in \mathcal{G}, \tag{4b}$$

$$P_g = P_g^\pi + P_g^o, \ \forall g \in \mathcal{G}, \tag{4c}$$

$$P_g^\pi = 0, \ \forall g \in \mathcal{G}: \rho_g = 0, \tag{4d}$$

$$\text{Constraints (1b)-(1e)}, \qquad [\lambda],$$

$$\sum_{g\in\mathcal{G}} P_g^o \leq \sum_{i\in\mathcal{NC}} D_i, \qquad [-\eta]. \tag{4e}$$

The objective function (4a) still represents the total electricity generation cost. Physical dispatches of generators regardless of their locations are decomposed into two parts: P_g^π, which are subject to the carbon price and have marginal costs of b_g^π; and P_g^o, which are exempted from carbon price and have marginal costs of b_g^o. For each generator, the summation of P_g^o and P_g^π, which are nonnegative, must equal its physical dispatch, P_g, as in (4b)-(4c). Power generated by zero-emitting units ($\rho_g = 0$) is exempted from the carbon price as in (4d). All original SCED constraints (1b)-(1e) are also included.

Constraint (4e) represents the carbon emission allocation for pricing. Specifically, the total electricity exempted from the carbon price, $\sum_{g\in\mathcal{G}} P_g^o$, should not surpass $\sum_{i\in\mathcal{NC}} D_i$, the total load of the noncarbon-priced region. It means the portion of dispatches that do not include carbon price π in their offers are considered to serve the noncarbon-priced region $\mathcal{NC}$. The remaining net dispatches considered to serve carbon-priced region $\mathcal{C}$ are subject to carbon price π. Thus, low-emitting units in the carbon-priced region are prioritized over high-emitting units in the noncarbon-priced region for dispatching power if their original marginal costs are lower or equal without carbon pricing. Conversely, high-emitting units in the noncarbon-priced region are not encouraged to dispatch as their power dispatch, P_g, is likely to be considered P_g^π subject to carbon price charge. While utilizing low-emitting units in the carbon-priced region can result in emissions, the two-way border adjustment enables net emission reduction system-wide. Overall, constraint (4e) improves the utilization of low-emitting units and discourages high-emitting units.

D. Universal Carbon Pricing Model

For comparison purposes, we consider a universal carbon pricing model where a common carbon price π is applied to the whole network. It is the original SCED (1) with π applied for all generators, i.e., no variation in carbon pricing policies among jurisdictions. This is the hypothetical case as it is challenging to have all states agree on a common carbon price [9]. Also, emitting units in densely populated areas with high power demand are subject to the same carbon price as units in remote and sparsely populated areas. We will investigate this implication on the health impacts in the numerical analysis.

IV. Economic, Environmental, and Health Impacts

A. Wholesale Market Electricity (LMP) Prices

The LMP at bus i measures the change in the dispatch-optimized objective function to a change of the nodal demand D_i. Thus, the LMP settlement for carbon-priced and noncarbon-priced regions is as follows:

$$\text{[non-border]} \qquad \text{LMP}_i = \lambda_i, \forall i \in \mathcal{I}, \tag{5a}$$

$$\text{[border adjustment]} \quad \text{LMP}_i = \begin{cases} \lambda_i & \text{if } i \in \mathcal{C} \\ \lambda_i - \eta & \text{if } i \in \mathcal{NC} \end{cases} \tag{5b}$$

where $-\eta$ is the shadow price of carbon allocation constraints (3e) and (4e) and $\eta \geq 0$ can be considered as the LMP of carbon emission allocation. In the non-border adjustment, D_i only appears in the power balance constraint of node i. Thus, similar to the original SCED, the LMPs are the shadow prices (λ_i, $\forall i \in \mathcal{I}$) of the nodal power balance constraint (1c), applied for both carbon-priced and noncarbon-priced regions. In formulations (3) and (4) of the one-way and two-way border adjustments respectively, noncarbon-priced regions' nodal demand D_i appears in both nodal balance constraint (1c) and the allocation constraints (3e) and (4e) respectively. Thus, the LMPs of the noncarbon-priced region's buses become $\lambda_i - \eta$, incorporating both the shadow prices of the original nodal balance constraint and the newly imposed allocation constraint for carbon border adjustments.

B. Emission, Air Quality, and Health Impact

Figure 2 depicts our framework with a case study on the stylized WECC power network covering U.S. Western States. The original SCED model where carbon prices are not adopted (π=0) is used as the emission baseline. We estimate the change in economic values of health impacts induced by the change in pollutant emission caused by SCED from the baseline.

