The Intergenerational Incidence and Social Welfare of Renewable Energy Support Policies vs. Carbon Pricing

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This paper examines the lifetime and intergenerational economic incidence of renewable energy (RE) subsidies and carbon pricing for climate change mitigation, employing a calibrated dynamic general-equilibrium model with overlapping generations for the U.S. economy. We explore the political economy implications of the different regulatory approaches based on majority voting of generations alive at the time the policy is introduced. We emphasize issues for policy design focusing on the financing of RE subsidies and policy interactions with distortionary income taxation. Notwithstanding the supremacy of carbon pricing on grounds of aggregate efficiency, we find that smart designs for RE support policies, which link the financing of the support for RE technologies to the carbon intensity of fossil-based energy technologies, constitute a politically viable option.

Many economists seem to agree that carbon pricing is the most cost-effective regulatory strategy for decarbonizing energy systems (Metcalf, 2009; Tietenberg, 2013), along with policies to address positive externalities related to technological innovation through R&D investments and learning (Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012). Policies aimed at subsidizing the deployment of renewable energy (RE) technologies are often considered a costly second-best option failing to adequately reflect the heterogenous marginal social costs of multiple fossil-based and RE technologies. Moreover, by lowering the price of energy services, RE subsidies undermine incentives for energy conservation (Holland, Hughes and Knittel, 2009). Yet policies promoting clean energy from RE sources such as wind and solar are the most widely adopted form of actual low-carbon policy (Meckling, Sterner and Wagner, 2017).[1]

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[1]As of 2016, about 110 jurisdictions worldwide—at the national or sub-national level—had enacted policies subsidizing wind and solar power (REN, 2017). In the United States, the federal government provides sizable production and investment tax credits for renewables and more than half of the states have

Setting aside the role of R&D and learning externalities which provide a rationale for RE subsidies, a crucial dimension for policy appraisal is the question how the policy-induced burdens and benefits are distributed among heterogeneous agents (for example, households, generations, industries, firms). This paper argues that the focus of economists on cost-effectiveness may be misplaced when the ultimate goal is to reduce carbon dioxide (CO_2) emissions. We examine the lifetime and intergenerational economic incidence of RE support and carbon pricing policies and investigate the question which of these fundamentally different strategies is politically more viable when the societal consensus for or against a low-carbon policy depends on the outcome of majority voting. Only households alive when the policy is introduced can take a vote, and the voting decision depends on the expected lifetime impacts of the policy which materialize through both the uses- and sources-side of income.

The heterogeneity of lifetime impacts for households of different age is potentially large—both for a given policy and across policy choices. For example, subsidizing capital-intensive clean energy technologies under a RE support scheme may yield disproportionately large benefits to households which derive a large fraction of their (remaining lifetime) income from capital. In contrast, broad-based carbon pricing leads to higher increases in today's energy prices while the efficiency gains from directly pricing pollution may largely materialize through positive growth effects benefiting future generations.

To conceptualize and quantitatively assess these trade-offs for designing climate and technology policy, our analysis employs a calibrated dynamic general-equilibrium model with overlapping generations. We analyze the problem of regulating CO_2 emissions in a model where the supply of and demand for energy and non-energy goods derive from a disaggregated multi-sector input-output production structure including specific detail on the energy sector with respect to primary energy carriers, RE resources for electricity generation, energy-intensive industries, and sector- and fuel-specific carbon inputs. The model thus combines elements of a standard Auerbach and Kotlikoff (1987)-type OLG approach with those of energy-economy models typically employed to investigate climate policy issues (see, for example, Paltsev et al., 2005; Caron, Rausch and Winchester, 2012) and is well-suited for investigating the macroeconomic impacts of RE support and carbon pricing policies on households of different generations, energy supply and demand, CO_2 emissions, and interactions with major tax distortions.

Recognizing that instrument choice is instrument design (Weisbach, 2011), our analysis goes beyond a pure analysis of different generic instruments for decarbonization (RE support vs. carbon pricing) by emphasizing issues of design which are important for real-world climate change mitigation policies. First, we explore

adopted renewable portfolio standards mandating minimum levels of renewable generation (U.S. Department of Energy, 2016). The Renewable Energy Directive by the European Commission (2010) established an overall policy for the production and promotion of energy from renewable sources in the EU requiring to fulfil at least 20% of its total energy needs with renewables by 2020; a new regionally binding target seeks to increase this share to 27% by 2030.

the question how the financing of technology subsidies under current RE support schemes, such as feed-in tariffs or renewable energy quotas, can be improved to more efficiently exploit abatement opportunities. Second, we take into account the interactions between distortionary income taxes (which are needed to finance observed levels of public spending) and the incentives established by RE support and carbon pricing policies. Specifically, we analyze here the implications for alternative ways of recycling the revenues from carbon pricing and for different choices for financing RE subsidies.

Our main findings are as follows. First, focusing on the intergenerational incidence, we find that under carbon pricing with lump-sum rebates, current (i.e., existing today) old generations suffer less than current young generations and future generations. This is because carbon pricing induces switch towards RE, which is quite capital intensive, and thus capital return falls less compared to the reduction in wage. This leads to the smaller loss for current old or capital-rich generations. In the case of using the carbon revenue for reducing labor tax, this trend becomes weaker since labor tax cut benefits more on current young and future generations since they derive larger share of income from labor. In the case of using carbon revenue for reducing capital tax, relative to carbon pricing with lump-sum rebates, both current old and middle generations and future generations are better off. Current old and middle generations benefits from the immediate appreciation of their capital asset values, while future generations benefits from the improved economic growth by reducing the distortionary capital income tax, and this economic growth benefit accumulates over time until the economy reaches the new steady state. In the case of the RE support policies, the pattern of the intergenerational incidence is similar to carbon pricing with capital tax cut. Since the RE production is quite capital intensive, subsidizing RE is indirectly subsidizing capital. However, they are not as sharp as directly reducing capital tax, and also carbon pricing encourages more on the reduction of electricity demand (or subsidy mitigates this reduction), and thus the RE subsidies are less efficient and the welfare impact of each generation is worse than carbon pricing with capital tax cut. That said, the RE support policy with smart financing where electricity tax is based on carbon intensity of electricity generation (*Green offsets*) is favorable than carbon pricing with lump-sum rebates for almost all the generations.

Second, we look at the political economy of renewable energy subsidies. The setup is that we take a vote today, so only the current generations can take a vote, and their voting decisions depend on their expected remaining lifetime welfare impact. We find that older generations prefer even the generic RE support policy where we finance the subsidy by the tax on the whole electricity (*RES*) over carbon pricing with lump-sum or labor tax cut, and *RES* would have decent chance to win. When we consider the more sophisticated RE support policy (*Green offsets*), the same older generations vote for *Green offsets*, and *Green offsets* is likely to be chosen over carbon pricing with lump-sum or labor tax cut. However, if carbon pricing with capital tax cut is an available policy option, almost all the generations prefer carbon pricing with capital tax cut. Thus, to the extent that the option of capital tax cut is limited, the choice of the RE support policy, especially when we link the financing to the carbon intensity of electricity generation, can be a viable option from a political perspective.

Third, as another social welfare measure, we consider the Utilitarian social welfare function, which aggregate the welfare impact of all the generations without any inequality aversion. We find that even the generic RE support policy is as efficient as carbon pricing if the revenues from carbon pricing are returned as lump-sum rebates *and* emission reduction is small. This is because of the existence of the distorting income taxes. The extra cost because of the distorting income taxes (known as tax interaction effect in the literature) is smaller for *RES* than carbon pricing. If we use the carbon revenues to reduce the income taxes, *RES* is more costly, regardless the stringency of emissions reduction. When we consider *Green offsets*, we find that regardless the stringency, *Green Offset* is more efficient than carbon pricing with lump-sum rebates. While carbon pricing with labor tax cut is still more efficient, the difference is small. However, carbon pricing with capital tax cut is clearly more efficient than *Green Offset*.

