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EXPLORING THE IMPACTS OF A NATIONAL U.S. CO_2 TAX AND REVENUE RECYCLING OPTIONS WITH A COUPLED ELECTRICITY-ECONOMY MODEL

JUSTIN CARON[*,‡,§], STUART M. COHEN[†], MAXWELL BROWN[†] and JOHN M. REILLY[*]

[*]*Joint Program on the Science and Policy of Global Change*
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge
MA 02139, USA

[†]*National Renewable Energy Laboratory*
15013 Denver West Parkway
Golden, CO 80401, USA

[‡]*HEC Montréal, 3000 chemin de la Côte-Sainte-Catherine*
Montreal, QC, H3T 2A7, Canada
[§]*justin.caron@hec.ca*

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This paper provides a comprehensive exploration of the impacts of economy-wide CO_2 taxes in the U.S. simulated using a detailed electric sector model [the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS)] linked with a computable general equilibrium model of the U.S. economy [the Massachusetts Institute of Technology's U.S. Regional Energy Policy (USREP) model]. We implement various tax trajectories and options for using the revenue collected by the tax and describe their impact on household welfare and its distribution across income levels. Overall, we find that our top-down/bottom-up models affects estimates of the distribution and cost of emission reductions as well as the amount of revenue collected, but that these are mostly insensitive to the way the revenue is recycled. We find that substantial abatement opportunities through fuel switching and renewable penetration in the electricity sector allow the economy to accommodate extensive emissions reductions at relatively low cost. While welfare impacts are largely determined by the choice of revenue recycling scheme, all tax levels and schemes provide net benefits when accounting for the avoided global climate change benefits of emission reductions. Recycling revenue through capital income tax rebates is more efficient than labor income tax rebates or uniform transfers to households. While capital tax rebates substantially reduce the overall costs of emission abatement, they profit high income households the most and are regressive. We more generally identify a clear trade-off between equity and efficiency across the various recycling options. However, we show through

[§]Corresponding author.

a set of hybrid recycling schemes that it is possible to limit inequalities in impacts, particularly those on the lowest income households, at relatively little incremental cost.

Keywords: Climate policy; CO_2 tax; carbon tax; distributional impacts; equity; progressivity; household welfare; double-dividends; model coupling; top-down/bottom-up coupling.

1. Introduction

A tax on carbon dioxide (CO_2), if sufficiently stringent, has the potential to transform the U.S. energy sector and affect the structure of the economy. Such a tax may also raise equity concerns by differentially affecting households of different income levels. However, the tax will also create significant government revenue, leading to an important policy dimension as the revenue can be used ("recycled") to offset concerns related to economic growth and disparities in household impacts.

We present a comprehensive exploration of the implications of a national tax on US CO_2 emissions with a focus on the distributional consequences of various tax revenue recycling methods. Compared with previous work in this area, a primary contribution of this paper is the inclusion of a detailed representation of the electricity sector within a top-down/bottom-up modeling framework. The National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) (Eurek *et al.*, 2016), an electric sector model, is linked with the Massachusetts Institute of Technology's U.S. Regional Energy Policy (USREP) model (Rausch *et al.*, 2010; Rausch and Reilly, 2015), a computable general equilibrium model of the U.S. economy. This approach allows us to accurately capture differential impacts among households with the necessary technology, market, resource, and regional detail. A detailed description of the electricity sector is important as it is the largest source of US CO_2 emissions (US EPA, 2015), and most studies find that the electricity sector would make a disproportionally large contribution to abatement under uniform economy-wide CO_2 pricing policies. At the same time, electricity sector models generally do not have links to the macro-economy and are therefore unable to simulate different revenue recycling strategies, nor can they comprehensively assess the impacts of emissions reduction policies on households, including effects on wages, capital, good prices, and returns to natural resources.

We evaluate several combinations of tax trajectories and revenue recycling methods. Tax pathways include two 2020 starting levels, \$25 per ton[1] of CO_2 and \$50 per ton of CO_2, and two annual rates of increase for the tax, 1% and 5%. Revenue recycling schemes include lump-sum rebates to households (a tax and dividend policy), labor and capital income tax reductions (tax reform measures), and various combinations of the above. The CO_2 tax pathways and revenue recycling schemes implemented in this study align with those of the Energy Modeling Forum 32 (EMF32) model intercomparison project (Fawcett *et al.*, 2018). The different tax pathways allow us to

[1]Throughout, "ton" represents a metric ton. All \$ values in the model (including tax levels) are expressed in 2016\$.

disentangle the effects of varying tax stringency based on high initial tax levels and/or high growth rates. The rich set of revenue recycling schemes allows us to describe efficiency considerations (measured by overall welfare impacts) and distributional considerations (measured by the progressivity/regressivity of impacts) for a large suite of policy-relevant options. In particular, a major contribution of the paper is investigating the potential for alleviating distributional concerns by compensating the lowest-income households and identifying the cost of additional transfers to households that keep the tax progressive overall.[2]

A number of analyses of US CO_2 tax revenue recycling have been conducted in the literature (Goulder, 1995; Parry, 1995, 1997; Rausch *et al.*, 2010; Carbone *et al.*, 2013; Goulder and Hafstead, 2013; Mathur and Morris, 2014; Williams III *et al.*, 2014; Rausch and Reilly, 2015; Marron and Morris, 2016; Cronin *et al.*, 2017). All studies agree that welfare and distributional implications significantly depend on how CO_2 tax revenue is recycled. However, no consensus has been established regarding the progressivity or regressivity of the tax itself. For example, several studies, including Mathur and Morris (2014), indicate that a CO_2 tax (absent any impacts from revenue recycling) is regressive, while others, such as Rausch *et al.* (2010) and Cronin *et al.* (2017) find it to be progressive. All agree, however, that the tax's distributional impacts ultimately depend as much or more on how the CO_2 tax revenue is recycled than the direct effect of abatement costs. Studies also often suggest that there is a tradeoff between maximizing economic output (efficiency) and making the CO_2 tax neutral or progressive (equity). For instance, Goulder and Hafstead (2013) find that a tax equivalent to \$10 per ton of CO_2 starting in 2013 and increasing by 5% per year until 2040 reduced GDP by 0.56% when revenues are returned in lump-sum fashion to households, 0.33% when revenues are used to reduce personal tax rates, and 0.24% when revenues are used to reduce corporate tax rates. The latter finding is relevant to the "double-dividend" hypothesis. The "strong" form of the double-dividend hypothesis asserts that, by using the tax revenue to reduce other pre-existing distortions (e.g., increase employment by reducing labor taxes), a CO_2 tax could produce net economics gains (Parry, 1997). A weaker form asserts a more-broadly-accepted implication that some revenue recycling methods can reduce economic losses brought about by the CO_2 tax, relative to other revenue recycling methods (Parry, 1997). The "strong double dividend" moniker thus refers to an economic benefit of what alone is essentially tax swap (shifting taxes from one part of the economy to another) plus the dividend of reduced economic damages from CO_2, even though most of these studies do not explicitly evaluate avoided climate change-related damages. While several studies have found that capital tax reductions are a particularly efficient way of recycling revenue, existing studies are split regarding their generation of a "strong double dividend" (Sancho, 2010).

[2]To be explicit, a progressive outcome is one which benefits (detriments) lower income classes more (less) whereas a regressive outcome implies the opposite.

We expand upon this double-dividend literature by providing estimates derived from a coupled top-down/bottom-up model and considering a richer set of revenue recycling options, with a focus on the cost of alleviating equity considerations.

Our results show that significant efficiency gains can be attained by using the revenue from the CO_2 tax to reduce capital income taxes. Under specific assumptions, these can lead to a strong double dividend. While such tax rebates lead to regressive impacts, insuring progressivity in impacts or compensating low-income households does not require sacrificing much of these efficiency gains.

The paper is structured as follows: In Sec. 2, we briefly describe the coupled ReEDS-USREP modeling framework and tax scenario design. We present results for the policy's effect on electricity generation and prices in Sec. 3 and economy-wide emissions and macro-economic effects on labor and capital markets, as well as household welfare in Sec. 4. Section 5 reports distributional effects by household income quintile. Section 6 provides overall discussion and conclusions.

2. Methodology and Scenarios

2.1. *The linked ReEDS-USREP model*

This section contains brief descriptions of both the ReEDS and USREP models as well as their linkage. More detailed model descriptions can be found in the Appendix. The current version of the linked model builds on work by Rausch and Mowers (2014).

ReEDS is an electric sector capacity expansion model that minimizes system cost while satisfying electric sector energy and capacity requirements from 2010 to 2050 in myopic two-year time-steps. The costs portrayed in ReEDS encompass generating and transmission capacity expansion costs as well as operational costs for a wide array of generation technologies. Geographically, ReEDS represents 134 load balancing areas as well as 356 renewable resource regions. A primary strength of ReEDS is its representation of variable renewable generation (VRG) technologies and their unique operating characteristics. The ReEDS model used for this analysis is adapted from the version used for the 2016 NREL Standard Scenarios report (Cole *et al.*, 2016). Technology costs and fuel prices are taken from the Energy Information Administration 2016 Annual Energy Outlook Reference Case (EIA, 2016). The model includes existing U.S. electric sector policies such as air pollution limits, renewable portfolio standards, and tax credits. However, because of the linkage between ReEDS and USREP, the version used herein does not include the renewable electricity tax credit extensions of December 2015. While the resulting near-term renewable growth might be less than expected in later model versions, cross-scenario comparisons and broader economic impacts should not be significantly impacted.

USREP is a top-down, computable general equilibrium (CGE) model that disaggregates the United States into six separate regions and has global coverage with 15 international regions. The model represents five energy sectors, six non-energy, composite sectors and six factors of production. Firms maximize profits, and equilibrium is reached in perfectly-competitive markets where prices equate to marginal costs. The ability to substitute between inputs is determined through calibrated constant elasticity of substitution (CES) functions. The model endogenously describes trade between US regions and with the rest of the world. Utility-maximizing households are divided into nine income classes[3] and are characterized by expenditure patterns and income sources, which allows for a detailed representation of distributional impacts and consumption changes. Households choose to substitute between labor and leisure with the tradeoff calibrated to generate a (compensated) labor supply elasticity of 0.3. Labor is mobile across sectors within a region but not between regions. Capital is split between new malleable and vintaged capital, limiting the scope for re-allocation of capital in response to the CO_2 tax. New malleable capital is perfectly mobile across sectors and regions within the United States. Inter-period adjustments produce path-dependency, and the resulting recursive-dynamic equilibrium is not necessarily inter-temporally optimal (the same is true for ReEDS). USREP is calibrated using a number of data sources from GTAP, IMPLAN, the U.S. census bureau, and the EIA (AEO, 2016) (see Appendix for more details.)

Both ReEDS and USREP solve in two-year intervals. Following benchmarking in the initial linked period, subsequent periods are solved through an iteration between the models in which the quantity and price of electricity inputs and output is passed along until convergence is realized.

2.2. *Scenarios*

The scenarios implemented in this study align with those of the Energy Modeling Forum 32 (EMF32) model intercomparison project (Fawcett *et al.*, 2018). The scenarios vary along two dimensions: (i) the CO_2 tax trajectory; and (ii) the tax revenue recycling method.

In addition to a no-tax reference case, we model tax trajectories that start at either \$25 or \$50 per ton of CO_2 in 2020 then increase at either 1%[4] or 5% annually in real terms.

Most of our analysis will be centered on the following four recycling schemes (scenario labels in parentheses):

(i) equal lump-sum rebates to all households (*HH*);
(ii) a capital income tax reduction (*K*);
(iii) a labor income tax reduction (*L*);
(iv) even split between a capital tax reduction and a uniform lump-sum rebate to households (*K-HH*).

In addition, we analyze four hybrid revenue recycling schemes in which additional lump-sum payments to the lowest income quintile of households ensure that their

[3]Aggregated to income quintiles in the results sections.
[4]These percentage increases are in real terms, as there is no inflation in our model.

welfare is unchanged relative to the no-tax reference case. They allocate the remainder in the following ways:

(v) reduce capital taxes (*TLQ-K*);
(vi) reduce labor taxes (*TLQ-L*);
(vii) reduce capital and labor income tax reductions evenly (*TLQ-L-K*);
(viii) reduce capital income taxes but a portion of revenue is used to keep the lowest quintile's welfare unchanged while ensuring progressivity across income all income quintiles through additional lump-sum transfers (*P-TLQ-K*).

With a no-tax reference case, five CO_2 tax pathways, and eight revenue recycling methods, we analyze a total of 41 scenarios.

We impose government revenue neutrality in all scenarios. In the *HH* scenario, for instance, this constraint implies that some of the revenue is withheld from households and kept by the government to compensate for the losses incurred by reduction in other tax revenue (the "Haircut"). In the *K* and *L* scenarios, capital and labor taxes are only reduced by an amount that leaves government revenue fixed relative to the reference case.

3. Electricity Sector Outcomes

To better understand the welfare impacts which will be presented in Sec. 4.4, we start by discussing electricity sector outcomes followed by impacts on the non-electricity sectors and factor of production.

The electricity sector responds rapidly to the onset of a carbon tax, mainly driven by re-dispatching of existing capacity (or "fuel-switching") which allows for an immediate but costly reduction in emissions. Capturing such effects is a major strength of our coupled modeling approach, as top-down economic models are unlikely to capture such dynamics.