Besides CO_2, fossil fuel generators also emit several harmful pollutants proportional to their power dispatches:

$$e_g^m = \rho_g^m P_g, \ \forall g \in \mathcal{G}, \quad \forall m \in \{SO_2, NO_x, PM_{2.5}\}, \tag{6}$$

where ρ_g^m is the emission rate of generator g for pollutant m. The pollutant emissions obtained from (6) can be converted into equivalent changes in ambient concentration of $PM_{2.5}$. In particular, the ambient concentration of $PM_{2.5}$ in the county c, denoted as z_c, is caused by pollutants emitted within c and pollutants sent to c from other counties s as follows:

$$z_c = F_{unit} \sum_s \sum_m T_{s,c}^m F^m e_s^m \ \text{with} \ e_s^m = \underline{e}_s^m + \sum_{g \in s} e_g^m, \tag{7}$$

where e_s^m is the total amount of pollutant m emitted within county s caused by electricity production $\sum_{g \in s} e_g^m$ and other economic sectors $\underline{e}_s^m$; F^m is the ionic conversion factor for pollutant m (see Table A-5 of [25]); and F_{unit} is unit conversion factor (28,778 μg-year/ton-sec). Finally, $T_{s,c}^m$ (sec/m^3) is the transfer coefficient for pollutant m from county s to county c whose value is based on the source-receptor (S-R) matrix following the Climatological Regional Dispersion Model [25].

Denote Δz_c as the difference in the county $PM_{2.5}$ concentration between the baseline, z_c^b, and the specific case study, z_c, i.e., $\Delta z_c := z_c^b - z_c$. The change in $PM_{2.5}$ concentration based on the change in pollution emission is as follows:

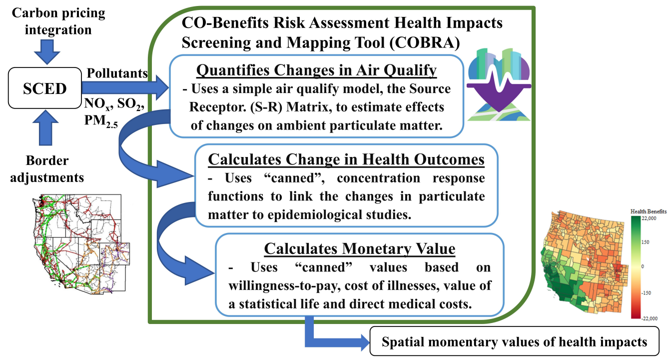

Fig. 2: Health Benefits estimation in COBRA [25].

$$\Delta z_c = F_{unit} \sum_s \sum_m T_{s,c}^m F^m \Delta e_s^m \tag{8}$$
$$\text{with } \Delta e_s^m = \sum_{g \in s} (e_g^m - e_g^{m,b}),$$

where $e_g^{m,b}$ is the amount of pollutant m emitted by unit g in the baseline (the original SCED model without carbon prices).

$PM_{2.5}$ exposure leads to multiple adverse health effects (e.g., cardiovascular, heart attacks, work loss days, ..., etc) [27]. Reductions in $PM_{2.5}$ concentrations lowers the risk of future adverse health effects by a small amount for a large population. For a specific adverse health effect h in county c, the change in corresponding health impact, Δy_c^h, is a function of the county's change in $PM_{2.5}$ concentration Δz_c. The specific function can be linear, log-linear, or logistic following epidemiological studies:[1]

$$\Delta y_c^h = \begin{cases} \beta_c \Delta z_c & \text{[linear]} \quad (9a) \\ y_c^{h,b}\left(1 - \dfrac{1}{\exp(\beta_c \Delta z_c)}\right) & \text{[log-linear]} \quad (9b) \\ y_c^{h,b} - \dfrac{y_c^{h,b}}{(1-y_c^{h,b})\exp(\beta_c \Delta z_c) + y_c^{h,b}} & \text{[logistic]} \quad (9c) \end{cases}$$

$$h \in \{\text{cardiovascular, heart attacks, asthma, bronchitis,}$$
$$\text{chronic lung disease, work loss days, ..., etc}\},$$

where β_c is the regression parameter and $y_c^{h,b}$ is the health impact in the baseline. In epidemiological studies, Δy_c^h typically represents (i) the change in incidence rate, (ii) the change in the annual number of cases of the adverse health effect per 10^5 population, and (iii) the change in the occurrence probability of the adverse health effect h in county c in the linear, log-linear, and logistic model respectively. Δy_c^h is converted into the expected number of cases avoided for an adverse health effect h by considering the county population as follows:

$$Cases_{\text{Avoided}}^{h,c} = \begin{cases} \Delta y_c^h \times population_c & \text{[linear]} \quad (10a) \\ \dfrac{\Delta y_c^h}{10^5} \times population_c & \text{[log-linear]} \quad (10b) \\ \Delta y_c^h \times population_c & \text{[logistic]} \quad (10c) \end{cases}$$

[1] The log-linear model is commonly used to estimate the air pollution effect on all-cause mortality, hospitalizations, asthma-related ER visits, and work loss days. The logistic model is used for non-fatal heart attacks, and minor and asthma-elated effects (breath shortness, cough, or wheezing).