This paper contributes to the existing literature in three important ways. First, our paper contributes to the empirical literature on assessing the efficiency and distributional impact on climate policies. While many studies examine the distributional impact of carbon pricing policies, including Hassett, Mathur and Metcalf (2009), Rausch et al. (2010), and Fried, Novan and Peterman (2017), the analysis on renewable energy subsidies is relatively scarece. Some studies, including Goulder, Hafstead and Williams (2016) and Rezai and van der Ploeg (2017), examine the renewable energy subsidies, but focus on the efficiency impact rather than the distributional impact.[2] Few studies examine the distributional impact of renewable energy subsidies. One exception isBöhringer, Landis and Reanõs (2017), and they investigate the distributional impact of renewable energy subsidies in Germany. However, they consider the distributional impact among different income groups in a static framework, whereas our paper considers the distributional impact among generations who live multiple time periods and thus our analysis incorporates the welfare impact of the policy shock over time.

Second, this paper contributes to the empirical literature on assessing the intergenerational impact of environmental policies. While a plenty of studies investigate the distributional impact based on the annual incidence of the policy (Hassett, Mathur and Metcalf (2009), Rausch et al. (2010), and Rausch, Metcalf and Reilly (2011)), the analysis, considering the life-cycle perspective, of intergenerational incidence is relatively scarce. Although this literature has recently been growing (Rausch (2013), Williams et al. (2015), Fried, Novan and Peterman

[2]Both Goulder, Hafstead and Williams (2016) and Rezai and van der Ploeg (2017) consider the time dimension, so they do consider the impact in the short-run and long-run. However, they do not consider the distributional impact among the households living in the same time period.

(2017), and Rausch and Yonezawa (2018)), none of them investigates renewable energy subsidies.

Third, our paper looks at the political economy perspective in the environmental policies. Previous studies examine the political aspect of environmental taxes. In particular, Cremer, De Donder and Gahvari (2004), Aidt (2010), and Habla and Roeder (2013) investigate the impact of the way they recycle the revneues from environmental taxes. Besides the environmental taxes, Habla and Roeder (2017) examines the political economy of mitigation and adaptation. However, to the best of our knowledge, our paper is the first paper to look at the political economy of the renewable energy subsidies.

The reminder of this paper is structured as follows. Section I describes the analytical framework, laid out the policy scenarios, and provides some basic conceptual considerations about intergenerational incidence. Section II describes how we calibrate and solve the numerical model. Section III presents the intergenerational incidence results of our simulation. Section IV presents the social evaluation of these policies. Section V concludes.

I. The Model

A. Overlapping generations households

Time is discrete and the economy is populated by overlapping generations. A new generation of households g is born at the beginning of year $t = g$ and exits at the end of year $t = g + N$.[3] The generation g is endowed with $\omega_{g,t} = \omega\,(1+\gamma)^g$ units of time in each period $g \leq t \leq g + N$.[4] γ denotes the exogenous steady-state growth rate of the economy.[5]

In each period households allocate their time between labor and leisure. We assume that households are forward-looking with perfect foresight over their finite lifetime. Full consumption, $z_{g,t}$ consists of leisure time, $\ell_{g,t}$, and (material) consumption, $c_{g,t}$ in a constant-elasticity-of-substitution (CES) function. Lifetime utility of generation g, u_g, is of the constant-intertemporal-elasticity-of-substitution form (CIES) and thus additively separable over time. Each generation chooses optimal consumption and leisure paths over their life cycle subject to lifetime budget and time endowment constraints. The lifetime utility maximiza-

[3]We use "household" and "generation" interchangeably. Each household represents the number of individuals (with age 20 or older) in a given age group.

[4]ω is a constant income scaling factor, which is determined in the initial calibration procedure to reconcile household behavior with the aggregate benchmark data.

[5]γ should be viewed as a combined growth rate representing exogenous population growth and labor-augmenting technological progress.

tion problem for generation g is given by:

$$\begin{aligned} \max_{c_{g,t},\,\ell_{g,t}} u_g\left(z_{g,t}\right) &= \sum_{t=g}^{g+N}\left(\frac{1}{1+\hat{\rho}}\right)^{t-g}\frac{z_{g,t}^{1-1/\sigma}}{1-1/\sigma} \\ s.t. \qquad z_{g,t} &= \left(\alpha c_{g,t}^{\nu}+(1-\alpha)\,\ell_{g,t}^{\nu}\right)^{\frac{1}{\nu}} \end{aligned}$$

$$\begin{aligned} \sum_{t=g}^{g+N} p_{y,t}\, c_{g,t} &\leq p_{k,0}\,\overline{k}_g+\sum_f p_{f,t}\,\overline{z}_{f,g}+\sum_n p_{n,t}\,\overline{z}_{n,g}+\sum_{t=g}^{g+N} p_{l,t}\,(1-\tau_L)\,\pi_{g,t}\,(\omega_g-\ell_{g,t})+p_{y,t}\,\overline{tr}_{g,t} \\ \ell_{g,t} &\leq \omega_g \\ c_{g,t} &\geq 0 \quad , \quad \ell_{g,t}\geq 0 \end{aligned}$$

where σ is the intertemporal elasticity of substitution, $\sigma_{cl}=1/(1-\nu)$ is the elasticity of substitution between consumption and leisure, and α determines the relative importance of material consumption vis-à-vis leisure consumption. $\hat{\rho}$ is the subjective utility discount factor, and $p_{x,t}$, $x=\{y,k,l,f,n\}$, denote the price for the output good, the purchase price of capital asset, the wage rate, the price for the fuel-related natural resource $f=\{$*Coal, Natural Gas, Crude Oil*$\}$, and the price of the resource for non-fuel electricity production $n=\{$*Nuclear, Hydro, Wind*$\}$, respectively. $\pi_{g,t}$ is an index of labor productivity over the life cycle. $\overline{z}_{f,g}$ and $\overline{z}_{n,g}$ denote the endowment with natural resource f and resource for non-fuel electricity production n by generation g. τ_L is the labor tax, which is imposed on the wage, and capital tax, τ_K, is imposed on the rental rate, R_t, and depreciated capital as we see in the following equation describing the relationship between capital rental rate and price of capital asset: $p_{k,t}=(1-\tau_K)\,R_t+(1-\delta(1+\tau_K))$.

Households collect income from the endowments of capital, natural resource and time as well as government transfer ($\overline{tr}_{g,t}$). They first decide how to allocate their lifetime income over time. Given the expenditure for z, households decide in a second stage how much to spend on consumption and leisure.

It is assumed that endowments of natural resource, resource for non-fuel electricity production and government transfers to households grow exogenously at the steady-state growth rate, and the corresponding income accrues to households in proportion to their population share, where $\zeta_{g,t}=(1+\gamma)^g/\sum_{i=t-N}^{t}(1+\gamma)^i$. This implies that endowments of natural resource, resource for non-fuel electricity production and government transfers are constant over the life-cycle.[6]

[6] We assume that at any given point in time, the ownership of natural resources is equally distributed among households based on population size. In reality, the distribution of resource ownership may be positively correlated with age and overall asset income. Thus, our estimates of welfare impacts may be biased—although the net impact remains unclear: old generations, on the one hand, may be affected more negatively due to owning disproportionately large resources in dirty energy production while, on the other hand, they may also be better off due to owning disproportionately large resources in clean (i.e., wind- and solar-based) energy production.

The allocation of time between leisure and labor as well as the composition of the full consumption between material consumption and leisure differs depending on age. We abstract, however, from age-specific preferences for material consumption.[7]

$\overline{k}_g$ denotes the capital holdings of generation g. Initial old generations, i.e. generations born prior to period zero, are endowed with a non-zero amount of capital. The initial distribution of capital across these generations is chosen so that the economy is on a balanced growth path (see Section II.A for details). We assume that newborn households enter with zero capital, i.e. we rule out intergenerational bequests.