Figure 1, which plots outcomes with the tax relative to the No-Tax reference case, shows that immediately after the introduction of the tax in 2020, CO_2 emissions fall by 30–60% in the \$25 and \$50 per ton CO_2 tax cases. They continue to decline gradually as CO_2 taxes rise under these assumed tax paths. The electricity sector's CO_2 reductions in 2050 range from approximately 50% (\$25 tax rising at 1%) to nearly 90% (\$50 tax rising at 5%). These findings suggest that very significant reductions are attainable in the electricity sector. Yet, reductions eventually flatten out even in with most stringent taxes, reinforcing previous NREL work that finds that the cost of reducing the last 10% of electricity emissions is extremely high.

Electricity prices immediately increase by about 25% and 50% in the \$25 and \$50 tax cases, relative to the reference no-tax scenario.[5] However, the sharp increases in

[5]These prices do not include CO_2 emissions costs, but they do reflect changes to production costs from fuel and non-fuel operation and maintenance induced by the CO_2 tax. Though ReEDS has some limited foresight with respect to the CO_2 tax, there is little pre-2020 response to anticipated prices. In reality, forward looking agents, knowing that future carbon taxes will be introduced, might have an incentive to invest in low carbon options before the 2020 introduction of the tax.

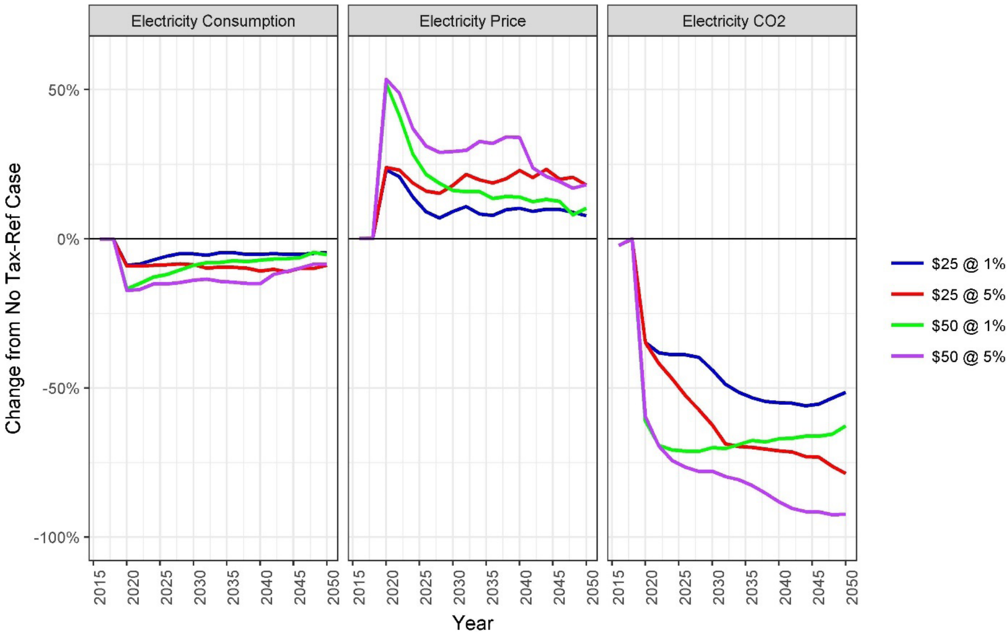

Figure 1. Electricity sector outcomes by tax pathway (HH revenue recycling scheme)

electricity prices moderate quickly, and by 2050 the price increase relative to the reference ranges is between 10% and 20%. Most of the initial price spike is gone by 2025. In the high tax-growth \$50 @ 5% case, the price spike also drops initially, from a 50% increase to about 30%, and then drops again around 2040. This second drop occurs because capacity reserves constraints become less binding in the \$50 @ 5% case after 2040 as cost-competitive natural gas with carbon capture and sequestration (CCS) supplies both energy and reserves, reducing the reserve price contribution to electricity prices. Other scenarios utilize different technologies for energy and capacity requirements, maintaining higher reserve prices throughout.

Figure 1 also shows that at the onset of the tax, electricity consumption (and thus production) decreases by approximately 13% under the \$25 tax and approximately 20% under the \$50 tax. The decline in electricity consumption also moderates slightly over time — not surprisingly given the electricity price path.

While the impacts to consumption and price are dampened over time, the reductions in emissions continue to increase. By 2050 the changes to price and consumption in the \$25 @ 5% and \$50 @ 5% scenarios are approximately equivalent although the higher tax level yields a greater reduction in CO_2 emissions. This result occurs because the 5% tax growth rate pushes more gas and coal out of the electricity mix, and these technologies have higher operations and maintenance (OM) costs than renewables. We will see later that high taxes generate substantially more electricity sector investment in the early years than low taxes, where compliance is initially dominated by fuel switching from coal to gas.

Results shown in Fig. 1 are for the scenario with the HH revenue recycling mechanism (lump-sum rebates), but we find that the way in which revenue is recycled has very little effect on outcomes in the electricity sector.

Generation mix, capacity mix and re-dispatching.

Tracking the evolution of generation and capacity mixes allows us to better understand the dynamics of electricity price, consumption and emissions. Figure 2 presents the annual electricity generation and capacity mix by tax level for the HH revenue recycling scheme. Table A.2 in appendix presents the corresponding percent changes, by technology, relative to the No-Tax reference case.

The largest relative changes are in the coal, gas, wind, and solar generation technologies. Hydropower and nuclear are not substantially affected by the CO_2 tax implementation because they emit no CO_2 and have little to no new capacity growth potential due to high capital costs. Only small quantities of new nuclear capacity are built in the final years of the tax scenarios in the case of 5% tax growth.

Coal accounts for approximately 28% of 2050 generation in the reference case, but is eliminated from the 2050 generation mix in all but the lowest tax scenario ($25 @ 1%). The reduction in coal-based generation is reinforced by rapidly retiring coal capacity[6] due to low capacity factors after CO_2 taxes raise the marginal cost of coal-based electricity. The rate at which coal generation declines depends largely on the stringency of the tax. With an initial tax of $25 per ton, coal generation remains in the electricity portfolio through 2050 with the 1% tax growth but disappears by 2030 with a 5% tax growth. Under the $50 per ton initial CO_2 tax, coal generation ceases almost immediately with only a few of the most-efficient generators continuing to produce.

Under all tax pathways, natural gas-based generation initially increases relative to the reference case. The duration of this increase depends on the tax stringency: under the $25 @ 1% pathway, natural gas generation remains higher than in reference case for the entire 2020–2050 time period; in the $25 @ 5% scenario, gas-based generation remains higher until the late-2030s but declines thereafter. Under the $50 @ 5% tax pathway, we see an immediate and large increase in 2020 natural gas generation that quickly switches to a decrease relative to the reference case by 2030. Natural gas-fired generation without CCS continues to decline in the $50 @ 5% scenario, but high taxes in later years allow rapid growth in gas-based capacity with CCS beginning in the late 2030s. This result is in line with the finding from many studies (Kerr, 2010) that natural gas can serve as a bridge to a low emission technology mix as it can provide flexible and reliable generation but with lower emissions intensity than coal. Our simulations demonstrate that natural gas is the preferable generation technology under moderate CO_2 taxes, but if the CO_2 tax is high enough, natural gas generation would decrease. The level of taxation at which the reduction of natural gas generation occurs

[6]ReEDS retires coal capacity when operated below a capacity factor threshold as a proxy for early retirements once fixed costs are no longer being recovered. The minimum capacity factor threshold is 6% in 2022, increases linearly to 50% by 2040, and remains flat thereafter.

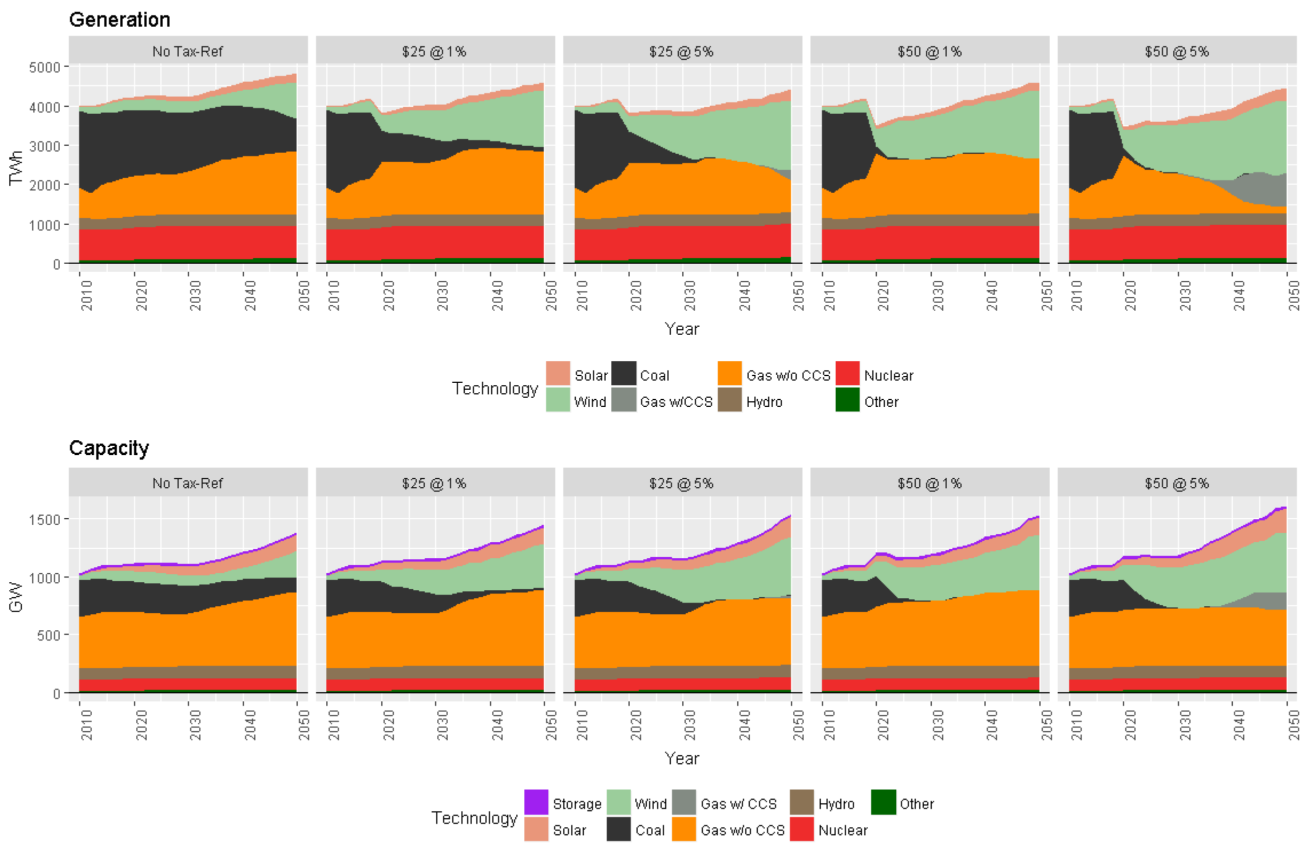

Figure 2. Electricity generation by technology and tax pathway (HH revenue recycling)[7]

[7]"Other" includes generation from biomass, landfill gas, geothermal, oil–gas–steam generators, and net energy from storage systems. "Curtailment and Losses" includes transmission losses and curtailed variable renewable energy.

depends on fuel prices and the cost of competing technologies. It remains an important part of the electricity mix in all cases, however. Coal with CCS is available in ReEDS but is not cost-competitive relative to other technologies using the AEO16 reference case cost assumptions.

Wind is the primary renewable generation technology to displace coal and natural gas generation, with substantial increases relative to the reference under all tax pathways. The increase in 2050 wind generation relative to the no-tax reference case varies from 511 TWh in the least aggressive tax pathway ($25 @ 1%) to 980 TWh with the most aggressive tax pathway ($50 @ 5%). Rapid wind expansion is enabled in part by growth in natural gas capacity, which supplies capacity reserves and grid flexibility that variable renewable resources cannot. While storage technologies are available, they are out-competed by gas for providing flexibility services. In contrast, solar expands but remains a small share of generation. While we find that wind capacity is more cost-effective than solar capacity under the AEO16 reference case renewable technology cost assumptions, other cost scenarios included in the EMF32 exercise demonstrate that the balance between wind and solar deployment is sensitive to these assumptions.

Finally, when comparing electricity generation to capacity (top and bottom panels of Fig. 2), it becomes apparent that emissions reductions aren't solely attributable to new capacity. Although there is a large increase in low-carbon investment, significant reordering of dispatch due to changes in merit order also occurs in the early years of the tax. This re-dispatching explains the initial spike in prices displayed in Fig. 1.

4. Economy-Wide Impacts

This section discusses economy-wide impacts. We focus on understanding how the economy adjusts to the CO_2 tax and how this affects the sources of tax revenue and overall burdens on households.

We first consider how other sectors outside of electricity are affected by the tax by looking at impacts on price, output, imports, and exports. We then describe the response of factor markets. These help explain the tax's impacts on welfare. We then present economy-wide CO_2 emissions and sources and evolution of CO_2 tax revenue. Finally, we describe how household welfare is affected by the choice of revenue recycling scheme.