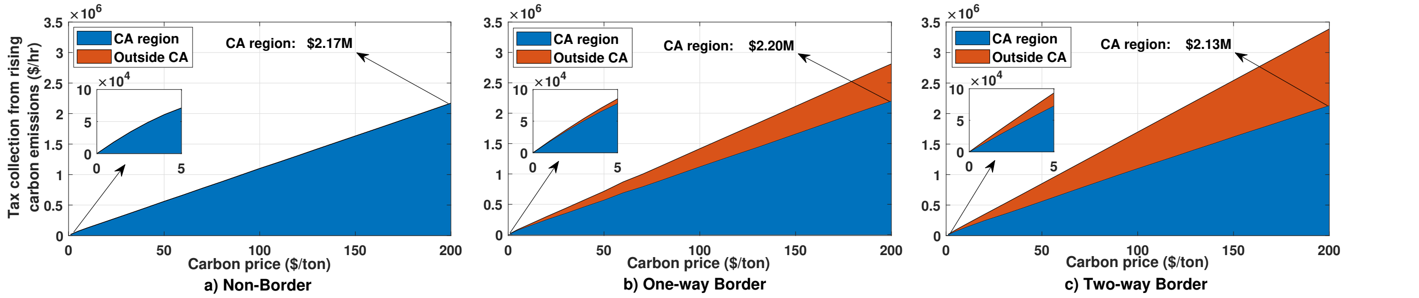

Fig. 3: Carbon tax revenue from pricing carbon emissions in different SCED models.

Finally, the cases avoided can be converted into the economic value of health effects in a county c as follows:

$$Benefits_c = \sum_h UnitValue_c^h \times Cases_{\text{Avoided}}^{h,c} \tag{11}$$

where $UnitValue_c^h$ is the unit value of monetizing health endpoints. It captures direct medical costs, the loss of income, inflation, and various economic factors (see Table F-1 in [25]). In this paper, we employ unit values of health ending points corresponding to long-term emission exposure impact. A positive value of $Benefits_c$ means the community benefits from air quality improvement while a negative value indicates it is exposed to the increasing air pollution.

Remark: By setting up the emission baseline and calculating the change in pollution emission from the baseline (Δe_s^m, for individual pollutants, e.g. SO_2, NO_x, $PM_{2.5}$), we can assess the actual environmental and societal impacts of power system decarbonization policies, i.e., carbon pricing and border adjustments in this paper, applied specifically on the power system, offsetting emissions induced by other economic sectors.

V. Numerical results

A. Simulation Setup

We align the pollutant emission rates of individual generators ($\rho_g^m, \forall g, \forall m$) taken from EPA's Emissions & Generation Resource Integrated Database (eGRID) database [24], with generators in the WECC 10k test case [26] by matching their latitude-longitudes. For illustration purposes, we consider the case that the carbon price is imposed in the state of California (CA). Thus, CA acts as the carbon-priced region ($\mathcal{C}$), and the remaining states in WECC are considered as the noncarbon-priced region ($\mathcal{NC}$). We use CVXPY/CPLEX to solve SCED models and link the dispatch-induced emissions to COBRA for analyzing their health impacts on communities in the stylized WECC region using PyAutoGUI, as illustrated in Figure 2. The air pollutant emission changes in each setting of the carbon price and border adjustment compared to the baseline, i.e., Δe_c^m, are imported to COBRA through EPA's Avoided Emissions and Generation Tool (AVERT). The air pollutant changes include reductions/increases in emissions of NO_x, SO_2, NH_3, VOCs, and $PM_{2.5}$ in every WECC county. Since the SCED is hourly based whereas COBRA requires the inputs to be converted into annual based, we scale up air pollutant changes by 8760 and then scale down the COBRA outcomes of health benefits impact analysis by 8760 to quantify the spatial air quality and health impacts of power dispatches.