B. Production

For each industry ($i = 1, \ldots, I,\ i = j$), gross output (Y_i) is produced in each period using inputs of labor (L_i), capital (K_i), natural resource for fuels including coal, natural gas, and crude oil (F_i), and non-fuel resource for electricity production including nuclear, hydro and wind (N_i), and produced intermediate inputs (X_{ji}):[8]

$$Y_i = F_i(L_i, K_i, F_i, N_i; X_{1i}, \ldots, X_{Ii})\,. \tag{1}$$

We employ constant-elasticity-of-substitution (CES) functions to characterize the production technologies and distinguish various types of production activities in the model: fossil fuels (indexed by f), non-fuel electricity (indexed by n), refined oil, fuel-generated electricity, agriculture, manufacturing, services, transport, and energy-intensive industries. All industries are characterized by constant returns to scale—except for fossil fuels and non-fuel electricity, which are produced subject to decreasing returns to scale—and are traded in perfectly competitive markets.[9]

As an example, we show the production function for fossil fuel f. A nested CES function is used to combine a fuel-specific resource, capital, labor, and intermediate inputs:

$$Y_f = \left[\alpha_f\, R_f^{\rho_f^R} + \nu_f \min\left(X_{1f}, \ldots, X_{If}, V_f\right)^{\rho_f^R}\right]^{1/\rho_f^R} \tag{2}$$

where α, ν are share coefficients of the CES function and $\sigma_f^R = 1/(1-\rho_f^R)$ is the elasticity of substitution between the resource and the primary-factors/materials composite. The primary factor composite is a Cobb-Douglas function of labor and capital: $V_f = L_f^{\beta_f} K_f^{1-\beta_f}$ where β is the labor share.

[7] Figure A5 in the Appendix depicts the nested CES structure for material consumption.

[8] We abstract from the various tax rates that are used in the model for reducing notational burden. The model includes ad-valorem output taxes, corporate capital income taxes, payroll taxes (employers' and employees' contribution), and import tariffs. We also suppress the time index here.

[9] The nested CES structures for each sector are depicted in Figures A1–A4 in the Appendix.

Electricity sector.—Since we consider the policies on electricity sector, it deserves further details. We assume the following types of generations: fossil fuels, nuclear, hydro and wind with natural gas backup) shown in Figure A4 in the Appendix. Since we consider the natual gas backup, we assume that the intermittency issue of wind is overcome, and thus the electricity is a homogenous commodity whether it is generated from fossil fuels or wind.

The nested CES structure of wind electricity is included in Figure A4. The natural gas backup and value-added composit are combined as Leontief (i.e., elasticity of substitution is zero) so that we ensure the complete backup. While the cost shares and elasticities of substitution are based on Paltsev et al. (2005), we include the material cost by assuming that all the electricity technologies use the same cost share of material input.

C. *Aggregate demand and capital accumulation*

The demand side of our aggregate economy in time period t is characterized by national account balances relating capital income (W_t), labor income (L_t), income from natural resource (Z_t), government transfers (T_t), private sector consumption (C_t), public sector consumption (G_t), investment (I_t), net exports (NX_t), and tax rates on capital, labor, consumption, output, and carbon emissions. These include the aggregate income balance:

$$W_t + L_t + Z_t + T_t = C_t + I_t + G_t + NX_t. \tag{3}$$

In period t, gross investments (I_t) add to the next periods capital stock (K_{t+1}) according to the standard accumulation equation:

$$K_{r,t+1} = (1 - \delta)\, K_{r,t} + I_{r,t}\,, \tag{4}$$

where δ is the constant depreciation rate and where I_t is a Leontief composite of inputs. For simplicity, the model abstracts from capital adjustment costs. Savings and labor are supplied as a results of intertemporal optimization decisions by the different generations of households.

D. *International trade*

Domestic goods are differentiated with foreign goods following the Armington (1969) assumption in the context of the small open economy of the US. The price of the foreign goods is denominated by the foreign exchange rate. Following the small-open economy model of Rasmussen and Rutherford (2004), we assume that along the reference path, the current account deficit and GDP grow at the same rate. For the counterfactual policy scenarios, we hold the sum of present values of the current account deficits constant at the reference level by endogenously adjusting the foreign exchange rate.

The total supply of good i is a CES composite of a domestically produced variety and an imported one:

$$X_i = \left[\psi_i^m \, ZD_i^{\rho_i^m} + \xi_i^m \, ZM_i^{\rho_i^m}\right]^{1/\rho^m{}_i} \tag{5}$$

where ZD is domestic goods and ZM is imported goods. The ψ^m's and ξ^m's denote the CES share coefficients and the Armington substitution elasticity between domestic and the imported varieties in these composites is $\sigma_i^m = 1/(1-\rho_i^m)$. Domestically produced goods, Y, are transformed into exports, ZX, and domestic supply, ZD, according to a constant elasticity-of-transformation (CET) function:

$$\left[\psi_i^x \, ZD_i^{\rho_i^x} + \xi_i^x \, ZX_i^{\rho_i^x}\right]^{1/\rho^x{}_i} = Y_i \tag{6}$$

where the ψ^x's and ξ^x's denote the CET share coefficients and $\sigma_i^x = 1/(1+\rho_i^x)$ is the transformation elasticity between domestic and exported varieties in these composites.

E. Emissions

We consider only the carbon emissions generated through fossil fuel combustion, which occurs in fixed proportions to the consumption of fossil fuels in industry and final demand sectors. A carbon pricing policy works to reduce CO_2 emissions through various channels: *(i)* reductions in sectoral output, *(ii)* switching toward fuels with lower carbon intensity, and *(iii)* substitution of fossil energy inputs with non-energy (e.g., capital, labor, other material) inputs.

F. Modeling the renewable energy support and carbon pricing policies

Renewble energy support policies.—With the natural gas backup, the wind power overcomes the intermittency issue, and that enables us to assume that the electricity is a homogenous good, and the consumers pay the same price regardless the type of electricity generation (P_{ele}). However, the tax on electricity demand (τ_{ele}^e), which finances the RE support policies, can be differentiated among different types of electricity generation, the producer-prices (P_{ele}^e) can differ.

$$P_{ele} = P_{ele}^e(1+\tau_{ele}^e) \tag{7}$$

where the index e is the electricity generation type (Coal, natural gas, nuclear, hydro, and wind).

In our model, renewable energy support policies are implemented as the subsidy (sub) for the renewable electricity production (or wind). The renewable electricity producer receives the price including the subsidy ($\mathbf{P}_{ele}^{wind}$)

$$\mathbf{P}_{ele}^{wind} = P_{ele}^{wind}(1+sub). \tag{8}$$

The subsidy level is endogenous such that we can achieve any given emission path, and the electricity tax to finance the subsidy is adjusted such that the RE support policies are revenue-neutral. The equation 8 indicates that the subsidy imposes a downward pressure on the electricity price. As a generic RE support policy, we consider the uniform electricity demand tax, or τ^{e}_{ele} is the same among different types of electricity generation. As a more sophisticated RE support policy, we assume that the electricity demand tax is proportional to the carbon content of each generation type.

Carbon pricing policies.—We consider the carbon pricing policies in the electricity sector. If the producers consume fossil fules to produce electricity, they have to pay the tax based on the carbon content.[10] While we can set any level of carbon pricing, to be able to compare with the RE support policies, we keep track of the emissions in the electricity sector, and the renewable energy support policies are adjusted such that the emissions in the electricity sector is the same as carbon pricing.[11]

Carbon pricing policies raises the government revenues. Since we consider the revenue-neutral policies in this paper, we recycle these revenues. We consider three ways: 1. Return as lump-sum rebates based on the population size; 2. Lower the labor income tax; 3. Lower the capital income tax.

G. Focus of the analysis: policy design features

To quantitatively assess the intergenerational incidence and social acceptance of RE subsidies vs. carbon pricing, we use counter-factual analysis assessing the general equilibrium effects of alternative regulatory policies against a "no-policy" baseline of our model. Table 1 summarizes the different policy cases.

We analyze the following issues of policy design in addition to the comparison of generic RE support and carbon pricing policies. We consider two types of RE support policies differentiated by the way of financing the support policies. The first one uses the tax on the whole electricity demand (RE Subsidy / RE quota). The second one uses the electricity tax that is proportional to the carbon content of the electricity generation (Green offsets). Thus, the electricity from coal-fired power plants are heavily taxed, and the electricity from other fossil fuels are also taxed but less than the coal-fired electricity. However, the electricity from renewable energy, hydro and nuclear is not taxed.

We compare these RE support policies and carbon pricing policies that are differentiated by the way of recycling the revenues from carbon pricing. The carbon revenue is returned as lump-sum rebates, is recycled through the reduction of labor tax, or is recycled through the reduction of capital tax. To consider

[10] Our model does not consider any uncertainty (and thus it is deterministic), and thus carbon tax and emissions trading system are equivalent in our framework.