4.1. *Sectoral effects on prices, production, exports and imports*

The CO_2 tax ultimately affects all sectors of the economy, but impacts are largest for sectors that are either energy-producing or energy-intensive in their production. Figure 3 presents the changes in output price, output, imports, and exports of the nine sector types represented by ReEDS-USREP for the lowest and highest tax pathways ($25 @ 1% represented with solid lines and $50 @ 5% represented with dashed lines). The vertical axis scales are different for each sector reflecting differences in the magnitude of impacts across sectors. From the top-left to bottom-right, the graphs are roughly sorted in decreasing order of change relative to reference. The results are

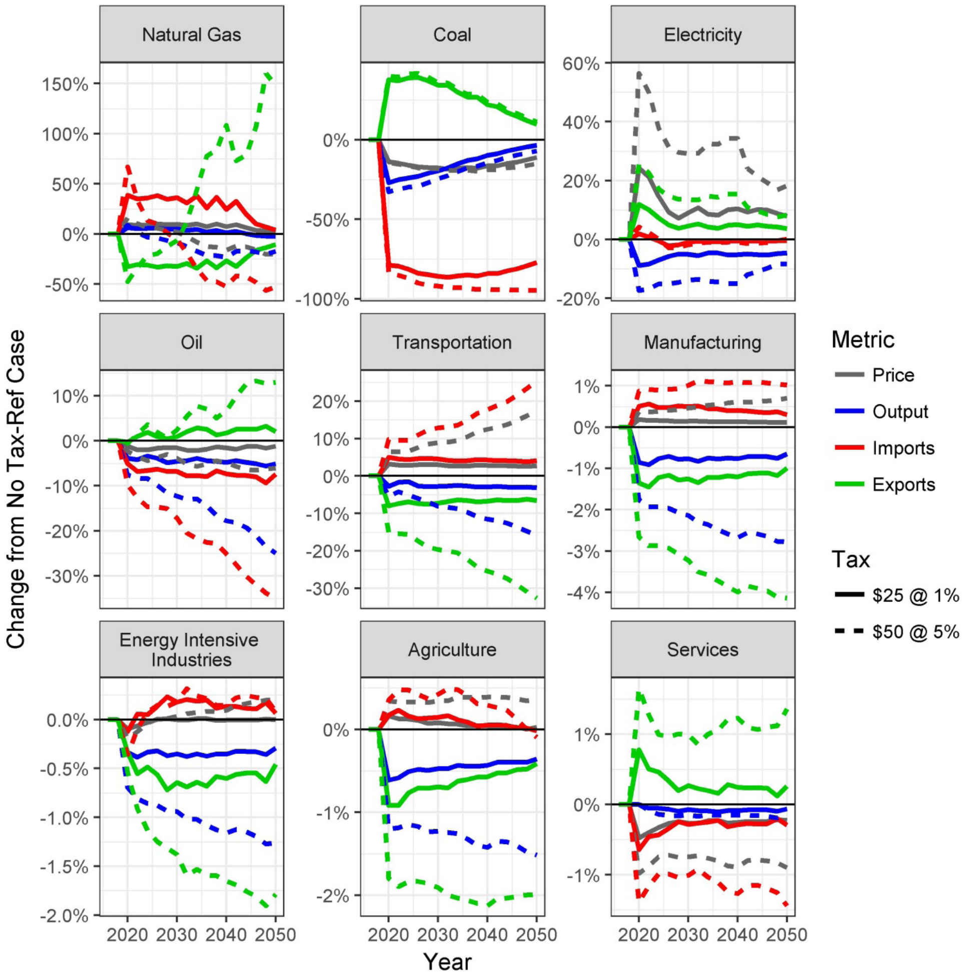

Figure 3. Sectoral metrics for selected tax pathways (HH revenue recycling scheme). All panels display percentage differences to the no-tax reference case. Note the differences in y-axis scales

shown here for the HH revenue recycling scheme, but sectoral impacts are largely insensitive to the choice of revenue recycling scheme as can be seen in Fig. 3 of the appendix.

Each of the energy-producing sectors of coal, natural gas, and oil is affected differently by the CO_2 tax. The coal sector faces an immediate and relatively large decline in imports along with smaller relative decreases in price and output. Coal exports from the United States increase as there is a reduction in domestic demand that reduces the price of US coal in international markets. This outcome is driven by the fact that we do not implement policies in countries outside of the US. If other countries were to limit their own demand for US coal, output may drop even more.

The response of the natural gas sector depends on the tax level. In all cases, there is an immediate increase in output and prices given that the electricity sector initially increases its gas use relative to the reference case. With the \$50 @ 5% tax pathway, natural gas sectoral output begins to decline relative to the reference case starting in 2024 whereas output with the \$25 @ 1% tax pathway remains above the reference case until the mid-2040s. Similarly, the price of natural gas is greater than the reference case over the entire modeled time period under the \$25 @ 1% tax pathway, but under the \$50 @ 5% tax pathway gas prices decline relative to the reference case by 2030.

The oil sector faces a fate similar as the coal sector in that prices, output, and imports decrease but exports increase. The crude oil sector stands out in that it has the greatest difference in relative changes in output between the lowest and highest tax pathways. Under the \$25 @ 1% tax pathway, oil sector output in 2050 declines by 5%, yet under the \$50 @ 5% pathway output declines by 25% despite an increase in exports — representing the largest relative changes in output between the two tax pathways of any sector. This result is partially driven by the fact that the version of USREP used for this study allows no transportation sector fuel options other than oil-based fuels. Therefore, the transportation sector requires a higher tax to reduce its emissions relative to the more flexible electricity sector. Transportation is the most affected of non-energy sectors with a relatively large increase in price and decrease in output.[8]

Outside of transportation, relative changes for other non-energy sectors are smaller in magnitude but non-negligible. Manufacturing, energy intensive services, and agriculture, which use energy as an input to production, experience increased prices and imports and reduced output and exports when a CO_2 tax is imposed. For these sectors, reduced consumption is driven both by a reduction in household income and an increase in the relative prices of these goods. Outcomes are different for the services sector, which sees a small reduction in output, combined with a *reduction* in output price and imports and an *increase* in exports. For the services sector, the negative effect of reduced income on consumption outweighs the potential positive substitution effect through which consumers now favor relatively inexpensive services over more expensive energy-intensive goods.

4.2. *Factor market outcomes*

Alongside impacts on the goods markets described above, impacts on factor prices are major determinants of a CO_2 tax's impacts on household welfare, as they affect their income. In this section, we present impacts on labor, capital and resource owners. These are more affected by the choice of revenue recycling scheme than changes in product markets. Therefore, we plot results for the *HH*, *K* and *L* recycling schemes. Results for other recycling schemes generally fall between these three cases. Throughout, we refer to the "returns" to a factor of production as demand, in value terms: its equilibrium price times equilibrium quantity demanded/supplied.

[8]While transportation imports and exports have large percentage changes, absolute quantities in the reference case are very small because the sector is primarily domestic, so these changes are small in absolute terms.

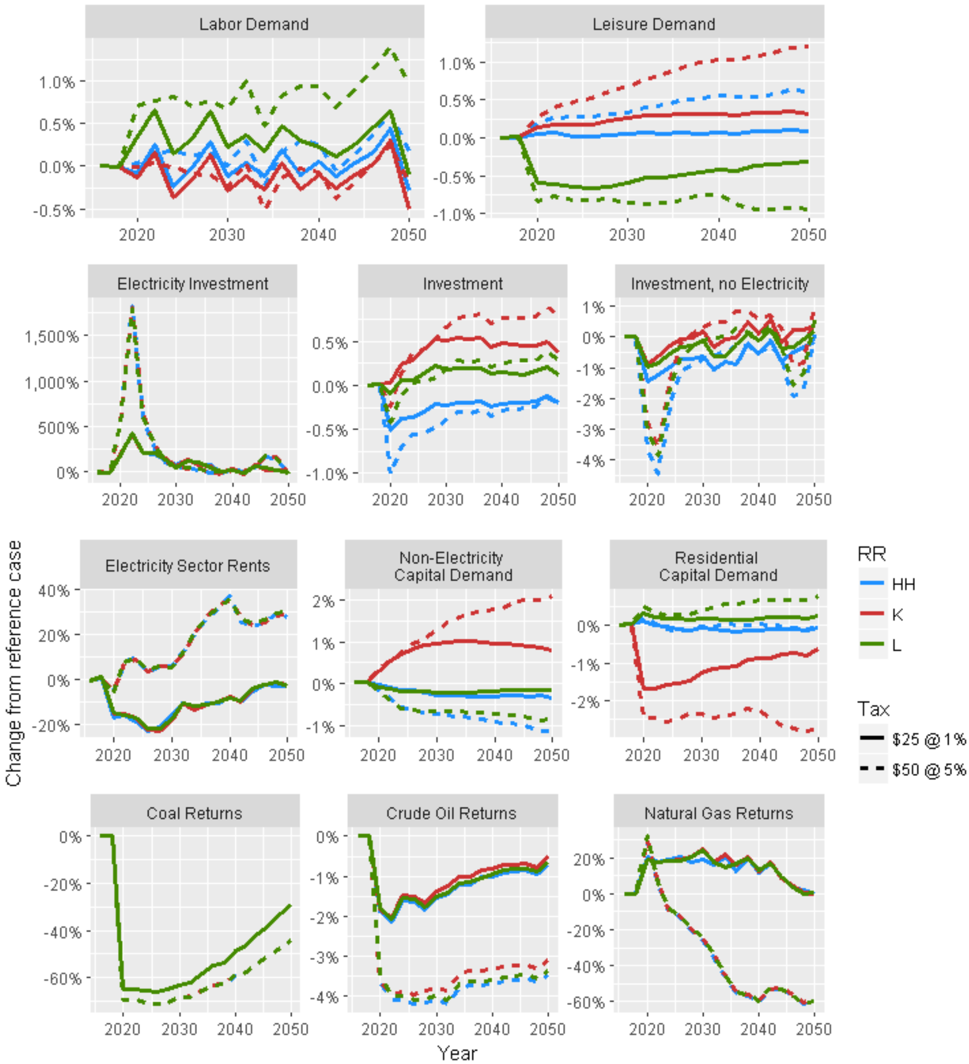

Figure 4. Summary of factor market outcomes for 3 different revenue recycling schemes and 2 tax pathways; all panels display percentage differences to the no-tax reference case

The first row in Fig. 4 pertains to labor markets, plotting labor and leisure demands to demonstrate the tradeoff between spending time working for wages versus leisure[9] (implemented in the model to generate wage-responsive labor supply). Under the *HH* revenue recycling method, the \$25 @ 1% tax does not have a substantial impact on labor markets but the more stringent tax leads to an increase in leisure and a slight reduction in demand for labor as consumption becomes more expensive. Although recycling revenue to reduce capital income tax rates (*K*) does not greatly impact labor

[9]Labor demand here is the equilibrium value of labor on the market (wage bill), i.e., the returns to labor. Leisure demand is the equilibrium value of leisure.

demand, it does lead to an increase in leisure under both tax pathways, as the marginal value of leisure increases in line with the increase in income from capital returns. With the labor tax rebate (*L*), the value of work increases relative to leisure because less income tax is being paid, so consumers choose to work more and spend less time on leisure.

The second and third rows of graphs pertain to capital markets. The second row describes the change to investment: electricity sector, economy-wide, and non-electricity investment. In USREP, total investment is a function of savings from the previous period and is thus linked to overall economic activity. In all but the \$25 @ 1% tax pathway with *K* recycling there is an immediate drop in economy-wide investment in 2020 that then rebounds over the modeled time period. This rebound is especially strong with capital income tax rebates, which increase the value of capital ownership and thus investment. When excluding electricity, every scenario results in a drop in investment in the initial year with a much more precipitous drop in the \$50 @ 5% tax pathway. Electricity sector investment increases rapidly in response to the onset of a CO_2 tax before falling to lower levels (but still notably higher than in the no tax reference case). While the initial increase in electricity sector investment is large from a relative standpoint, this change is relative to a reference investment level which is quite low in the 2020s.[10] The ReEDS model does include growth penalties that incur additional costs for rapid capacity builds, but there are no provisions requiring continued use of previously built capacity if the least-cost solution instead incentivizes new capacity construction. This inherent flexibility along with limited foresight means that modeled system response might be faster than would be observed in reality.

Consistent with other electricity sector results, electricity sector investment and rents do not vary greatly across revenue recycling methods but do vary across tax levels. Higher CO_2 taxes require more capital investment than lower taxes because low-emitting sources (wind, PV) have a higher ratio of capital-to-operating expenses than higher-emitting sources being built (e.g., natural gas combined cycle plants). In turn, higher investment leads to higher returns to capital.

The second row describes rents, in value terms, from the electricity sector (the returns to electricity sector capital and electricity sector profits), capital returns from all other sectors, and residential capital demand (housing). The former is mostly determined within ReEDS while the latter two are determined within USREP. With the higher tax, the share of low- or zero-emitting electricity generation increases, but the price is (in a general sense) still determined by the more pollution-intensive generators on the margin. Therefore, there is an increase in overall electricity rents with higher tax rates as low- or zero-emitting generation is able to gain higher rents per MWh produced than their relatively high-emitting counterparts. With low tax rates, which result in less renewable penetration, the CO_2 tax reduces the rents from the electricity sector.