B. Results and Discussion

1) LMPs and Carbon Tax Revenues: Figure 3 shows the CA's carbon tax revenue under different SCED models. The tax revenue is at its lowest under non-border adjustment (Figure 3a) since it only comes from CA's generators. The tax revenue is higher under one-way border adjustment (Figure 3b) since it additionally imposes the carbon price on net power imported to CA. The tax revenue is at its highest under two-way border adjustment (Figure 3c). There is less revenue obtained from the CA region since low-emitting generators in CA are rebated on carbon price if they export electricity outside CA. However, more tax revenue is collected from outside CA as the scheme prioritizes considering dispatches from emitting units in this region as being exported to CA, which are subject to CA's carbon price. The higher tax revenue can be used to subsidize CA's customers and support clean energy projects in CA and the remaining WECC.

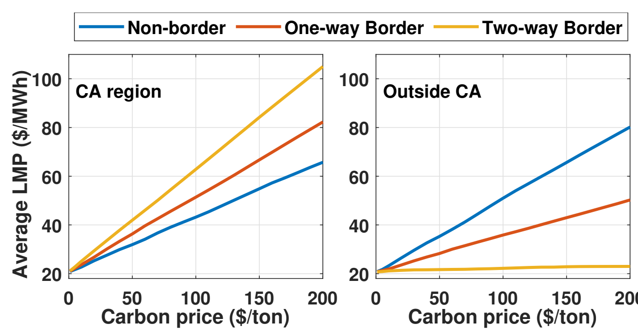

Fig. 4: Average LMP for different SCED models.

Figure 4 indicates that border adjustments can limit the LMP increase in the noncarbon-priced region while causally allocating more energy costs to the carbon-priced region. LMPs in the noncarbon-priced region with border adjustments are lower than those without border adjustments. Without border adjustments, increasing CA's carbon price impresses LMPs in both CA and outside CA, so customers in the noncarbon-priced region are affected by higher energy costs induced by carbon pricing policy outside their region. Also, the two-way border adjustment is better than the one-way counterpart at equitably distributing energy costs as it limits the LMPs outside CA close to the original values in the baseline of $\pi = 0$. This is theoretically aligned with equation (5) discussed in Section IV.A. Mathematically, the allocation constraint (4e) in two-way border adjustment is tighter than constraint (3e) of the one-way border adjustment, implying a higher value of η^* in (5) rebated to customers in the noncarbon-priced region under the two-way border adjustment. Note that while LMPs in CA under border adjustments are higher than those without border adjustment, the higher CA's carbon tax revenue (see Figure 3) can be used to subsidize energy costs of CA's customers, thus compensating for the LMP increases.

2) Impacts on Emitting Resource Dispatches: The changes in power dispatch of emitting resources (particularly, coal and gas) under carbon prices and different border adjustments, as reported in Figure 5, illustrates the environmental leakages induced by partial carbon pricing policies and how border adjustments can reduce their intensities:

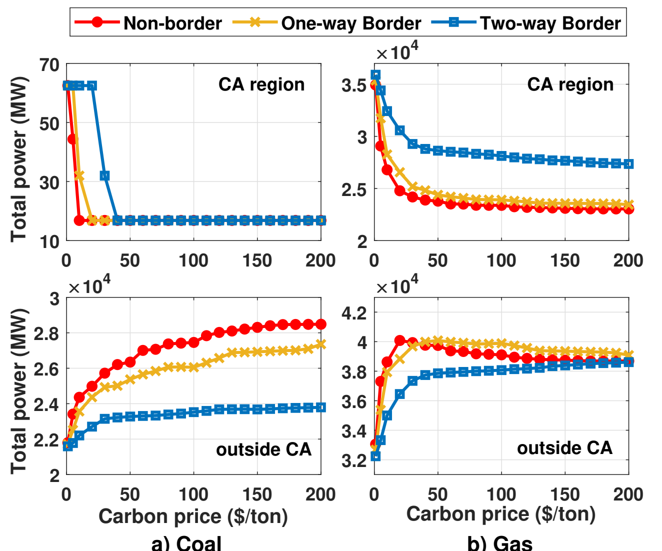

Fig. 5: Electricity generated from coal and gas units in carbon-priced and noncarbon-priced regions (CA and outside CA).

In the non-border adjustment, while electricity generated from emitting resources (especially coal) in the carbon-priced region is reduced, there are increases in electricity generated from fuel resources and emissions in the noncarbon-priced region. This is because the carbon price impresses the marginal costs of emitting units in the carbon-priced region (CA), thus their dispatches are replaced by emitting units in the noncarbon-priced region (e.g., coal and gas power plants outside CA) whose marginal costs are becoming relatively lower compared to CA units. Also, there is a considerable increase in electricity generated from coal units outside CA since coal units (despite their high carbon emission rate) generally have lower fuel operation costs b_g^o than gas units.