[11] We also check our results by setting the same economy-wide emissions to consider the leakage to non-electricity sector. We confirm that the leakage effect is not very different from carbon pricing and RE support policies, and the choice of setting the same economy-wide or electricity sector emissions does not affect the insights derived in this paper.

Table 1. Overview of alternative policy designs to regulate electricity-sector CO_2 emissions

Policy case	Description
Renewable energy support policies	
RE subsidy / RE quota	RE subsidy refinanced in budget-neutral way through electricity demand tax or equivalent RE quota
Green offsets	Intensity standard mandating a minimum amount of RE to electricity-sector CO_2 emissions
Carbon pricing policies	
CO_2 pricing_lumpsum	Carbon pricing through tax or emissions trading with equal per-capita lump-sum rebates
CO_2 pricing_labor tax	Carbon pricing through tax or emissions trading with labor income tax recycling
CO_2 pricing_capital tax	Carbon pricing through tax or emissions trading with capital income tax recycling

only the non-enviornmental impact of the policies, the level of renewable energy subsidy is adjusted such that the emissions reduction in the electricity sector is equal to that of carbon pricing scenarios.[12]

H. Main drivers of the intergenerational incidence

The economic incidence of a policy shock is generally determined by how households are impacted on their expenditure and income side (Atkinson and Stiglitz, 1980). Differences in impacts arise because in the OLG setting the composition of both expenditures and income varies depending on age. Given a humped-shaped labor productivity profile over the life cycle and the desire to smooth consumption over the lifetime, households derive a high share of their income from labor when young and accumulate savings which are then consumed when labor productivity declines with increasing age. Figure 1 shows the calibrated income profiles by age along the "no-policy" balanced growth path for "future" generations, i.e. those born after the first period of the model (i.e., year 2015). This implies that, for example, a drop in wages will hit middle-aged households with relatively high labor productivity more than old generations. Heterogeneous impacts can also arise on the expenditure side. First, households of different age differ with respect to their propensity to consume (or save). For example, if the price for aggregate consumption increases following climate policy, older generations with a higher propensity to consume are hit more (everything else equal) than younger generations which use a higher share of their income to accumulate future savings. Second, the impacts across generations may differ to the extent that households' preferences for consumption goods vary by age.

Following a policy shock, all households will be affected identically once the economy has reached a new steady-state equilibrium. The intergenerational in-

[12]We also adjust the carbon price for the cases of labor tax cut and capital tax cut so that the emissions reduction will be the same as the case with lump-sum rebates. Since the impact of alternative revenue recycling on the emissions is small, the adjustment of carbon price is negligible.

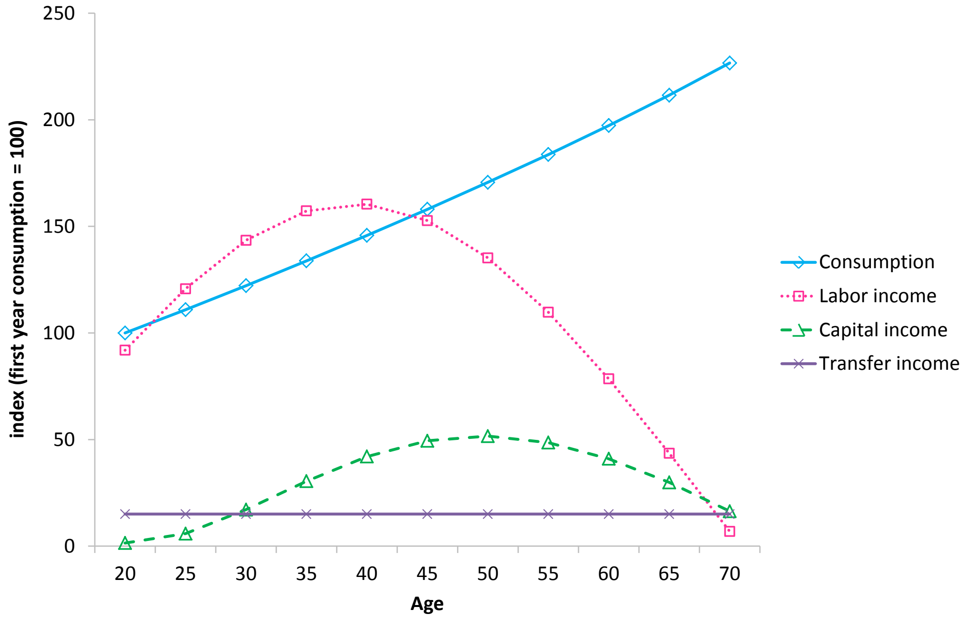


Figure 1. Calibrated life-cycle profiles for consumption and income (by type) along steady-state reference path

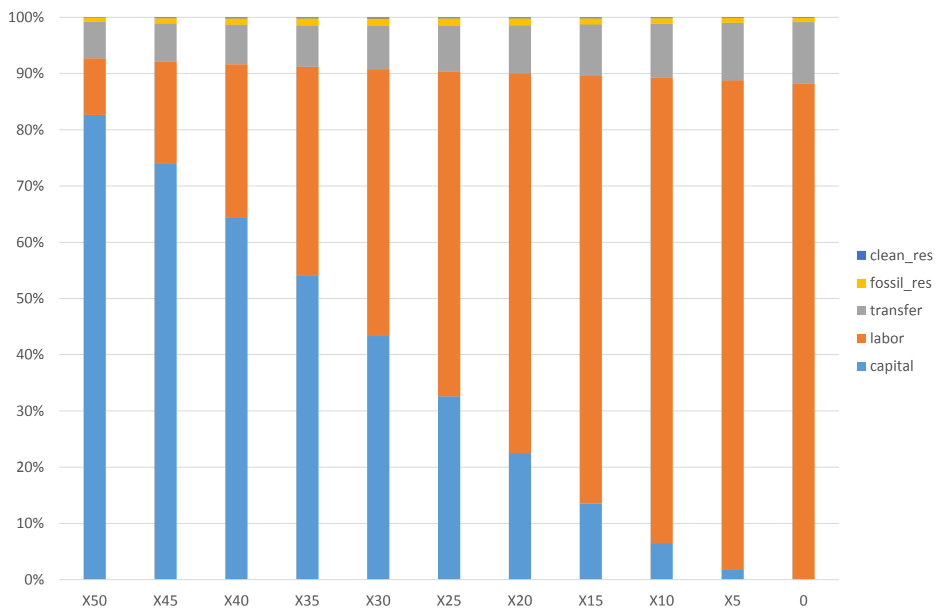


Figure 2. Composition of income by source for "current" generations, i.e. those alive at first period ($t = 0$)

cidence can, however, differ largely for generations alive during the transition period. For "current" generations, i.e. those who were born before or in the first period of the model (before year 2015), the main driver is the heterogeneity with respect to the composition of income. Figure 2 shows the composition of income by income source for "current" generations. Generations born before 2015 own shares of the existing capital stock of the economy at time $t = 0$. Consistent with the steady-state reference calibration of our model, we have inferred the distribution of capital assets among these generations from the calibrated life-cycle capital income profiles as shown in Figure 1. As the *share* of capital income increase with age, generations born earlier derive a larger share of income from capital (for example, the generation 1965 has a higher capital income share than generation 2010). Similarly, the younger a generation, the larger is the share of income from labor. Thus, for a given change in the rental rate for capital or the wage rate, "current" generations are impacted differently. In addition, the impacts may also vary as different types of climate policy affects the returns to capital and labor differently.

As with "current" generations, the impacts of climate policy for "future" generations depend on the composition of income. As the income composition is identical for "future" generations along the *reference path*, differences in the impacts among households depend on when a household is born into the economy and how the household is exposed to the policy shock over the (remaining) lifetime. The timing is important even for a carbon pricing which is constant over time as the returns to capital and labor change over time along the transition of the economy to a new long-run equilibrium.