[10]Electricity investment in the No-Tax Ref case is \$13.9 billion in 2020 and \$5.9 in 2022 whereas average annual investment is \$27.7 billion.

Under the *HH* revenue recycling method, non-electricity capital returns are only marginally affected under the lower tax but decrease more substantially with a strong tax. Residential capital demand with *HH* revenue recycling decreases but to a lesser extent than with other revenue recycling methods.[11] Non-electricity investment and capital demand rises under the *K* scheme, as it increases the value of capital investments. The *L* recycling method has a slightly smaller impact on non-electricity capital demand than the *HH* revenue recycling method because consumption is less impacted.

The fourth row of graphs pertains to resource factors, describing the returns to fossil fuel resource ownership, depicted in the model as fuel-specific fixed factors. These outcomes are not substantially affected by the recycling scheme. Coal and crude oil factor returns decrease immediately after the CO_2 tax is applied, but the opposite is true for natural gas, which faces increased demand as it is the least CO_2-intensive fossil fuel. While increased demand for natural gas persists throughout the study period for the \$25 @ 1% tax pathway, it is short lived with the higher tax pathway, and returns to the owners of the natural gas resource quickly fall below reference levels as zero-emitting technologies increase their share of the generation mix. The impacts on natural gas and coal resource factors are much larger than those to crude oil, which is used primarily in the less-responsive transportation sector and is heavily involved in international trade. The upward trend after the initial shock to coal returns is due to the coal returns declining in the reference as well as a gradual increase in exports. Our model does not explicitly allow for liquefied natural gas, limiting the scope for gas exports that could facilitate a similar rebound in returns as shown for coal.

This section has highlighted the wide-ranging implications of CO_2 taxation on factor returns. Impacts are largest for fossil resources, while the tax's direct impacts on labor and capital markets are negative but only very weakly so (as can be seen under HH). The choice of recycling scheme dominates the CO_2 tax's direct effect on these markets. These factor market impacts have important implications for income-driven welfare impacts and their distribution, which we turn to next.

4.3. *CO_2 emissions reductions*

In the no-tax reference case, we find (Fig. 5) that economy-wide emissions are stable and even slightly decreasing in the later years of the simulation period. This is largely due to assumed energy efficiency improvements in all sectors in USREP and the decreasing carbon intensity of the electricity sector predicted by ReEDS. Forecasted US CO_2 emissions in the reference scenario over the 2020–2050 time period are 166.7 billion tons of CO_2 with an average annual emissions rate of 5,209 million tons.

[11]In general, residential capital has an inverse relationship with market capital (electricity and non-electricity combined). Under the *HH* recycling scheme, residential capital demand is not significantly affected. Under the *K* revenue recycling scheme, residential capital demand decreases despite the fact that household incomes increase: contrary to market capital, it does not profit from the income capital tax rebate. Under the *L* scheme it increases because the higher post-tax wages increase household income.

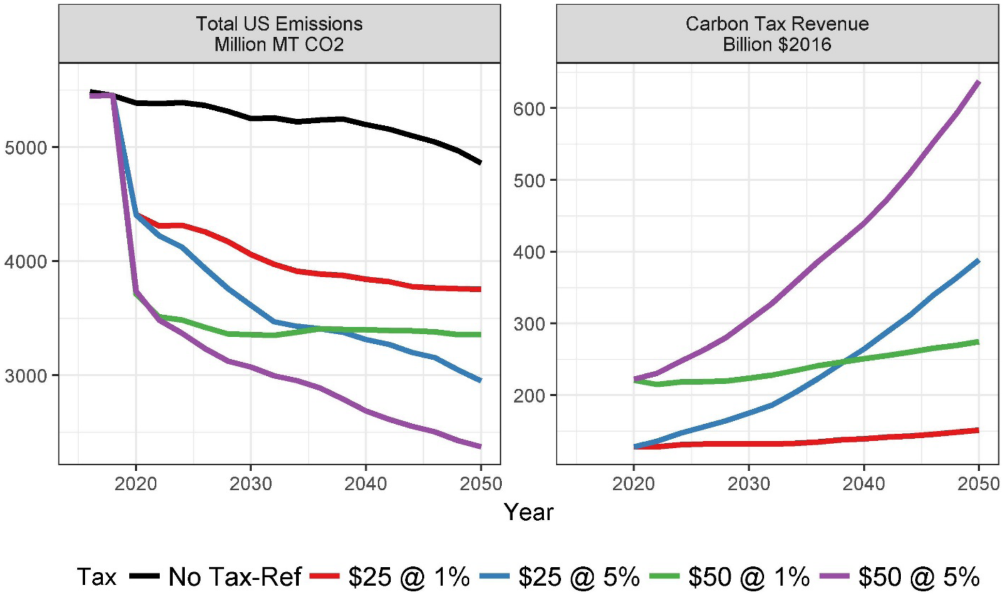

Figure 5. Total US emissions and CO_2 tax revenue by tax level (for HH revenue recycling)

In all cases, fuel switching in the electric sector leads to large reductions in emissions immediately following the onset of the tax. Cumulative emissions reductions in the CO_2 tax scenarios over the 2020–2050 time period range from 39.0 billion tons of CO_2 (23.4% reduction) under the $25 @ 1% tax pathway to 73.2 billion tons of CO_2 (43.9% reduction) under the $50 @ 5% tax pathway. Emissions reductions increase with the initial tax level and over time with rising tax rates. By 2050 emissions are reduced by 22.7% relative to the reference under the $25 @ 1% tax pathway and by 51.1% under the $50 @ 5% tax pathway. The $50 @ 1% and $25 @ 5% pathways have emissions falling between those with the $25 @ 1% and $50 @ 5% trajectories.

Reductions in emissions relative to the reference case continue to increase in the 5% growth rate scenarios, but stagnate and eventually decrease in the 1% growth rate scenarios.[12] An important implication is that 1% annual growth in the CO_2 tax is approximately enough to offset increased emissions as the economy grows but more rapid increases, e.g., 5%, are needed to foster continued reductions in absolute emissions.

Most of the cumulative emissions reductions under all tax pathways are attributable to the electricity sector, which is responsible for 71–74% of reductions, as can be seen in Fig. 6, which plots the share of reduction by sector. Transportation is responsible for the second-highest share of emissions reduction, especially under $50 @ 5% pathway where it accounts for 11.7% of all reductions. The shares do not vary significantly across revenue recycling methods. The large role for electricity is partially a feature of our model, as abatement outside of the electricity sector is modeled via energy and fuel

[12]All prices are real in the model, so this result is not due to the tax rates being outpaced by inflation.

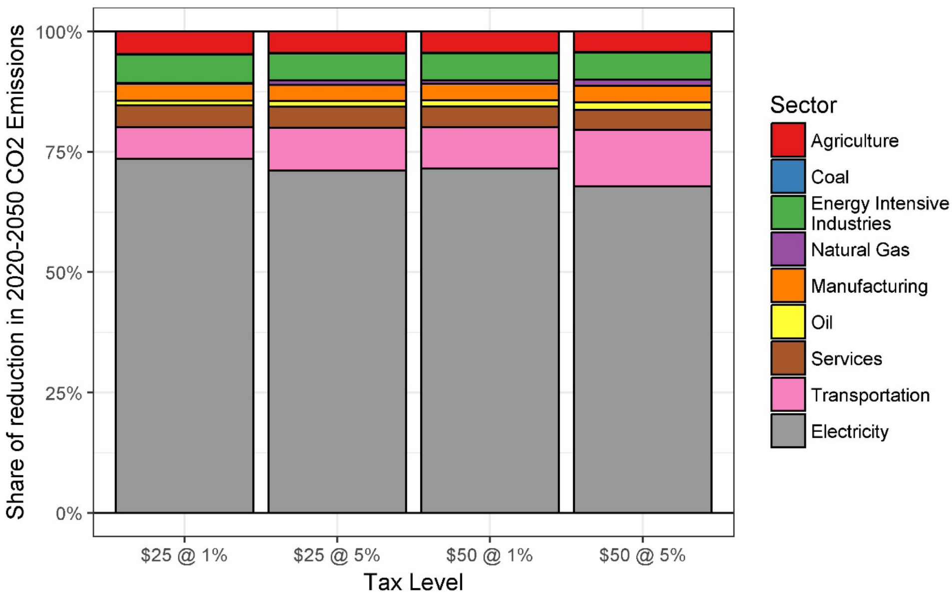

Figure 6. Share of emissions reduction by sector and tax level (*HH* revenue recycling)[13]

substitution in aggregate production functions that do not represent discrete new technology options that could quickly replace CO_2 intensive options. While discrete abatement options may exist in many sectors (e.g., electric vehicles in the transportation sector), the CO_2 price needed to incentivize their adoption is likely to vary, giving a smoother aggregate emissions reduction as the tax rises. Still, the electricity sector is the single largest emissions source in the US, and the ability to quickly fuel shift by changing the merit order of dispatch is relatively unique. While some industrial facilities have fuel switching capability, few of those systems use coal, limiting possible CO_2 reductions.

4.4. *CO_2 tax revenue*

The CO_2 taxes generate a substantial amount of revenue (Fig. 5), ranging from \$142 billion and \$579 billion by 2050 under the \$25 @ 1 and \$50 @ 5% tax pathways, respectively.

In order to summarize the sources of revenue over the 2020–2050 time period, Table 1 displays the net present value of the revenue, in \$billion, generated by a \$25 @ 5% tax. NPV's throughout this paper are computed over 2017–2050 using a 3% social discount rate consistent with U.S. Office of Management and Budget guidelines for long-term cost-benefit analyses. Results are shown for the *HH*, *L* and *K* recycling schemes. To help understand the role of adjustment in the economy to the tax, the first column displays the revenue which would have been collected if all emissions remained

[13]"Energy Intensive" represents a set of energy intensities industries; these results reflect end-use emissions, so neither coal nor natural gas production makes up a significant share of emissions reduction because the sectors themselves do not emit a significant amount.

Table 1. The sources of tax revenue for the \$25 @ 5% scenario, with adjustment from reference solution (HH, K and L columns) and without ("No adjustment reference" column). The latter is computed by multiplying reference emission levels with the CO_2 tax rates.

	NPV of CO_2 tax revenue collected (\$bn)				Percentage change to reference		
	No adjustment	With adjustment			With adjustment		
	Reference	HH	K	L	HH	K	L
ELE	1685.6	594.7	595.5	600.6	−64.72	−64.67	−64.37
TRN	1325.7	1180.4	1183.2	1182.5	−10.96	−10.75	−10.80
EIS	397.9	308.9	310.1	309.4	−22.38	−22.07	−22.25
MAN	241.2	186.9	187.4	187.2	−22.49	−22.30	−22.37
SRV	207.9	139.6	140.3	140.1	−32.83	−32.52	−32.60
AGR	202.5	133.2	133.8	133.5	−34.23	−33.96	−34.07
OIL	121.9	103.2	103.5	103.4	−15.34	−15.16	−15.20
GAS	71.9	56.4	56.4	56.7	−21.53	−21.47	−21.13
COL	6.2	4.9	4.9	4.9	−21.67	−21.64	−21.67
Total ind.	4260.8	2708.3	2715.0	2718.3	−36.44	−36.28	−36.20
Households (by income quintile, where Q1 represents the lowest-income households)							
Q1	94.1	84.8	84.4	84.1	−9.84	−10.27	−10.63
Q2	127.9	115.1	115.0	114.9	−9.99	−10.02	−10.10
Q3	170.9	153.7	154.2	154.2	−10.09	−9.80	−9.78
Q4	177.7	159.4	160.2	160.3	−10.28	−9.82	−9.76
Q5	173.8	155.7	156.7	156.9	−10.40	−9.81	−9.72
Total hh.	744.3	668.7	670.6	670.5	−10.16	−9.90	−9.92
Total	5005.2	3377.0	3385.6	3388.7	−32.53	−32.36	−32.30

constant at their baseline reference level.[14] The last block of three columns displays the percentage change in revenue collected relative to the no adjustment counterfactual.

This table allows to answer three sets of questions: (i) who pays for the tax?; (ii) by how much does adjustment by consumers and producers reduce revenue? and (iii) how is tax revenue affected by the way in which it is recycled?

First, we consider who pays for the emissions tax. Without adjustment to the tax, the electricity sector would be paying the most tax, while with adjustment (see the *HH* column, for instance) the transportation sector would be paying the most tax. This reflects the fact that the electricity sector reduces its emissions proportionally more than the transport sector in response to the tax while the transportation reduces its emissions proportionally less than average. Households would pay 14% of the total tax without adjustment but 20% with adjustment. Households reduce the tax they pay by about 10% by adjusting their consumption patterns, less than the economy as a whole. These are "direct" payments: the tax payed at the point of emission. Electricity consumed by households is taxed in the electricity sector and not by the households. Also,

[14]This is simply computed by multiplying the amount of CO_2 emitted by each sector or household in the no-tax reference case by the tax level implied by the \$25 @ 5% scenario.

the numbers in this table do not inform us about the distribution of tax burdens, simply the point of revenue collection.