Border adjustments can reduce environmental leakages, particularly the migration of electricity generated from fuel resources. The one-way border adjustment can slightly reduce the electricity generated from coal in the noncarbon-priced region by imposing a carbon price on electricity exported to CA. The two-way border adjustment is better at limiting the increase of electricity generated from coal units outside CA since it simultaneously imposes carbon prices on electricity imported into CA and prioritizes the dispatch of low-emission units in CA, mostly gas-based, instead of higher-rate emitting units outside CA. This implies the more balancing results of distributing emissions and health benefits resulting from power system operations between carbon-priced and noncarbon-priced regions. Given the physical limits of an existing generation mix, border adjustments alone cannot eliminate the environmental leakage of partial carbon pricing. Dispatches from emitting resources in the noncarbon-priced region remain necessary to offset the reduction in electricity generated from emitting resources in the carbon-priced region, ensuring a balance between supply and demand.

3) Carbon Emission and Health Benefits: Figure 6 shows the changes in carbon emissions and health benefits in both carbon-priced and noncarbon-priced regions as CA's carbon price increases. Figure 7 depicts the total emission and health benefits of the whole WECC system. Together, these results highlight the environmental inequity arising from uneven carbon pricing policies implemented across the commonly shared power network. They also show that border adjustments, by reducing environmental leakage, narrow gaps in health impacts and emissions between the two regions.

In the non-border adjustment, when CA's carbon price increases, emissions decrease in the carbon-priced region (CA) but increase in the noncarbon-priced region (outside CA) due to the shift in dispatch of emitting resources (e.g., coal and gas). Figure 6a shows that CA exhibits the lowest emissions while regions outside CA experience the largest increase in carbon emissions. Thus, while communities in the carbon-priced region (CA) have positive net health benefits thanks to air quality improvement, the health benefits of communities in the noncarbon-priced region (outside CA) become negative indicating increases in pollutant exposure. This is because many units outside CA may have emission rates higher than those within CA. These external units become more attractive economically as CA's carbon price increases, leading to increased dispatch from them, thus increasing total carbon emissions. Figure 7a shows that the non-border adjustment has the highest total emission, increasing and converging to near the original value of the baseline, i.e. original SCED without carbon pricing (π=0). Thus, its corresponding total health benefit in Figure 7b is slightly reduced after reaching its peak as CA's price increases. Indeed, when the carbon price is only imposed on a certain part of the network without border adjustments, the increasing carbon price might not reduce, instead it potentially increases the total carbon emission and affects the total health benefits in the whole network.

The one-way border adjustment slightly reduces gaps in carbon emissions and health benefits between carbon-priced and noncarbon-priced regions as observed in Figure 6. It marginally reduces carbon emissions and slightly improves health benefits in the noncarbon-priced region. There are no significant differences in the carbon-priced region from the non-border adjustment case since the one-way border adjustment does not change how emission in CA is priced. It also does not utilize low-rate emitting units in CA. It only discourages electricity generated from fuel resources outside CA from being exported to the CA region. These units, however, can still serve customers in the noncarbon-priced region. Hence, as observed in Figure 7, the change in its total carbon emission is similar to that under non-border adjustment although its total emission is marginally lower.

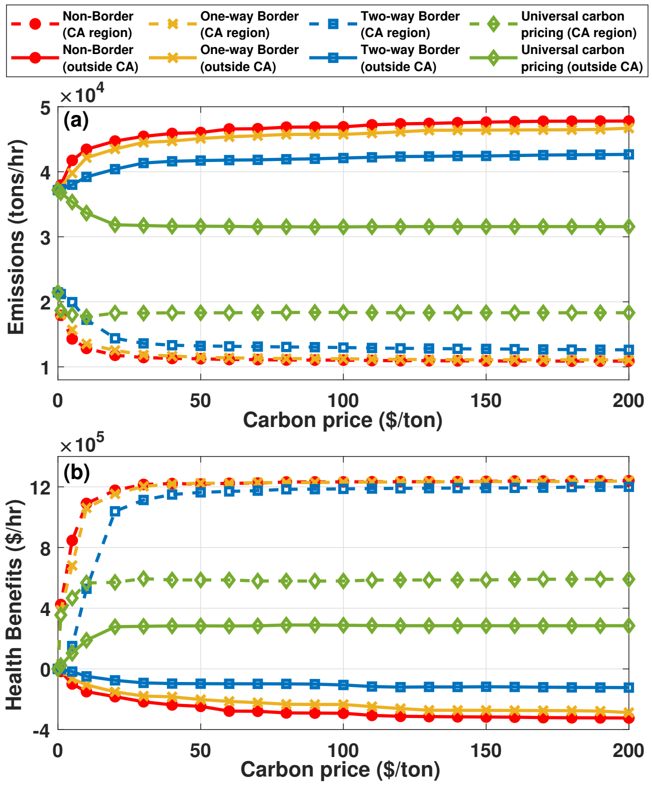

Fig. 6: Carbon emissions and health benefits in carbon-priced and noncarbon-priced regions (CA vs outside CA).