II. Data and Empirical Strategy

A. *Data and calibration*

We make use of social accounting matrices (SAMs) that are based on data from the Global Trade Analysis Project (GTAP) Version 9 (Aguiar, Narayanan and McDougall, 2016).[13] Table 2 shows the primary factors of production and commodities in our model. The five energy commodities are directly taken from GTAP whereas the five non-energy commodities are aggregations of commodities detailed in the GTAP data. Primary factors in the dataset include labor, capital and natural resource. Benchmark expenditures on government services and the trade deficit are directly taken from the GTAP data. Based on Congressional Budget Office (2012), our central case assumes that benchmark labor and capital income tax rates are 30% and 17%, respectively.

[13]The GTAP dataset provides consistent global accounts of production, consumption, and bilateral trade as well as consistent accounts of physical energy flows and carbon dioxide emissions. The dataset identifies 140 countries and 57 commodities, and we aggregate all the non-US countries and regions into an aggregate "Rest of the World" region which is used to calibrate international trade flows for the small open economy.

Table 2. Model details.

Primary factors of production	Commodities (GTAP code)
Capital	Crude oil (OIL)
Labor	Coal mining (COA)
Resource	Natural gas extraction (GAS)
	Refined oil (P_C)
	Electricity (ELY)
	Agriculture[a]
	Energy-intensive industries[a]
	Transportation[a]
	Services[a]
	Manufacturing[a]

Notes: [a]Indicates that the commodity is based on an aggregation of several commodities which are represented in the original GTAP data.

To describe the evolution of labor productivity over the life cycle, we assume the following age-dependent productivity profile:

$$\pi_{gt} = \exp\left(\lambda_0 + \lambda_1(t-g+21) + \lambda_3(t-g+21)^2 + \lambda_3(t-g+21)^3\right) .$$

The λs are chosen based on the respective averages of age-specific labor productivity for households belonging to various income groups as provided in Altig et al. (2001).[14]

Table 3 provide the chosen values for the response parameters in the functional forms describing production and consumption technologies (see Figures A1 to A5 in the Appendix for how each parameter enters the nested CES functions).

We create a "no carbon-policy" reference path of the economy which is consistent with the projections of the Annual Energy Outlook by Energy Information Administration (2016). This involves the following steps. First, we follow Rasmussen and Rutherford (2004) and first solve the utility maximization problem of a reference generation along a balanced growth path. Second, we calibrate the model to a steady-state baseline which is setup based on the outcomes of the reference generation and an extrapolation of the 2015 Social Accounting Matrix using exogenous assumptions on the growth rate of output (γ), the interest rate ($\bar{r}$), and the capital depreciation rate (δ).[15]

We solve the model for 150 years (i.e., $T = 150$) and assume that the deterministic lifespan of households is 50 years ($N = 49$). To reduce computational complexity, we solve the model with 5-year time steps. Moreover, we assume that households are born into the economy at age 20 (and thus die at the age of 70).[16]

[14]Specifically, the parameter values are: $\lambda_0 = 1.0785$, $\lambda_1 = 0.0971$, $\lambda_2 = -0.0015$, and $\lambda_3 = 7 \times 10^{-6}$.

[15]While the GTAP benchmark year is 2011, we do a forward calibration to 2015, which is the benchmark year in this model, by using the forecast of GDP and energy demand from the World Energy Outlook 2015 (IEA, 2015).

[16]Given our computational strategy for terminal approximation, we have verified that $T = 150$ is sufficient to achieve convergence towards a new steady-state equilibrium after policy shocks have been implemented.

Table 3. Reference values of substitution elasticities for production and consumption technologies.

Parameter	Substitution margin	Value
σ_{en}	Energy (excluding electricity)	1.0^a
σ_{enoe}	Energy—electricity	0.5^a
σ_{eva}	Energy/electricity—value-added	0.5^a
σ_{va}	Capital—labor	1.0^a
σ_{klem}	Capital/labor/energy—materials	0^a
σ_{cog}	Coal/oil—natural gas in ELE	1.0^a
σ_{co}	Coal—oil in ELE	0.3^a
σ_{nele}	Resource—Capital/labor/energy/materials in non-fuel ELE	Calibrated.
σ_{rklm}	Capital/labor/materials—resource	0^a
σ_{gr}	Capital/labor/materials—resource in primary energy	Calibrated.
σ_{govinv}	Materials—energy in government and investment demand	0.5^a
σ_{ct}	Transportation—Non-transport in private consumption	1.0^a
σ_{ec}	Energy—Non-energy in private consumption	0.25^a
σ_{c}	Non-energy in private consumption	0.25^a
σ_{ef}	Energy in private consumption	0.4^a
σ_i^D	Foreign—domestic	4
σ	Intertemporal elasticity of substitution	0.65
σ_{cl}	Leisure—material consumption	0.9
α	Weight on material consumption in full consumption	0.5

Notes: [a]Parameter values are based on Paltsev et al. (2005) and Rausch (2013).

B. *Computational Strategy*

To approximate the infinite horizon economy by a finite-dimensional complementarity problem, we follow the "state-variable targeting" approach outlined in Lau, Pahlke and Rutherford (2002). Assuming that households' utility functions are time-separable, one can decompose the infinite-horizon economy into two distinct problems with one running from $0, \dots, T$ and the other one running from $T+1, \dots, \infty$. Here, T denotes the last period of the numerical model. The level of post-terminal capital can then be computed endogenously by assuming that investment grows at the same rate as output: $I_{r,T}/I_{r,T-1} = 1+\gamma$.

In addition, we need to determine the distribution of terminal assets, along with the paths for post-terminal consumption of generations which are alive in the post-terminal years. We follow here Rasmussen and Rutherford (2004). While assets held at the start of the initial period are exogenous, a policy shock to the model may affect savings at a given interest rate and consequently the profile of asset holdings and the trade deficit in the new steady state. Assets held in year T, which are terminal assets, are therefore computed as endogenous variables such that the model is on a steady-state growth in T. This implies that the percentage change in welfare, as measured by the equivalent variation ($ev_{\hat{g}}$) of each of the generations living post-terminal periods are of equal magnitude: $ev_{\hat{g}} = ev_{\hat{g}-1}$ where $T - N < \hat{g} \leq T$ identifies generations living beyond the terminal period. Moreover, we need to ensure that consumption profiles of households living post-terminal periods are held at the steady-state level. Given the post-terminal consumption demands by these generations, this requires that the price path for consumption goods declines with the interest rate consistent with a steady-state projection of the terminal-period price of consumption.

We formulate the equilibrium of the OLG economy as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). Our solution approach comprises two classes of equilibrium conditions: zero profit and market clearance conditions. The former condition determines activity levels and the latter determines prices. Numerically, we formulate the problem using the General Algebraic Modeling System (GAMS) and use the Mathematical Programming System for General Equilibrium (MPSGE) (Rutherford, 1999) and the PATH solver (Dirkse and Ferris, 1995) to solve for equilibrium prices and quantities.

III. Incidence Results

This section presents the intergenerational distributional effects of the different RE support policies and carbon pricing. We first focus on a central case to provide economic intuition for the patterns of intergenerational impacts under each policy. We then investigate the question how robust the incidence assessment is with respect to a number of model features and parameter assumptions, providing the basis for assessing the social welfare of RE support policies vs. carbon pricing.[17]

A. *Central case*

Our central case assumes a \$50 carbon tax per ton of CO_2. We measure the utility impact for each generation g, defined as Δu_g, by the equivalent variation (EV) expressed in percent of "no-policy" remaining lifetime income (including leisure). Figure 3 shows the intergenerational incidence for different RE support schemes and carbon pricing with alternative revenue-recycling assumptions: Panel (a) reports the impacts relative to the no-policy case and Panel (b) the impacts relative to the case of carbon pricing with lump-sum rebates (CO_2 *pricing_lumpsum*).