Second, the fact that economic actors respond to the tax implies a total tax revenue collected that is 32.5% lower than without adjustment. This is significant but suggests that while the taxes reduce emissions, they are far from eliminating the tax base.

Third, the information in Table 1 indicates the CO_2 tax revenue does not vary greatly across revenue recycling schemes. We conclude again, as was the case for the electric sector, that CO_2 abatement and revenue collected can be estimated while staying agnostic about the choice of revenue recycling scheme.

4.5. *Aggregate welfare impacts*

This section discusses the aggregate welfare impacts of the tax. These are largely determined by the choice of revenue recycling scheme. We stress that welfare impacts discussed throughout the paper, unless otherwise specified, do not include the tax's benefits from the reduced climate change externality. If the benefit of the reduced externality is included, we will show that all taxes and revenue recycling methods result in a net benefit to society.

The welfare measure used here, *equivalent variation* (EV), reflects changes in household consumption, leisure, and residential capital returns. These correspond to the elements of the household's within-period utility function, excluding investment in market capital, which contributes to welfare in subsequent years as the returns to this capital generate consumption that is then included in welfare in later years. Aggregate US welfare change is computed by summing equivalent variation across household types and regions based on an implied utilitarian welfare function. In some results, we also discuss the tax's impact on household consumption only. While an incomplete measure of welfare, consumption is an important component of GDP that may be of interest to policy makers. The distinction between consumption and EV matters most when comparing the L and K recycling schemes.

Figure 7 summarizes how revenue is recycled in each scheme by displaying NPV's of revenue. Here, "To Households" represents the amount of revenue given to households through lump-sum rebates; "Haircut" represents the portion of the revenue that must be kept by the government in *HH* to keep the its budget unchanged; "To Labor" and "To Capital" represent the revenue used to reduce labor and capital income tax rates; "To Quintile 1" represents the transfer required to compensate the poorest income quintile; and "For Progressivity" represents the lump-sum transfers needed to ensure that the policy remains progressive across income quintiles.

Figure 7 also displays the NPV of the welfare loss (EV) in each scenario and illustrates four important points:

(i) the total amount of CO_2 tax revenue is similar across revenue recycling schemes;
(ii) the destination of tax revenue has significant consequences on the policy's resulting welfare;

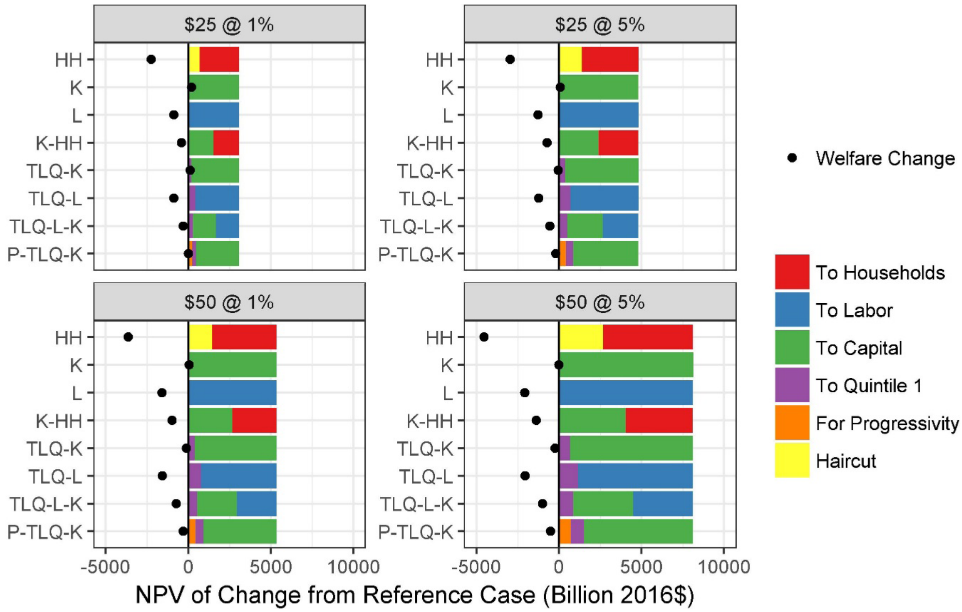

Figure 7. NPV of revenue recycled by recipient, tax pathway, and revenue recycling scheme; NPV of welfare loss by tax pathway and revenue recycling scheme. NPVs computed for the 2017–2050 time frame using a 3% discount rate

(iii) the loss in welfare is in most cases comparatively small relative to the amount of revenue collected; and

(iv) a relatively small portion of the CO_2 tax revenue is required to enforce progressivity and/or to keep the lowest quintile unharmed by the policy.

We discuss the implications of these results in more detail below.

Before investigating the NPV of welfare loss in more detail, we first describe the patterns of welfare impacts over time. The annual percent change in aggregate welfare (for all households) relative to the reference no-tax case is presented in Fig. 8 for each tax level and revenue recycling scheme. The size of sudden drop at the onset of the tax (in 2020) depends on the initial level of the tax and, corresponds to a 0.28% decrease in welfare with a $25 per ton initial tax and a 0.57% decrease in welfare with a $50 per ton initial tax. The size of this initial shock does not vary much across revenue recycling schemes, although *HH* and *K-HH* welfare losses are slightly lower in the very short-run.

The long-term outcomes, however, depend heavily on revenue recycling as welfare losses remain mostly constant under *HH* (less so in the 1% tax growth pathways) but decrease with all other schemes, implying that the tax's negative impacts diminish in time. Recycling revenue to labor taxes (*L*) leads to modest welfare gains relative to *HH*, but the largest gains come from revenue recycling mechanisms that reduce capital tax rates (*K*, *P-TLQ-K*, *TLQ-L-K and K-HH*, ordered in terms of benefits). This result

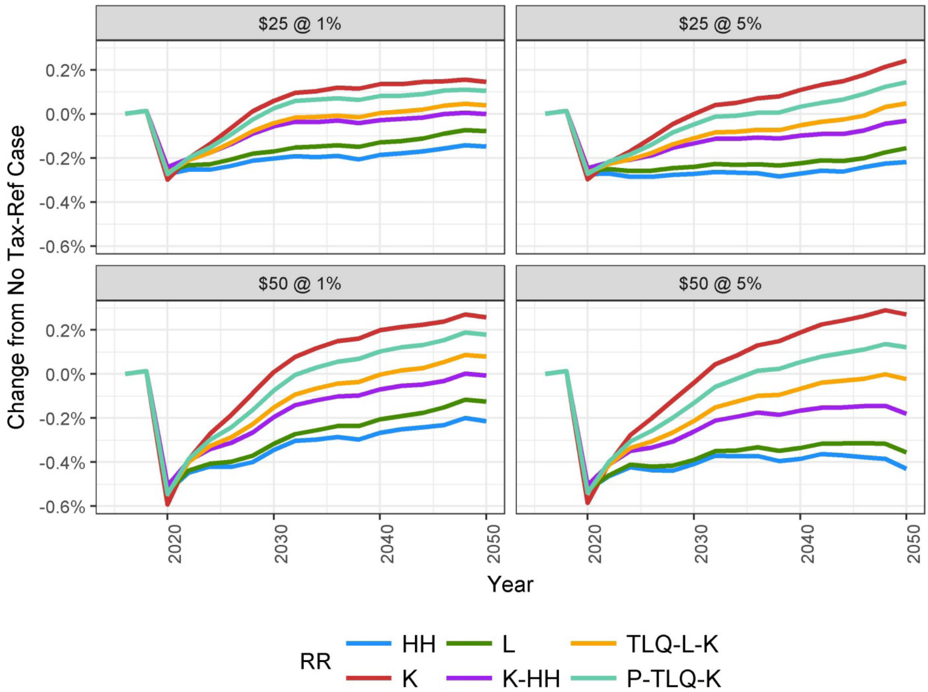

Figure 8. Change in welfare by tax pathway and revenue recycling scheme

is in line with the well documented idea that reducing the economic distortion introduced by capital income taxes can have important long-term benefits in terms of additional investment (Goulder and Hafstead, 2013; Rausch and Reilly, 2015; Goulder *et al.*, 1999; Jorgenson *et al.*, 2013). In many instances, results show that the efficiency gains may indeed by high enough to eventually lead to a *strong double-dividend*: net welfare gains from the CO_2 tax, even without considering the environmental benefits. Given the set of assumptions underlying this model,[15] this would occur under all tax pathways and approximatively 10 years after the onset of the tax.

Because of this additional efficiency gain, the long-term welfare gains in the *K* scenarios are actually stronger with more stringent taxes. Strong taxes accentuate the importance of revenue recycling: the greatest welfare benefits and losses are under the highest tax pathway, \$50 @ 5%, with the greatest losses under lump sum rebates to households (*HH*) and greatest gains with reducing capital tax rates (*K*). This outcome emphasizes that the same tax pathway can bring about a wide range of welfare implications depending on the choice of revenue recycling scheme.

The same welfare outcomes are also summarized in Table 2, which displays the NPV of welfare impacts across tax pathways and recycling schemes. The table shows,

[15]We do not assess the error bounds around our double-dividend result to determine its robustness and we do not explore how the result is sensitive to assumptions regarding key elasticities of substitution. Sancho (2010) for instance suggests that our results may be sensitive to our parametrization of the elasticity of substitution between capital and labor.

Table 2. Net present value (NPV) of welfare and consumption impacts (NPVs computed on a 2017–2050 basis using a 3% discount rate)

Tax	HH	K	K-HH	L	TLQ-K	TLQ-L	TLQ-L-K	P-TLQ-K
Percent change in Welfare, not including climate change benefits								
\$25 @ 1%	−0.20%	0.04%	−0.07%	−0.16%	0.02%	−0.16%	−0.05%	0.00%
\$25 @ 5%	−0.27%	0.02%	−0.13%	−0.23%	−0.01%	−0.22%	−0.10%	−0.04%
\$50 @ 1%	−0.33%	0.01%	−0.18%	−0.29%	−0.02%	−0.28%	−0.13%	−0.06%
\$50 @ 5%	−0.41%	0.00%	−0.25%	−0.37%	−0.04%	−0.37%	−0.18%	−0.09%
Change in NPV of Welfare per Capita, not including climate change benefits								
\$25 @ 1%	−\$2,802	\$494	−\$1,016	−\$2,197	\$288	−\$2,170	−\$762	\$21
\$25 @ 5%	−\$3,682	\$219	−\$1,817	−\$3,164	−\$103	−\$3,085	−\$1,370	−\$502
\$50 @ 1%	−\$4,554	\$155	−\$2,454	−\$3,955	−\$285	−\$3,911	−\$1,812	−\$769
\$50 @ 5%	−\$5,654	\$114	−\$3,424	−\$5,192	−\$581	−\$5,107	−\$2,482	−\$1,273
Change in NPV of Welfare per Capita, including global climate change benefits (using the global SCC)								
\$25 @ 1%	\$1,214	\$4,486	\$2,993	\$1,791	\$4,288	\$1,826	\$3,236	\$4,018
\$25 @ 5%	\$1,758	\$5,630	\$3,612	\$2,238	\$5,313	\$2,342	\$4,049	\$4,922
\$50 @ 1%	\$1,430	\$6,093	\$3,516	\$1,997	\$5,663	\$2,053	\$4,144	\$5,186
\$50 @ 5%	\$1,834	\$7,456	\$4,053	\$2,260	\$6,871	\$2,354	\$4,974	\$6,186
Percent change in Consumption, not including climate change benefits								
\$25 @ 1%	−0.33%	0.02%	−0.15%	−0.03%	0.00%	−0.06%	−0.03%	−0.03%
\$25 @ 5%	−0.49%	−0.06%	−0.30%	−0.09%	−0.10%	−0.15%	−0.12%	−0.15%
\$50 @ 1%	−0.57%	−0.06%	−0.35%	−0.12%	−0.11%	−0.19%	−0.14%	−0.16%
\$50 @ 5%	−0.81%	−0.18%	−0.58%	−0.23%	−0.24%	−0.32%	−0.27%	−0.33%
Change in NPV of Consumption per Capita, not including climate change benefits								
\$25 @ 1%	−\$2,982	\$176	−\$1,374	−\$238	−\$32	−\$580	−\$245	−\$299
\$25 @ 5%	−\$4,450	−\$571	−\$2,732	−\$846	−\$904	−\$1,391	−\$1,086	−\$1,330
\$50 @ 1%	−\$5,166	−\$535	−\$3,231	−\$1,078	−\$980	−\$1,717	−\$1,245	−\$1,479
\$50 @ 5%	−\$7,379	−\$1,636	−\$5,276	−\$2,057	−\$2,232	−\$2,944	−\$2,469	−\$2,963

successively, the percent change in welfare, relative to the reference welfare NPV; the average discounted total per capita change in welfare, expressed in \$/capita[16]; the same per capita impacts, now inclusive of the policies' global climate change benefits (computed by multiplying emissions reductions by the social cost of carbon estimate from US EPA (2017)[17]; and finally changes in consumption in percentage and per capita terms. The table summarizes four important findings:

(i) NPV welfare costs are overall quite low and never exceed \$5,654 per capita (0.41%);
(ii) Once climate change benefits are included, all of the simulated taxes provide net benefits to society — benefits are in the \$1000 to \$2000 range with HH recycling;
(iii) Benefits including climate benefits *increase* with tax stringency, implying that incremental benefits of stringent taxes outweigh their incremental costs;
(iv) Capital income tax rebates (*K*) yield NPV welfare benefits under all tax pathways even without including climate change benefits.