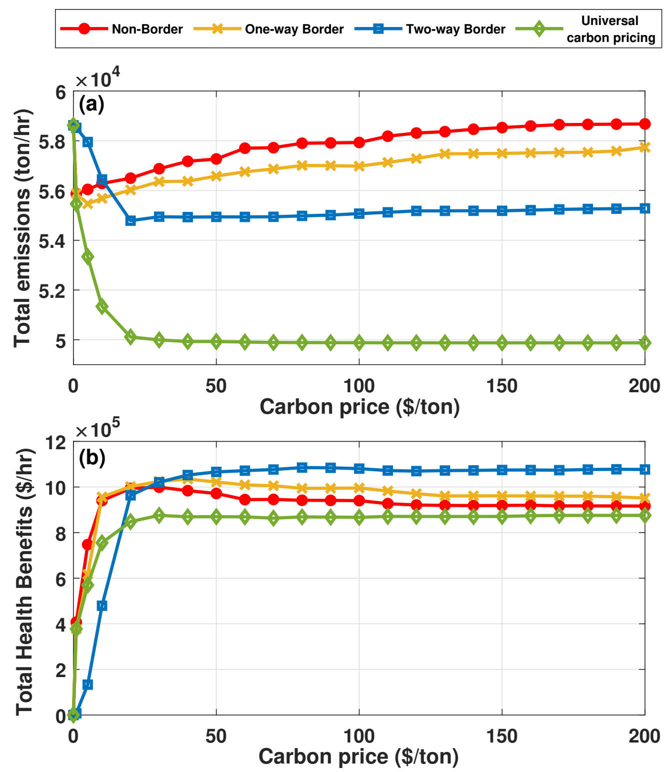

Fig. 7: Total carbon emissions and health benefits over the WECC network.

The two-way border adjustment is better at reducing environmental inequity than the non-border and one-way adjustment cases. It discourages the dispatch of high-emitting resources (especially coal units) in the whole network while simultaneously utilizing low-emitting units (high-efficient gas units) within the carbon-priced region (CA). As shown in Figure 6, although a slight amount of carbon emissions still occurs in CA as utilizing CA's low-emitting units, this approach avoids a significant increase in carbon emissions outside CA, thereby significantly reducing the negative environmental and health impacts on communities in the noncarbon-priced region. Hence, we achieve a steady and stable reduction of total carbon emissions, similar to the ideal case of universal carbon pricing as shown in Figure 7. Its total emission is much smaller than non-border and one-way border adjustments. Our findings align with the PJM two-node transmission grid studies [18].

The only scenario where carbon emissions in individual regions (Figure 6a) and total emissions of the whole network (Figure 7a) consistently decrease as the carbon price rises is when the price is universally applied across the entire network. Indeed, universal carbon pricing is known as the most effective policy for reducing total carbon emissions. However, within this scheme, emitting generators are uniformly subject to the same carbon emission price, irrespective of their geographical locations—whether they operate in densely populated urban centers or sparsely inhabited regions. Note that power demand centers and customers are significantly more concentrated in CA whereas high-emitting units are generally located in remote areas outside CA. Consequently, many emitting units in CA continue to operate due to their proximity to the demand even though they are subject to the same carbon price as units located outside CA (whose dispatches are constrained by the transmission network). As shown in Figure 6, although carbon-priced and noncarbon-priced regions all receive positive health benefits, the carbon emission reduction and the net health benefits in CA under universal carbon pricing are much smaller than in the other cases when only CA adopts carbon pricing. Interestingly, in Figure 7b, as carbon prices rise, the total health benefits associated with universal carbon pricing converge to a level lower than that observed in other cases. In contrast, the two-way border adjustment—despite achieving only half the carbon emission reduction of universal carbon pricing— exhibits a gradual increase in health benefits before converging to its peak, which surpasses all other cases. Therefore, contrary to expectations, universal carbon pricing does not consistently yield the greatest total health benefits, especially when renewable energy penetration is low, which will be discussed later. Also, achieving consensus among all states on a common carbon pricing policy is challenging due to the variations in state policies and economic conditions.

Figures 6 and 7 also show that further increases beyond a certain carbon price do not lead to additional emission reductions or improved health outcomes. Instead, they escalate total production costs and wholesale LMPs (see Figure 4). Therefore, recycling carbon tax revenue for clean energy projects alongside implementing border adjustments is crucial for achieving efficient and equitable decarbonization in both carbon-priced and noncarbon-priced regions, and jointly optimizing the total emission reduction and health benefit improvement at the system level.