The following insights emerge in terms of the intergenerational incidence:

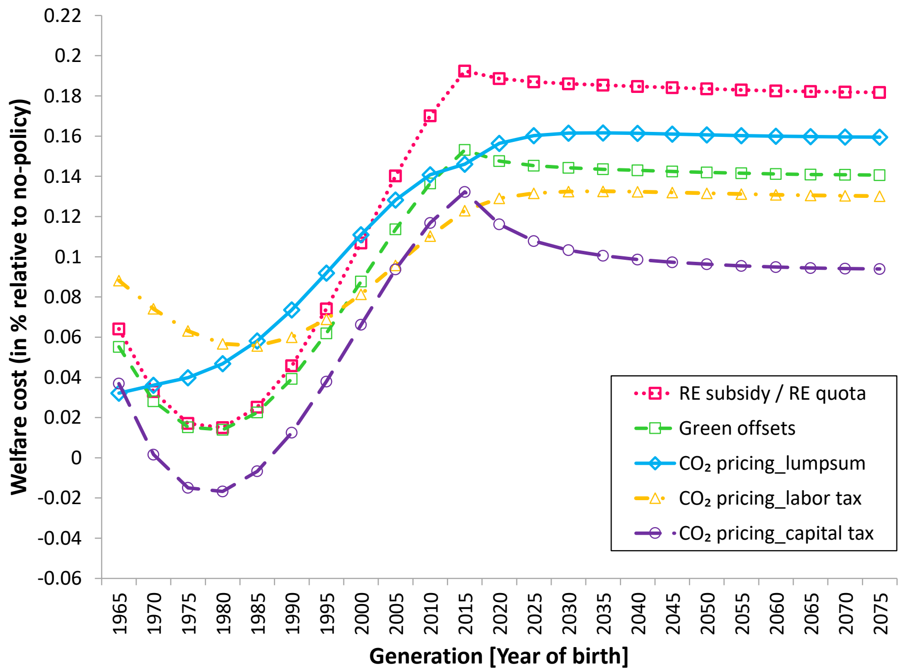
Result 1 *(Intergenerational incidence for a given policy)*:

(a) Under a carbon pricing policy with lump-sum rebates, current old generations incur the smallest welfare costs, while the losses become larger as the generations become younger (from current middle, young to future generations).

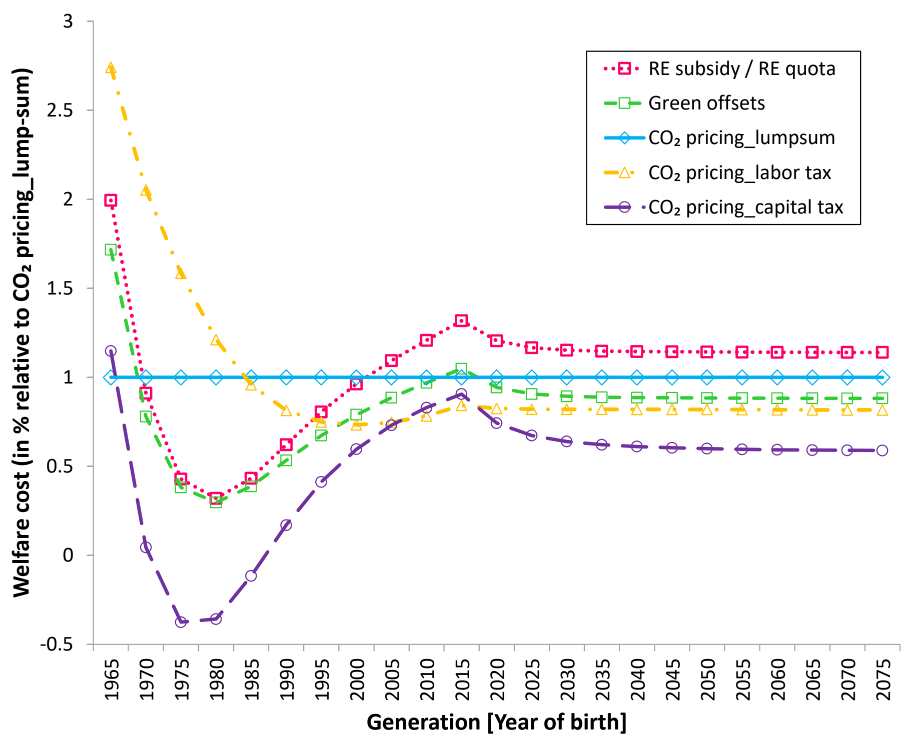
(b) A carbon pricing policy with labor income tax recycling places the smallest burden on current middle generations while current young and future generations suffer more.

(c) A carbon pricing policy with capital tax recycling yields a similar intergenerational incidence pattern compared to the RE support schemes.

[17]While the focus of this paper is the incidence and social welfare impacts of RE support policies, in the Appendix we report the CO_2 emission for completeness.



(a) Impacts by generation relative to the "no-policy" case.



(b) Impacts by generation relative to carbon pricing with lump-sum rebates.

Figure 3. Intergenerational incidence for different RE support schemes and carbon pricing with alternative revenue-recycling assumptions.

(d) *Under the RE support schemes, current old and middle generations incur smaller welfare costs while current young and future generations incur larger welfare costs.*

Explanations:

- 1a: Current old are affected the least as carbon pricing induces switch towards RE, which implies that capital asset price fall less compared to the reduction in wage. This benefits current old or capital-rich generations.
- 1b: Higher losses for current old who receive little income from labor as compared to current young.
- 1c: Reducing capital tax produces the direct and indirect benefits. The current old and middle generations enjoy the direct benefit because they derive large share of their income from capital asset and thus enjoy the increase in the value of capital assets. In contrast, the indirect benefit occurs through the larger investment. In other words, subsidizing capital stimulates investments and thus growth, and in the presence of distorting capital tax, subsidizing capital also means that the tax distortions are reduced, hence the efficiency is enhanced. These effects compound over time, so future generations benefit more from them relative to current young who don't live long enough to reap the longer-term benefits from capital subsidies.
- 1d: As RE production is capital-intensive, RE subsidy is effectively working as subsidy on capital income. As explained above, current old and middle generations gain from the direct effect or the increase in capital asset value. While the magnitude is modest, the indirect effect (e.g., growth-induced) occurs for the future generations is larger for the future generations.

Result 2 *(Incidence comparison across policies)*: Whether a RE support scheme outperforms carbon pricing depends on (i) the design of financing RE subsidies, (ii) the revenue recycling choices under carbon pricing, and (iii) the birth year (i.e., generation) of the household.

(a) *Except for current old and middle generations, carbon pricing with lump-sum rebates outperforms a RE subsidy/RE quota.*

(b) *A RE support scheme with green offsets (Green offsets) outperforms carbon pricing with lump-sum rebates.*

(c) *The RE support schemes outperform carbon pricing with labor income tax recycling for current old generations but leads to higher burdens for current young and future generations.*

(d) *Carbon pricing with capital income tax recycling outperforms RE support schemes for all generations.*

Explanations:

- 2a: Reducing the effective tax on capital through a RE subsidy is not high enough to produce efficiency gains, so it does not outweigh carbon pricing, which equalizes marginal abatement costs between non-renewable electricity generation.
- 2b: The RE subsidy with green offsets (Green offsets) improves the efficiency of the RE support scheme by equalizing marginal abatement costs between non-renewable electricity as carbon pricing does. Combined with the effect of lowering tax distortions on capital via the RE subsidy, green offsets becomes more efficient than carbon pricing.
- 2c: The benefit of labor tax cut do not fall on current old generations since they derive only smaller share of income from labor.
- 2d: Capital income tax recycling is sharper instrument than implicit capital subsidies under RE support schemes, and hence it favors better in terms of efficiency.

B. Robustness of incidence results

Table 4 explores how robust the findings of the central case is. We show the welfare cost relative to carbon pricing with lump-sum rebates for three generations (1975, 2015, and 2050) for current old, current young and future generations, respectively. At the top panel, we show the welfare cost of the central case, and we explore several specifications here: 1. different policy stringency (lower carbon price and higher carbon price); 2. no income tax distortions; 3. Lower capital intensity of RE technologies; 4. Higher substitution elasticity between energy and capital-labor composite.

POLICY STRINGENCY.—Generally, the policy stringency affects the welfare costs only in a limited way. Especially, the welfare costs of the RE support policies (both RE subsidy and Green offsets) are quite robust with regard to the policy stringency. When the stringency is lower, the benefit of reducing income tax is larger (and this benefit falls more on future generations), so the welfare costs of carbon pricing with labor tax cut and capital tax cut are smaller relative to carbon pricing with lump-sum rebates, and vice versa. Since the capital subsidy component of RE support policies is less sharp, while we see the same pattern but smaller in magnitude.