It is important to note that since the gains from capital income tax rebates take time to materialize, the relative gains of K relative to HH will decrease for higher rates of time discounting.

If evaluating welfare using consumption only, as done in the two bottom panels of Table 2, we observe several differences relative to the EV results. Percentage impacts are higher for all recycling schemes apart from *L*, with consumption changes as large as -0.81% (ignoring climate benefits) under the most stringent tax and with *HH* recycling. Under non-*L* recycling schemes, households temper total welfare impacts by substituting consumption for leisure. Since the benefits from leisure are ignored under this measure, negative impacts appear more significant. With labor income tax rebates, however, the opportunity cost of leisure increases and the opposite occurs.

4.6. *Aggregate welfare costs per ton of emission reduction*

Table 3 displays the NPVs of the welfare losses per cumulative emissions reductions over the 2020–2050 timeframe, an average abatement cost measure, for each tax level and revenue recycling mechanism. Positive values are losses; thus, a negative value indicates a welfare gain per ton of CO_2 abatement. These abatement costs reflect the order of revenue recycling schemes identified above, from most to least costly: *HH, L, K-HH*, *TLQ-L-K*, *P-TLQ-K*, and *K*.

The order of recycling schemes from most to least costly does not change when considering welfare costs per ton instead of gross welfare costs, reflecting the insensitivity of total emissions abatement to the choice of recycling scheme.

[16]Per capita values here are computed by dividing the NPV of welfare loss (or gain) by population in 2016.
[17]The damages included in the SCC are global. Assigning them to US households as we do implicitly assumes that global damages from climate change will be uniform across countries.

Table 3. Average abatement costs per ton, by revenue recycling mechanism and tax level, computed as NPV of welfare loss (2016$) per cumulative ton of CO_2 abated (2020–2050).

	HH	K	K-HH	L	P-TLQ-K	TLQ-L-K	Abatement cost, gross of revenue in HH
$25 @ 1%	21.0	−4.0	8.1	17.6	−0.2	6.1	80.9
$25 @ 5%	21.4	−1.3	10.6	18.5	2.9	8.0	88.6
$50 @ 1%	23.7	−0.8	13.3	21.5	4.2	9.9	93.9
$50 @ 5%	24.1	−0.1	14.6	22.2	5.4	10.6	106.8

In all scenarios, average abatement cost per ton increases with the tax stringency, reflecting increasing marginal costs over all abatement possibilities in the economy. The increase is very modest, however. To better understand the cost of abatement, net of the benefits of recycling, the last column of the table reflects abatement costs, for the *HH* scheme, gross of CO_2 tax revenue (computed by subtracting the rebates recycled to households from the welfare loss displayed in the first column). Note that these are *not* our expectations of the actual cost of policy. While the exact abatement costs gross of recycling benefits are impossible to obtain in our general equilibrium framework, this measure provides a reasonable approximation because a lump-sum rebate can be thought of as a transfer that does not substantially reduce or increase pre-existing distortions to the economy. With this measure, we approximate the gross abatement cost that would occur if the revenue was not recycled at all. Abatement costs per ton in this case would range from $80.0 per ton with the $25 @ 1 tax pathway to $106.8 per ton with the $50 @ 5% tax pathway. Overall, these suggests a reasonably flat economy-wide marginal abatement cost curve and indicates that the U.S. economy should be able to adjust to fairly stringent CO_2 taxes. This result emphasizes the point that welfare loss caused by CO_2 taxation is small relative to the amount of revenue recycled.

Finally, as an aside, the global nature of our model allows us to investigate whether emissions reductions in the U.S. (stimulated by the unilateral climate policy) will be negated by increased emissions in other countries ("carbon leakage"). In line with the relatively large literature on leakage, we find rates of leakage that are non-negligible but also not substantial enough to significantly alter the effectiveness of a US-only. Leakage rates are found to decrease with tax stringency. For the HH scenario, we find a rate of 19.9% for the $25 @ 1% tax, 16.3 % for the $25 @ 5%, 15.9% for the $50 @ 1 % and 13.8 % for the $50 @ 5% tax. China, India and Europe are the main sources of leakage.

5. Distributional Impacts

The choice of revenue recycling scheme has significant distributional implications across income quintiles. Figure 9 displays the NPV welfare impacts by quintile, absent emissions reductions benefits. The only strictly-progressive options are to either return the revenue to households in lump sum fashion (*HH*) or to enforce progressivity as in

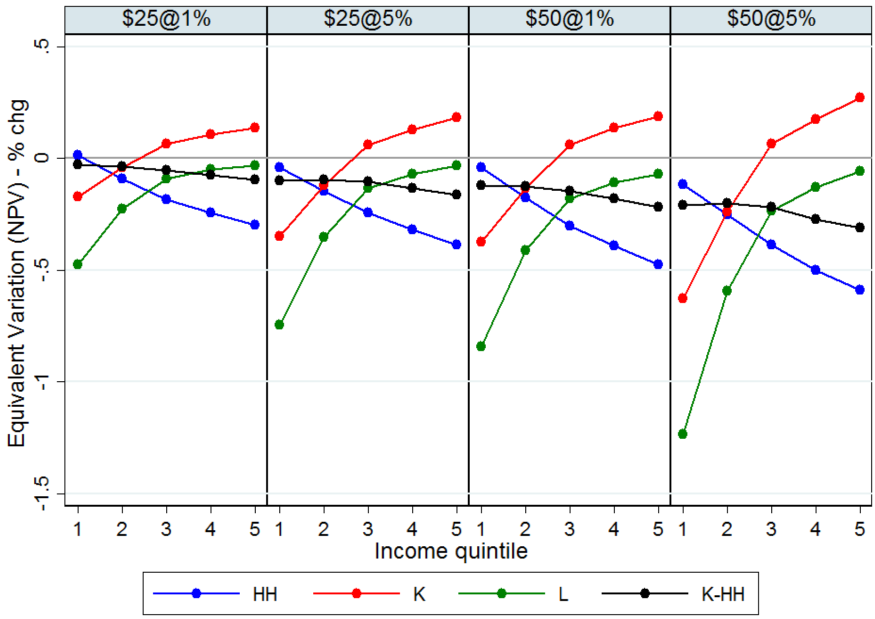

Figure 9. NPV of welfare change by tax pathway and revenue recycling method across income quintiles. "1" represents the population quintile with the lowest income, "5" the largest income

P-TLQ-K, which is not shown in Fig. 9, because impacts are constant across quintiles by construction. In the case of *HH*, the welfare of the lowest income households is nearly unaffected, while richer households have reduced welfare. The *K* and *L* schemes, while providing efficiency gains that reduce welfare loss, benefit the richer household types more and are strictly regressive. With *K*, the three richest quintiles see welfare gains. The *K-HH* scheme is neutral to mildly progressive, but it leads to welfare losses for all household types. While the spread of outcomes between household types is accentuated accentuated by large taxes, as larger tax revenues amplify impacts, distributional patterns are *qualitatively* unaffected by tax stringency.

5.1. *The welfare tradeoffs between efficiency and equity*

From the previous results, a trade-off between efficiency (reduced overall welfare costs) and equity (distributional of welfare changes) emerges: the *HH* recycling mechanism is progressive but incurs the largest overall welfare losses, while the *K* recycling mechanism is regressive but yields a positive overall welfare change.

To better investigate this trade-off, we summarize each revenue recycling scheme's progressivity using the Gini coefficient, a metric that captures the degree of inequality in a distribution (here welfare). In Fig. 10, the *y*-axis plots the percentage change in the Gini coefficient of the post-tax welfare distribution relative to the pre-tax distribution.[18]

[18]This is a variant of the Kakwani index used to compute the progressivity or regressivity of proposed changes to the tax code.

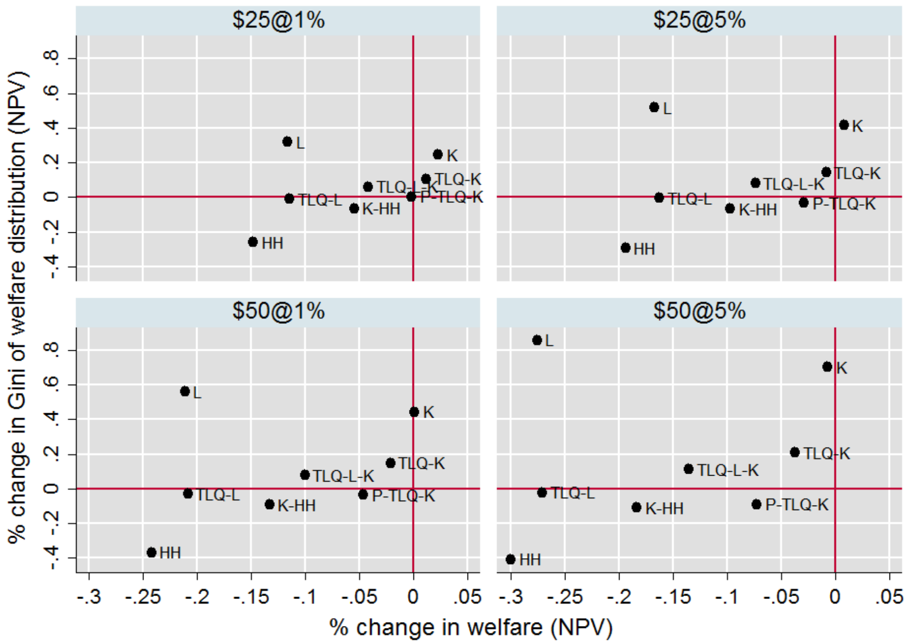

Figure 10. Plotting the efficiency-equity tradeoff: Schemes toward the right are less costly overall; schemes towards the bottom are more progressive

A positive number implies that the tax has increased inequality and is thus regressive, with the Gini increasing by the corresponding amount. On the x-axis, we plot the percent change in total welfare (across all households).

Figure 10 reveals that the efficiency-equity tradeoff generalizes to all recycling schemes and holds for all tax pathways: policies that are more efficient (less costly in terms of welfare and thus to the right on the graphs) tend to be more regressive (higher on the *y*-axis) and vice versa. Policies that are both higher and more to the left than others can be considered to be "dominated" along these dimensions. Using this metric, we see that the most regressive scheme uses labor income tax rebates (*L*) exclusively. Being also relatively inefficient, the *L* recycling scheme is thus dominated in both dimensions of the equity-efficiency tradeoff.

Figure 10 shows that apart from *L*, most revenue recycling schemes fall between the least-cost but most regressive *K* scheme and the most expensive but most progressive *HH* scheme. No scheme performs better than *K* and *HH* on both dimensions. Also, all schemes involving *L* in some form (*TLQ-L*, *TLQ-L-K* and *L*) are dominated by another scheme.

5.2. *The cost of compensating the lowest income households or insuring progressivity*

Figure 10 indicates that several efficiency-equity combinations are attainable by combining capital income tax rebates with other elements: *K-HH*, *P-TLQ-K*, and *TLQ-K*

Table 4. The aggregate welfare costs and revenue requirements of holding the welfare of households in the lowest income quintile constant.

	% Reduction in welfare costs relative to HH				Share of tax revenue transferred to Q1 households			
	\$25@1%	\$25@5%	\$50@1%	\$50@5%	\$25@1%	\$25@5%	\$50@1%	\$50@5%
HH	0	0	0	0	—	—	—	—
L	−21.3	−14.0	−12.8	−8.0	—	—	—	—
K-HH	−62.9	−50.1	−45.0	−38.7	—	—	—	—
K	−115.1	−104.2	−100.3	−97.8	—	—	—	—
TLQ-K	−108.1	−95.8	−91.1	−87.7	0.060	0.077	0.074	0.082
P-TLQ-K	−98.8	−85.1	−80.8	−75.8	0.074	0.093	0.089	0.099
TLQ-L-K	−71.5	−61.9	−58.6	−54.9	0.092	0.104	0.102	0.107
TLQ-L	−22.4	−16.2	−13.9	−9.6	0.140	0.143	0.143	0.142

all lie on an "equity-efficiency" frontier of undominated policies between *HH* and *K*. Moreover, these policies all lie below the K-HH line, suggesting that they improve upon simple combinations of the K and HH schemes. Thus, it seems possible to benefit from the efficiency of capital tax reductions while alleviating some of the distributional concerns. This section examines the costs of taking such measures to improve the tax's distributional impacts.

We focus first on the scenarios designed to compensate the lowest-income households through lump-sum transfers that leave their welfare unchanged relative to the no-tax reference (i.e., all scenarios involving *TLQ*). Results indicate that the cost of protecting the lowest income quintile is relatively small, both in welfare loss and the share of revenue that must be set aside for these transfers. As can be seen from the right panel of Table 4, the tax revenue devoted to protecting the lowest income quintile represents 14.3% of the total tax revenue collected in the inefficient *TLQ-L* scenario and only 7.7% in the efficient *TLQ-K* scenario (\$25 @5%). Notably the share of tax revenue required to protect the poorest quintile does rise with the tax level because the tax becomes more harmful to these households as stringency increases.