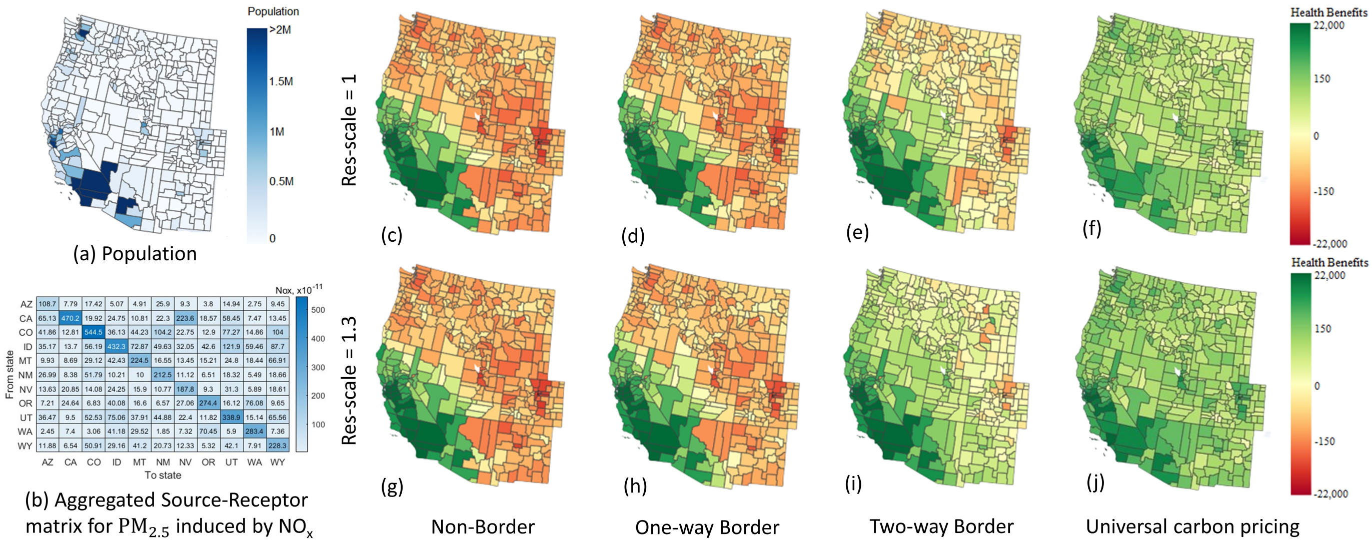

Fig. 8: Distribution of communities' health benefits under different carbon border adjustments and CA's renewable energy penetration when the health benefits of the CA region reach the upper limit.

4) Changes in air pollutants and health benefits among counties: Figure 8 illustrates the population distribution, air pollutant diffusion modeling data, and reports the spatial changes of health benefit impacts at county-level resolution under different SCED models. The population is highly concentrated in certain CA counties and sparse in the rest of WECC as shown in Figure 8a. Given a large number of WECC counties, we illustrate how air pollutants are diffused using the aggregated state-to-state S-R matrix in Figure 8b. Air pollutants generally travel inland from coastal areas. Emissions from CA generally affect CA and the nearby regions while areas far away from CA are unlikely to be affected. Note our results are conducted with detailed county-to-county S-R matrices of individual pollutants provided by EPA's COBRA [28]. The carbon price is set as π= 50\$/ton compared to the base case π=0. We scale renewable energy capacities in CA, denoted as Res-scale, from 1.0 to 1.3, to approximately simulate the impacts of recycling the carbon tax revenue for clean energy projects in CA (the carbon-priced region). Green/light green colors indicate that counties experience net positive health benefits due to improved air quality. Conversely, red/orange colors indicate that counties are exposed to higher levels of air pollutants, resulting in negative health impacts. Indeed, regardless of SCED models (Figures 8c-d-e and Figures 8g-h-i), once CA adopts carbon price, counties surrounding CA are also in green, i.e., the reduction of pollutant emission and air quality improvement in CA positively impact neighboring areas as they receive fewer pollutants. However, the health outcomes of counties far away from CA are unlikely correlated to air pollution reduction in CA as they are more affected by dispatches from their local non-renewable resources, which depend on the adopted border adjustments rather than CA's renewable energy penetration.