SIZE OF TAX DISTORTIONS.—Here we consider the hypothetical dataset where the initial income taxes are set to zero, and thus we do not consider the scenarios of reducing income tax. In the case of no income tax, RE support schemes are less efficient than carbon pricing with lump-sum rebates, so the welfare costs of RE support schemes are higher than carbon pricing for current young and future generations. However, the current old generations benefit from the RE support policies because of the increase in the capital asset value at the expense of other generations. Note that since the current old generation also benefit from carbon pricing with lump-sum rebates because the cost of climate policy is lower without income tax and thus no tax interaction effect. Since this benefit is quite small, the relative welfare impact of RE support policies for the current old generation appears large.

CAPITAL INTENSITY OF RE TECHNOLOGIES.—Here we reduce the capital input share of RE technologies by 25 percent and adjust the labor cost share accordingly. Because of the lower capital intensity of RE technologies, the current old generations gain less from the increase in capital asset value from capital subsidy effect (either capital tax cut or RE support policies). In contrast, the indirect benefit of capital subsidy effect (through induced growth) is not affected much because even reduced capital input still under distorting capital income tax and capital subsidy creates the similar benefit.

SUBSTITUTION ELASTICITY BETWEEN ENERGY AND CAPITAL-LABOR.—Here we double the substitution elasticity between energy and composite of capital and labor (we use 0.5 for the central case). Since the elasticity becomes larger, labor and capital are more flexible, and thus the tax distortions become larger. Thus, tax reduction are more beneficial, and all the policies are improved compared to carbon pricing with lump-sum rebates except for the current old generations in the case of RE support policies and carbon pricing with capital tax cut. There are two reasons. First, the indirect benefit (via induced growth) of capital tax cut and RE support policies occurs in the future, and the current old generations do not enjoy them (not fully at least). Second, since it is easier to substitute energy for capital and labor, we increase RE production less, and this softens the increase in capital asset value, which is bad for the current old generations.

IV. Social Evaluation of RE Support vs. Carbon Pricing Policies

A. Conceptual approaches

SOCIAL PREFERENCE AGGREGATION THROUGH VOTING.—While the welfare impact on future generations should be considered in some way, the acceptance of the policy is determined by the current generations, who exists at the time of voting. Since we assume that the policy is going to be chosen and implemented immediately, only the current generations, who exist at time 0, can take a vote. The voting decision depends on the expected lifetime impacts of the policy which materialize through both the uses- and sources-side of income.

SOCIAL WELFARE FUNCTION APPROACH.—While voting outcome is one way to consider social welfare, here we look at it in another way. Following Jensen and Rutherford (2002), we directly define the social welfare as:

$$SWF = \frac{\left(\sum_{h,g} Y^0_{h,g} u^{\rho}_{h,g}\right)^{1/\rho}}{\left(\sum_{h,g} Y^0_{h,g}\right)^{1/\rho}}, \tag{9}$$

Table 4. Impacts by generation for alternative policy designs relative to carbon pricing with lump-sum rebates

Sensitivity	Generation born in year		
	1975	2015	2050
Central case			
RE subsidy / RE quota	0.43	1.32	1.14
Green offsets	0.38	1.05	0.88
CO_2 pricing labor tax cut	1.58	0.84	0.82
CO_2 pricing capital tax cut	-0.37	0.91	0.60
Policy stringency (low)			
RE subsidy / RE quota	0.40	1.44	1.05
Green offsets	0.34	1.11	0.77
CO_2 pricing labor tax cut	1.65	0.60	0.58
CO_2 pricing capital tax cut	-0.54	0.76	0.21
Policy stringency (high)			
RE subsidy / RE quota	0.55	1.22	1.12
Green offsets	0.53	1.01	0.92
CO_2 pricing labor tax cut	1.43	0.93	0.91
CO_2 pricing capital tax cut	-0.10	0.96	0.80
No capital and labor income tax distortions			
RE subsidy / RE quota	9.23[a]	1.79	1.55
Green offsets	6.90[a]	1.46	1.23
Lower capital intensity of RE technologies			
RE subsidy / RE quota	0.86	1.31	1.15
Green offsets	0.74	1.04	0.90
CO_2 pricing labor tax cut	1.35	0.84	0.84
CO_2 pricing capital tax cut	0.05	0.93	0.63
Higher substitution elasticity between energy and capital-labor			
RE subsidy / RE quota	0.47	1.05	0.91
Green offsets	0.41	0.82	0.68
CO_2 pricing labor tax cut	1.18	0.56	0.54
CO_2 pricing capital tax cut	0.19	0.60	0.34

Notes: [a]The welfare impact of carbon pricing with lump-sum rebates in the case of no income tax is positive and small, and thus the relative welfare impact of RE policies become large.

where $Y^0_{h,g}$ is the remaining lifetime full-income at present value in the no policy scenario and ρ is the inequalty averson parameter. In this paper, we consider Utilitarian social welfare function, which means that there is no inequality aversion and thus ρ is set to 1.

B. Results

POLICY COMPARISON USING VOTING.—Table 5 shows the policy acceptance of RE support policies over carbon pricing. We reflect the different voting share for each generation taken from Census (2016). Generally, the younger generations vote less than older generations in the U.S. (i.e., 39.4% for 18 to 24 years old and 70.1% for 65-74 years old). Since we assume that the constant population growth, the characteristics of the higher voting ratio and smaller population size of older generations (compared to younger generations) counteract each other.

Result 3 Voting outcome for RE support policies vs. carbon pricing policies:

(a) If we compare the RE subsidy and carbon pricing with lump-sum rebates or labor tax cut), the RE subsidy has decent chance to win over carbon pricing regardless the policy stringency.

(b) If we compare the RE subsidy and carbon pricing with capital tax cut, the RE subsidy has no chance.

(c) If we compare Green offsets and carbon pricing with lump-sum rebates, Green offsets would be probably chosen. Against carbon pricing with labor tax cut, RES has decent chance to win.

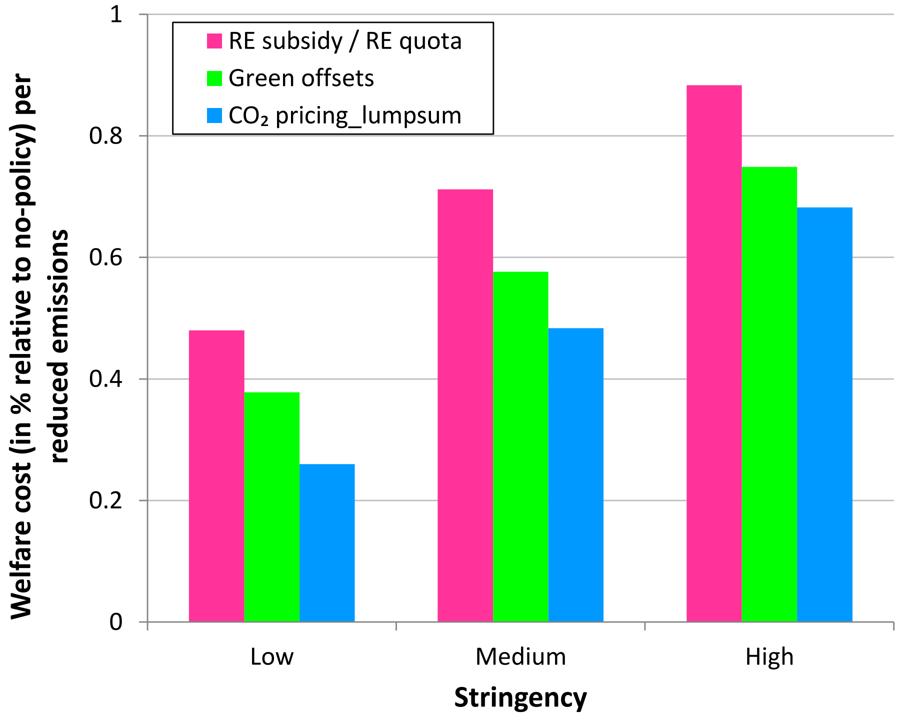
(d) If we compare Green offsets and carbon pricing with capital tax cut, Green offsets has no chance.