Similarly, very little of the efficiency costs afforded by capital tax reductions must be sacrificed to protect low income households. The left panel of Table 4 plots the percentage reduction in aggregate (across all households) welfare cost reduction in each scenario, relative to *HH* (the least efficient scheme), and shows that the cost savings afforded by *TLQ-K* (95.8% relative to *HH* under \$25 @5%) are close to those afforded by *K* (104.2%).

Having established the (low) welfare cost of using a small part of the revenue from *K* to compensate low-income households in *TLQ-K*, we finally turn to the possibility of using some of the revenue to provide transfers to all household types in order to insure that the tax's effect is progressive (or neutral) across the income quintiles. As can be seen from Table 4, the additional cost of ensuring progressivity in the P-TLQ-K scenario, relative to TLQ-K, is low. That is true both in terms of the share of revenue to be set aside (9.3% compared to 7.7%, see right panel for \$25 @ 5%) and in terms of welfare gains sacrificed (85.1% saving relative to HH compared to 95.8%, see left panel) for \$25 @5%.

6. Discussion and Conclusion

The findings presented in this paper result from the coupling of an economy-wide computable general equilibrium model with a detailed electricity-sector model. They present a comprehensive overview of the impacts of a wide range of potential CO_2 tax pathways and options for recycling the revenue that such taxes would generate.

The main findings that are relevant to policy-makers and other stakeholders include:

(i) The electricity sector will likely contribute much of the emissions reductions under a CO_2 tax, especially at low tax levels.
(ii) The electricity sector can achieve rapid and substantial CO_2 reductions through fuel switching. While fuel switching may temporarily raise electricity prices, the increase would rapidly attenuate with additional investment in natural gas generation (for low CO_2 taxes) and renewables (in all cases).
(iii) The CO_2 tax must increase at a fairly high rate to sustain reductions in emissions as the economy grows. 5%/year is sufficient, while 1%/year is not.
(iv) Welfare costs per ton of emission reduction are nearly the same regardless of CO_2 tax level and international CO_2 leakage does not significantly undermine the emissions reducing objective.
(v) Welfare costs (ignoring the benefits from reduced emissions) strongly depend on how the revenue is recycled, but are modest overall: between 0.2 and 0.4% in the least efficient recycling scheme, close to zero or even net gains with efficient recycling.
(vi) The amount and source of CO_2 revenue does not depend on revenue recycling scheme. Returning tax revenue to households in lump-sum fashion (*HH*) is the least efficient revenue recycling scheme but also the most progressive and the best for low income households.
(vii) Using the carbon tax revenue to reduce capital income taxes seems to be most efficient, but doing so primarily benefits richer households. This regressivity can be altered by additional transfers to lower-income households, which require only a small percentage of the overall revenue.
(viii) There is a clear trade-off between policy costs (efficiency) and progressivity of impacts (equity) across recycling schemes.

  - Using CO_2 tax revenue to reduce capital income appears as the most efficient policy but is least equitable to low-income households, while lump-sum rebates to households are the most progressive but least efficient, with labor income tax rebates dominated in both dimensions.

- Equity can be improved upon at relatively little cost in terms of efficiency. Combining capital tax rebates with additional transfers to compensate low-income households is not very costly: these would require only 6 to 8% of overall CO_2 tax revenue.
- Full progressivity of impacts can be insured with only 7% to 10% of revenue.

While many of these findings are qualitatively consistent with pre-existing literature, our quantitative estimates are specific to our modeling framework: substantial abatement opportunities in the electricity sector allow the US economy to accommodate extensive emissions reductions at relatively low cost. Thus, we find all CO_2 tax-recycling policies to have moderate welfare impacts on households. We find capital income tax rebates to have the potential of providing considerable double dividends, reducing the cost of CO_2 abatement by reducing the distortion caused by capital taxes. The efficiency of such a tax swap is well accepted by the literature. While we do find some "strong" double dividends in the later years, they are not large in relative magnitude and depend on the time horizon under consideration as well other modeling assumptions. That said, they are driven by the low abatement costs predicted by the electricity model. If the global avoided climate change benefits emissions are included, all tax levels and recycling schemes provide net benefits to society.

Our framework does provide us the unique ability to simulate and describe the distributional implications and efficiency of a set of hybrid recycling schemes. We find that while the trade-off between efficiency and equity is robust, and it is not possible to completely escape to escape the inherent regressivity of capital income tax reductions, it possible to improve upon the schemes typically discussed in the literature — lump-sum rebates and capital income tax reductions — using hybrid policies. For instance, we find that only a small share of the collected tax revenue must be set aside to keep the lowest income households unharmed by CO_2 taxation. Setting some revenue aside for transfers to households that keep the policy's impacts progressive similarly requires little sacrifice in terms of overall efficiency.

These results indicate a large scope for policymakers to adjust the tax code and alleviate the negative impacts effects of climate policy on specific demographics. Defining these adjustments needs not necessarily be undertaken in an energy-economic model like ours: another important finding of this study is that the problem of redistribution is largely separable from the problem of abatement efficiency. Across the revenue recycling schemes we considered, there are no significant differences in relative prices and output levels for a given CO_2 tax trajectory. However, by jointly addressing both the abatement and redistribution aspects of the problem, we believe our model to well describe the scope for redistribution possibilities: estimating the size of the collected revenue relative to welfare losses requires the most realistic modeling of the energy-economic system as possible.

As for any such exercise, all results presented here are contingent on the many assumptions underlying both models. Testing the robustness or sensitivity of results to variations in these assumptions is an interesting and necessary avenue for future research.

Appendix A

A.1 *Model descriptions*

A.1.1. *Regional energy deployment system*

Model structure

The ReEDS model solves for the least-cost system of electricity generation and transmission capacity in two year increments over the 2010–2050 time period. Functionally, ReEDS minimizes the 20-year net present value of investments and operation in sequential steps without full intertemporal optimization and only limited foresight into any CO_2 tax trajectory. The benefit to limited foresight is that nonlinear operations (e.g., those pertaining to renewable energy capacity value and curtailment) can take place between years to help better reflect true system operation. While limited foresight makes the model susceptible to market shocks and path-dependent solutions, it avoids unrealistic perfect-foresight behavior that would not be possible under real-life uncertainty. The ReEDS model version used for this analysis is similar to that used for the NREL 2016 Standard Scenarios report[19] (Cole *et al.*, 2016b) and is documented in detail in Eurek *et al.* (2016).

The major constraints in ReEDS ensure that electricity demand and reserves requirements are satisfied by a combination of generation, storage, and transmission technologies while accounting for power systems, transmission network, resource availability, and policy constraints. ReEDS represents electricity supply, generation, demand, and transmission in 134 balancing area (BAs) in the contiguous US as presented in Figure A.1. These same regions reflect the solar photovoltaic resource supply regions; however, wind and CSP resources are further disaggregated into 356 resource regions. Each BA must meet the operational, dispatch, and transmission constraints in 17 time slices, four for each season plus an additional "superpeak" time slice that represents the top 40 hours of electricity load in a year. ReEDS also represents a number of existing environmental and technology policies, including State Renewable Portfolio Standards (RPS) requirements, production and investment tax credits, and air pollution policies and regulations (CSAPR, CAIR, MATS, AB-32, RGGI).[20]

A strength of the ReEDS model is its detailed representation of variable renewable generation (VRG) technologies to better represent the challenge of integrating these

[19] Due to challenges in linking the ReEDS and USREP models, a slightly earlier ReEDS version is used for this work. This version does not include: (i) the updated hydropower formulation developed for the *Hydropower Vision* (DOE, 2016), (ii) updated state RPS constraints, and 3) improved historical calibration for 2010–2014. These differences somewhat reduce accuracy of the electric sector solution relative to the Standard Scenarios report (Cole *et al.* 2016b), particularly in the near term, but they should not substantially influence the cross-scenario comparisons and discussion for this work.

[20] As the Clean Power Plan has recently been withdrawn by the EPA, we do not model it in this analysis.

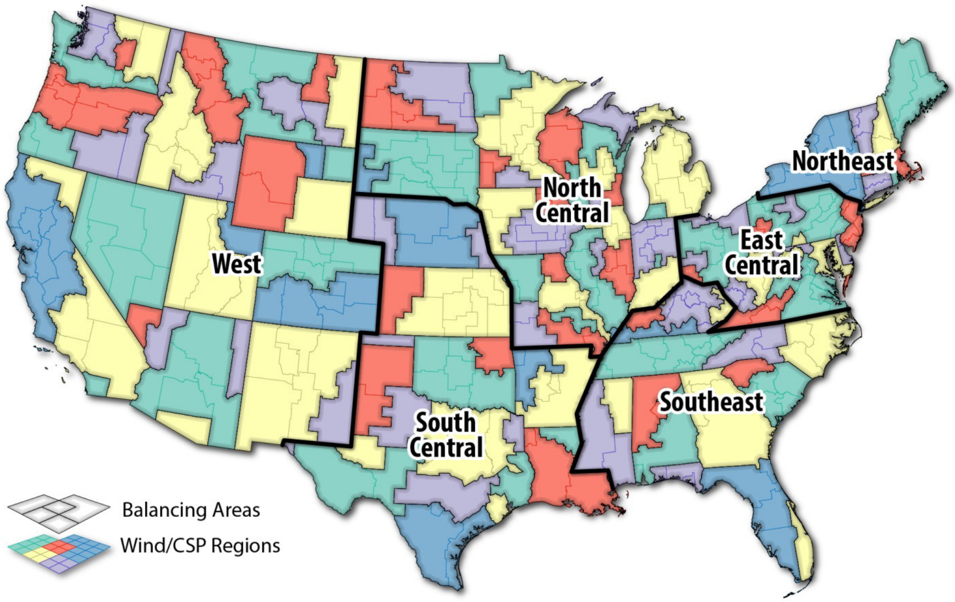

Figure A.1. ReEDS balancing area and wind/CSP resource region boundaries, with the six USREP U.S. sub-regions also labeled and denoted by thick black boundaries

resources into the electricity system. Each BA represents a solar photovoltaic (PV) resource supply region whereas wind and concentrated solar power (CSP) resources are further disaggregated into 356 subregions. For each technology and its associated resource region, costs are derived from detailed supply curves. The direct costs of VRG capacity expansion include not only base capital and operating costs but also region-specific grid interconnection costs. For each VRG technology, the model computes the three key variability parameters of capacity value, curtailments, and induced operating reserve requirements from forecast error. The calculations contain production profiles, statistical uncertainty in that production, and correlations across regions of VRG output. The variability parameters ensure appropriate competition between VRGs and other technologies to meet energy, reserves, and other system requirements. These parameters are updated after each solve to characterize reduced VRG resource quality with higher penetration, which could entail higher curtailments, lower capacity value, and greater reserves requirements; these effects then provide incentive for more flexible generation and storage technologies.

Data

The primary sources of data for the version of ReEDS used in this analysis are the Annual Energy Outlook (AEO) 2016 (EIA, 2016), the 2016 NREL Annual Technology Baseline (TB16) (Cole *et al.*, 2016a), and the ABB Velocity Suite (ABB Velocity Suite, 2017). The ABB Velocity Suite characterizes the existing fleet along with known new construction and retirements. Technology cost and performance data are derived from the AEO 2016 Reference Case; the ATB16 is used only for supplemental cost and performance assumptions not included in AEO2016 and the ATB16.

A.1.2. *U.S. regional energy policy model*

Model structure

USREP is a top-down, global computable general equilibrium (CGE) model that disaggregates the US into six separate regions (see) and 15 international regions, the latter consisting of either individual countries or aggregated regions. The USREP model represents five energy and six non-energy composite sectors. The sectors, productions factors, and income classes that are represented in each region are listed in Table A.1.

In USREP, capital, labor, and several natural resource factors comprise the primary production factors. Firms maximize profits and equilibrium is reached in the perfectly-competitive markets when prices equate to marginal costs. ReEDS also represents the electric sector using perfect competition but unlike USREP, ReEDS allows infra-marginal generation, which can lead to positive profits. The ability to substitute between inputs is determined through calibrated constant elasticity of substitution (CES) functions as described in Caron *et al.* (2015).

Households, the government, and corporate entities are the demand agents. Households are divided into nine income classes and are characterized by expenditure patterns and income sources which allows for a detailed representation of distributional impacts and consumption changes. Each household maximizes its CES utility from consuming goods, investment, and leisure subject to an income constraint. Households choose to substitute between labor and leisure with the tradeoff calibrated to generate a (compensated) labor supply elasticity of 0.3 (i.e., percent change in labor supply given a percent change in wages). Labor is mobile across sectors within a region but not between regions. Local, state, and regional governments are represented with a single entity for each region. The government entity purchases market good and services, transfers incomes, and raises revenue through taxes. Trade balances and government deficits, as a share of GDP, are held at base year levels.

Capital is split between vintaged and malleable capital. New malleable capital is perfectly mobile across sectors and regions within the United States. Therefore, capital returns across all US regions, including returns to electricity sector investment (as well as other rents and profits from the electricity sector) form a combined US pool with a unique price. All returns to capital and are redistributed to households in each region according to current capital ownership levels.

While total investment is determined by a fixed savings rate with new capital allocated to sectors based on the rate of return, the total amount of capital available in the economy reacts to the rate of return. This feature is implemented through a trade-off between consumption and residential capital in the households' utility function, calibrated to achieve a price elasticity of capital supply of 0.3.