Figures 8c-d-e (Res-scale = 1.0) and 8g-h-i (Res-scale = 1.3) show that more counties receive positive health benefits when we change the regulatory policy from non-border to two-way border adjustment. In the one-way border adjustment (Figures 8d and 8h), the observed improvement in health benefits—when compared to the non-border adjustment—is minimal. Most counties outside of CA—especially those situated far away from the state—are still in the red/orange zone. This indicates that these counties face heightened exposure to air pollutants from increasing electricity production fueled by non-renewable sources. Also, the improvement when we increase CA's Res-scale from 1.0 (Figure 8d) to 1.3 (Figure 8h) is marginal. While increasing CA's renewable energy penetration slightly expands the green zone, it does not affect regions far away from the state. The two-way border adjustment (Figures 8e and 8i) exhibits noticeable improvement when compared to the non-border adjustment case as there are more counties in the green zone. In other words, the two-way border adjustment can help distribute pollution reduction benefits more equitably by "spreading the green to the neighboring communities". The green zone (between Figures8d and 8h) also significantly expands, including many counties located far away from the state, when CA's renewable energy penetration increases, indicating the benefits of utilizing low-emitting resources in the carbon-priced region and limiting the use of high-emitting resources in the noncarbon-priced region. When the carbon price is universally applied to the whole network (Figures 8f and 8j), almost all counties receive positive health benefits. However, counties in CA, where the population is concentrated (Figure 8a), are less green than when the carbon price is only applied to CA (Figures 8c-d-e and Figures 8g-h-i). Indeed, recall the result of Figure 7b, the total health benefit (Figures 8f and 8j) are not the highest values compared to the cases when carbon price is only applied to CA (Figures 8c-d-e for Res-scale = 1.0 and Figures 8g-h-i for Res-scale = 1.3).

As shown in Figure 9, with increasing renewable energy penetration in CA, total health benefits in all SCED models increase. Also, universal carbon pricing does not always result in the highest total health benefits despite having the largest total carbon emission reduction, especially when renewable energy facilities in densely populated areas (CA) are not sufficient to replace electricity production from emitting resources (low Res-scale). It only achieve highest health benefits when CA's

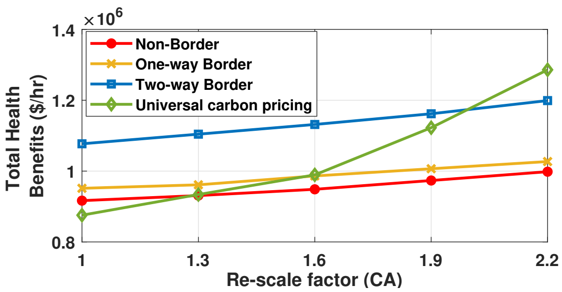

Fig. 9: Total health benefits versus CA's Res-scale factors.

renewables are sufficiently large (Res-scale =2.2). In contrast, the two-way border adjustment exhibits very high total health benefits even when CA's renewable energy penetration is not high, surpassing non-border and one-way border adjustments and higher than universal carbon pricing (Res-scale =1–1.9). Note increasing CA's renewable energy can be done by recycling CA carbon tax revenue, which is highest under two-way border adjustment. Also, having universal and perfect renewable energy or carbon pricing policies agreed upon by all jurisdictions is challenging. We have the following remark.

Remark: Both carbon pricing and renewable energy investment are needed for decarbonization as they complement each other. The result implies that appropriate design of regulatory constraints can help integrate state-determined environmental policies of carbon prices and renewable energy–even if these policies are not perfect and individually determined by jurisdictions– for effectively reducing emissions, improving air quality, and equitably distributing the decarbonization benefits.

VI. Conclusion and Future Work

This paper develops an integrated framework to assess power system operations' air quality and health impacts. When one part of the transmission network is subject to the carbon price, results show that environmental leakage can inequitably increase air pollution exposure and health damage in the noncarbon-priced region. Among the two popular border adjustments currently studied by RTOs, one-way and two-way models, the latter which includes both charges on imported to and rebates on export from the carbon-priced region is better at reducing environmental leakage and improving health benefits. It achieves higher carbon tax revenue for supporting renewable energy investment in the carbon-priced region and negligible change in LMPs of the noncarbon-priced region. Border adjustments reduce but cannot eliminate environmental leakages. They should be combined with renewable energy reinvestment through recycling carbon tax revenue for effective emission reduction and equitable health benefit distribution.

Overall, this study shows that a detailed quantification of socioeconomic and environmental impacts, e.g., air quality and health, of power grid decarbonization policies at the county resolution can be obtained. Thus, it is feasible to integrate these metrics into the grid operations, planning, and policy designs. Future works aim to leverage advances in machine learning to integrate these metrics as design objectives of power system decision-making problems, e.g., designing new border adjustment and carbon tax recycling schemes that support equitable energy transition considering variation in socioeconomic conditions of communities under the grid.

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