Capital and labor income tax rates are applied to capital and labor supply by households based on marginal tax rates, by income level and region, from the NBER taxsim data series (Feenberg and Coutts, 1993), as described in Rausch and Reilly (2015).

Differentiation between local (within-domestic region), domestic (within the U.S.), and international goods (aside from crude oil which is modeled as a homogenous product) is done through Armington trade assumptions. Therefore, each market consists of a three level nesting structure to represent less-restrictive substitutability for goods produced within the US than for those produced internationally (Caron *et al.*, 2015). Both domestic and international electricity trade (with Canada and Mexico) is modeled by ReEDS.

Table A.1. USREP model characteristics.

Regions	U.S. household income classes ($1000 of annual income)	Sectors	Production factors
United States	<10	Energy	Capital
Northeast	10–15	Coal	Labor
East Central	15–25	Natural gas	Resources
Southeast	25–30	Crude oil	Coal
North Central	30–50	Refined oil	Natural gas
South Central	50–75	Electricity (using ReEDS)	Crude oil
West	75–100		Land
European Union	100–150		
Japan	>150	Non-Energy	
Brazil		Manufacturing	
China		Services	
India		Agriculture	
Russia		Transportation	
Mexico		Energy-intensive products	
Canada		Other	
Australia & New Zealand			
Middle East		Final Demand	
Africa		Households	
Rest of Latin America		Government	
Rest of Europe and Central Asia		Investment	
Dynamic Asia (Hong Kong, Philipines, Malaysia, Taiwan, Singapore, Indonesia)			
Rest of East Asia			

Note: To simplify exposition, these income classes are aggregated to income quintiles in the results sections.

USREP is similar to ReEDS in that it also solves sequentially in 2-year solve intervals and assumes myopic behavior from market participants. As time moves forward, capital is depreciated and a portion of malleable capital becomes non-malleable and fixed to the sector it was installed in. This assumption of capital conversion limits the mobility of the total stock of capital in response to an unanticipated technological, market, or policy change such as that imposed by a CO_2 tax. As with ReEDS, inter-period adjustments produce path-dependency such that the resulting recursive-dynamic equilibrium is not necessarily inter-temporally optimal.

The production costs of fossil fuels increase over time based on depleting resource availability. The volatility of commodity markets, typically from technological developments or geopolitical factors, is difficult to encapsulate in a CGE framework but technological change is included through a rate of autonomous energy efficiency improvement (AEEI), which represents energy efficiency improvements absent of market forces. AEEI rates through 2016 are calibrated to approximate energy demand and CO_2 emission levels from AEO 2016. After that, they are assumed to increase by 1% annually (0.5% for electricity), levels that lead the model to approximate CO_2 emission projections from the AEO. These rates are applied to the use of energy by all sectors as well as households. Apart from these exogenous improvements, technologies remain the same as in the base year in this version of USREP, as no advanced technologies or major technological shifts, such as to electric vehicles or advanced manufacturing processes, are explicitly modeled in sectors outside of electricity.

Data

USREP is calibrated to an energy-economy dataset and a social accounting matrix (SAM) that is constructed with data from four different sources:

(i) The Global Trade Analysis Project (GTAP7): production and input-output tables for international regions, international trade, and trade elasticities in 2004 (Badri and Walmsley, 2008);
(ii) The Impact Analysis for Planning (IMPLAN) data set: production and input-output tables for US states, and capital demand and transfer data in 2006 (IMPLAN, 2008);
(iii) The U.S. Census Bureau: employment data as well as trade between US regions and international regions from 2006 and 2008 (US Census Bureau, 2010); and
(iv) The EIA: energy consumption, production, and trade in U.S. regions from the State Energy Data System from 2006 (USEIA, 2009).

U.S. GDP growth, energy consumption, CO_2 emissions, coal prices, and natural gas prices are calibrated to match historical trends and AEO16 Reference Case forecasts at the national level. This calibration is performed by making adjustments to available energy reserves (for fossil fuel prices), AEEI (for emissions and energy demand), and productivity (for GDP growth). Population growth is exogenously defined with data from the United Nations and U.S. Census Bureau.

A.1.3. *Linked model operation*

The first shared time period in which the models solve, 2010, entails an initial benchmarking that ensures that the representation of the electricity sector in ReEDS is consistent with its representation in USREP. USREP first solves for 2010 then communicates the resulting electricity demand, electricity price, and fossil fuel prices to ReEDS. ReEDS then communicates expenditures on electric sector capital, labor, and fuel that are compared with USREP's previous solution. The difference in communicated variables establishes static calibration parameters that maintain consistency between ReEDS and USREP results throughout the simulation. ReEDS results are treated as indices that reflect deviation from the equilibrium at the benchmark solution implicit within USREP's SAM.

Generation and load in ReEDS is tracked through the busbar (at the substation level) but USREP represents end-use electricity consumption. This inconsistency in quantities is addressed by converting bus-bar to end-use electricity demand by using the assumed rate of distribution losses in ReEDS (5.3%). Electricity prices are similarly busbar in ReEDS and end-use in USREP, so price communication requires estimation of the price component attributable to transmission and distribution to end-use consumption. In practice, these prices change over time and vary by geographic location and especially the generation and transmission system; however, a detailed representation of these prices is not currently possible within the scope of either model. To benchmark, the regional differences in the first linked solve are used to approximate the intra-BA transmission and distribution price components; these measured differences are assumed constant through post-2010 solve periods.

Following the benchmarking in the initial linked period, subsequent periods iterate between model solves and communicate parameters, as described below, until convergence is realized. As in Rausch and Mowers (2014), total U.S. electricity demand is used as the convergence parameter during intraperiod iterations and convergence in other variables is verified after all periods have solved. Similar to other top-down and bottom-up coupling exercises that focus on the electricity sector, convergence is typically quickly achieved given the electricity sector's relative small share in the overall economy.

The sequential procedure for solving the linked versions of the models and communicating results between ReEDS and USREP is as follows:

(i) Solve USREP.
(ii) Pass USREP equilibrium outcomes to ReEDS, including price indices for capital, wage, and service price indices for OM costs; fuel prices for coal and gas; and the electricity price, quantity, and the local slope of the electricity demand curve around the equilibrium outcome.

(iii) Define ReEDS parameters using USREP outcomes.

(a) Scale capital and OM costs using capital and OM price indices.
(b) Use USREP coal and gas price indices to scale coal and gas costs.
(c) Use USREP electric sector parameters to construct a piecewise linear electricity demand curve used in ReEDS constraints and objective.

(iv) Solve ReEDS.
(v) Pass ReEDS outcomes to USREP, including capital and OM expenditures, electric sector investment demand, fuel use and expenditures, and electricity demand.
(vi) Define USREP parameters using ReEDS outcomes.

(a) Use ReEDS electricity demand as the new exogenous equilibrium electricity production in USREP.
(b) Use ReEDS fuel, capital, and OM costs to define electric sector investment demand and commodity and factor usage in USREP.

(vii) Check convergence of U.S. electricity demand and return to Step 1 if convergence is not achieved.[21]

USREP results modify the typically-exogenous ReEDS electricity demand curve with electricity market results, affecting the supply-demand balance and planning reserve requirements. The area under the modified demand curve is also included in the objective function as a representation of consumer surplus. By treating electric sector profits as producer surplus, in this exercise the ReEDS model objective function represents social surplus and is able to approximate the equilibrium electricity prices and quantities. Electricity sector profits and capital returns are distributed to households in USREP in a similar manner as malleable capital.

[21]Throughout this analysis, the convergence criterion is a relative fractional change of 10^{-6} between iterations.

A.2. *Additional tables and figures*

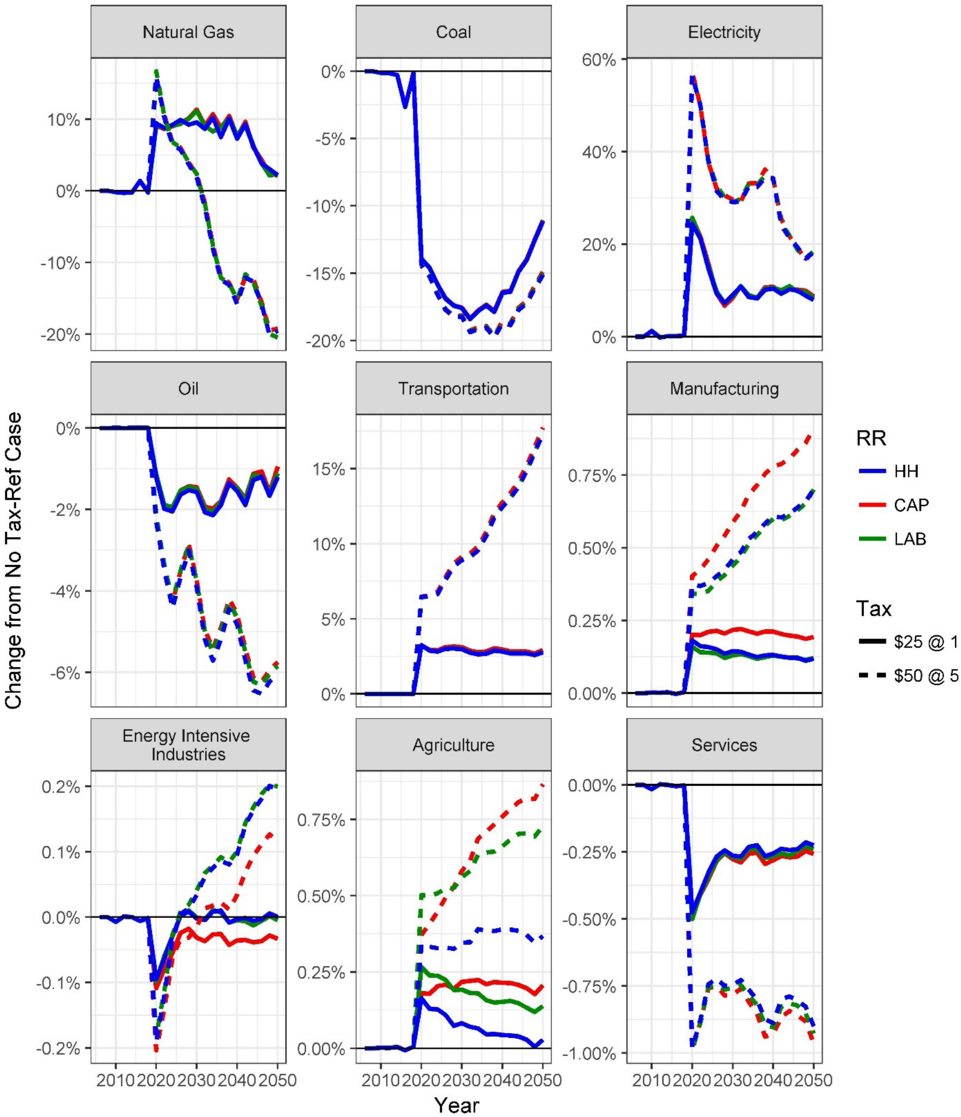

Figure A.2. Factor market price changes from the no-tax reference by tax level and revenue recycling method

Table A.2. Change in generation relative to the no-tax reference by year and technology.

	Coal	Curtailment and Losses	Gas w/o CCS	Hydro	Nuclear	Other	Solar	Wind
\$25@1%								
2020	−58.1%	−7.5%	72.3%	5.2%	3.0%	42.9%	1607.6%	254.2%
2030	−72.7%	92.6%	76.0%	6.0%	3.0%	86.2%	2399.4%	613.0%
2040	−90.7%	212.8%	116.2%	6.9%	3.0%	86.4%	3445.3%	923.9%
2050	−94.1%	555.0%	102.4%	8.2%	3.0%	93.3%	4108.5%	1292.6%
\$25@5%								
2020	−57.7%	−8.5%	70.0%	5.3%	3.0%	42.8%	1607.4%	253.7%
2030	−90.3%	209.6%	68.5%	6.4%	3.0%	85.9%	2501.4%	846.6%
2040	−99.8%	447.2%	74.2%	7.2%	3.0%	91.4%	3538.1%	1164.5%
2050	−99.8%	1099.6%	−2.5%	8.4%	9.9%	145.7%	5376.3%	1618.2%
\$50@1%								
2020	−91.4%	−9.7%	104.0%	5.4%	3.0%	55.6%	1629.7%	311.1%
2030	−99.4%	319.6%	82.1%	6.5%	3.0%	86.8%	2433.8%	911.9%
2040	−99.8%	441.0%	98.2%	7.2%	3.0%	90.2%	3363.9%	1148.3%
2050	−99.8%	1049.6%	80.9%	8.3%	3.0%	104.5%	4250.4%	1519.4%
\$50@5%								
2020	−88.7%	−4.0%	93.9%	5.4%	3.0%	55.8%	1629.1%	310.4%
2030	−99.7%	479.6%	34.4%	6.7%	3.0%	90.9%	2650.3%	1062.8%
2040	−99.8%	797.5%	−37.7%	7.6%	2.7%	124.0%	5206.2%	1393.2%
2050	−99.8%	1299.3%	−83.4%	8.0%	5.9%	147.5%	6129.6%	1652.1%

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