When the current generations have to vote either RE subsidy or carbon pricign with lump-sum rebates (or labor tax cut), the older generations, who have a large share of lifetime income from capital, vote for RE subsidy, whereas the younger generations, who have the large share of lifetime income from labor, vote for carbon pricing. As explained above for the intergenerational incidence, this pattern is explained by the income composition. First, labor tax cut is clearly not favorable for old generations because they do not work much any more in their remaining lifetime. Second, lump-sum rebates are also relatively large for younger generations because of their lower income.

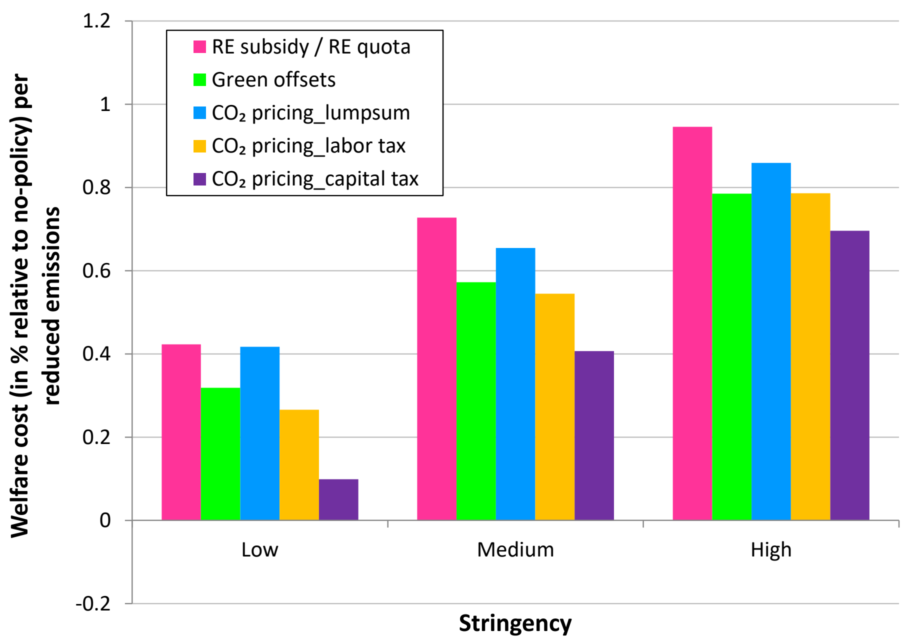
Next, we can consider green offsets where we finance the RE support policy in a smart way. In contrast to the RE subsidy, Green offsets will be probably chosen over carbon pricing with lump-sum rebates. This is because most generations prefer green offsets to carbon pricing with lump-sum rebates. Against carbon pricing with labor tax cut, the voting outcome is slightly better than the RE subsidy, but not much more. This is because the efficiency improvement of green offsets (relative to the RE subsidy) is not sufficient to win over carbon pricing with labor tax cut.

Looking at the hypothetical world where there is no income tax, the voting outcome of RE support policies are worse but only modestly. This is because even without the tax distortions, RE support policies increase the value of the capital asset, and thus the current old generations prefer the RE support policies. However, in this case, there is no efficiency improvement (and over-investment occurs), and the positive impact on the current old generations come with the expense of current young generations and future generations.

POLICY COMPARISON USING SOCIAL WELFARE FUNCTIONS.—Figure 4 shows the utilitarian welfare cost as percentage change of benchmark full income per tera ton of reduced carbon emissions. Figure 4(a) shows the welfare cost in the case of no income taxes, whereas Figure 4(b) shows the welfare cost in the case with income taxes.



(a) No income tax case: Utilitarian social welfare impacts per reduced emissions.



(b) With income taxes: Utilitarian social welfare impacts per reduced emissions.

Figure 4. Utilitarian social welfare impact (adjusted by reduced emissions) for different RE support schemes and carbon pricing with alternative revenue-recycling assumptions.

Table 5. Voting share for particular RE support scheme over carbon pricing for different sensitivity cases.

RE support scheme	over carbon pricing with		
	lump-sum rebates	labor tax recycling	capital tax recycling
RE subsidy / RE quota			
Policy stringency			
Low	60.4	48.9	0.0
Medium	60.4	48.9	0.0
High	52.8	48.9	0.0
Green offsets			
Policy stringency			
Low	82.7	57.6	0.0
Medium	82.7	57.6	0.0
High	82.7	57.6	0.0
No tax distortions			
RE subsidy / RE quota			
Policy stringency			
Low	50.8		
Medium	50.8		
High	60.4		
Green offsets			
Policy stringency			
Low	50.8		
Medium	60.4		
High	60.4		

In the case without income taxes, both the generic RE subsidy and the sophisticated version (Green offsets) are more costly than carbon pricing with lump-sum rebates (Figure 4(a)). This is true regardless the stringency. It is intuitive that if we have only carbon externality, taxing the emissions directly is the most efficient way to reduce emissions.

Result 4 With the income taxes, the comparison of Utilitarian social welfare between RE support policies and carbon pricing policies are following:

(a) If we compare the RE subsidy and carbon pricing with lump-sum rebates, they are similar in the case of low stringency. In the case of medium or high stringency, carbon pricing with lump-sum is less costly.

(b) If we compare Green offsets and carbon pricing with lump-sum rebates, Green offsets are less costly regardless the stringency.

(c) If we compare Green offsets and carbon pricing with labor tax cut, carbon pricing with labor tax cut is less costly, but the difference is small especially for the case of medium and high stringency.

(d) If we compare Green offsets and carbon pricing with capital tax cut, carbon pricing with capital tax cut is less costly.

In the case with income taxes, even the generic RE support policy can be as efficient as carbon pricing with lump-sum rebates when the stringency is low. Green offsets is more efficient than carbon pricing with lump-sum rebates, regardless the stringency. This is because of the distorting income taxes as Figure 4(a) shows without the income taxes, the RE support policies are more costly than carbon pricing with lump-sum rebates, regardless the stringency. As explained in the section of intergenerational incidence, since the renewable energy is quite capital intensive, the RE support policies induce more renewable energy, leading to more investment. Under the existence of distorting capital income taxes, investment is under-provided, and thus the increase of investment improves the efficiency of the economy via more growth (growth effect).[18] When we compare the RE support policies and carbon pricing policies, this growth effect of the RE support policies should be compared with the inefficiency of the emissions reduction of RE support policies, especially for the generic RE support policy. Both RE support policies have smaller pressure on the reduction of electricity demand because of the subsidy. Furthermore, the generic RE support policy does not have the fuel-switching incentive (i.e., from coal to natural gas) and have smaller incentive for switching from fuel-based to non-fuel-based electricity generations. As the stringency increases, the inefficiency of reducing emissions of the generic RE subsidy dominates the efficiency improvement of the growth effect. In contrast, since Green offsets reduces the emissions more efficiently than the generic RE subsidy, the growth effect dominates, regardless the stringency.

If the option of reducing income taxes by using carbon revenues is available, carbon pricing is more efficient than the RE support policies, since they directly exploit the efficiency improvement by lowering the distorting income taxes, while they reduce the emissions in a direct and efficient way. While carbon pricing with capital tax cut is clearly more efficient than RE support policies, the cost advantage of carbon pricing with labor tax cut over Green offsets is rather limited. This is consistent with the common characteristic of these numerical economic models including Goulder, Hafstead and Williams (2016), which is that capital tax is more distorting than labor tax.

V. Concluding Remarks

We have examined the lifetime and intergenerational economic incidence of renewable energy (RE) subsidies and carbon pricing for climate change mitigation, using a numerical dynamic general-equilibrium model with overlapping generations for the U.S. economy. The analysis has explored the political economy implications of the different regulatory approaches based on majority voting of generations alive at the time the policy is introduced. We have emphasized issues for policy design focusing on the financing of RE subsidies and policy interactions with distortionary income taxation.

We find that because of the initial income taxes, the RE subsidies are more efficient than carbon pricing with lump-sum rebates, especially if we finance the

[18] Since carbon pricing also induces more renewable energy, it also generates the growth effect, but the RE support policies generates larger growth effect because the RE support policies increases more renewable energy than carbon pricing.

subsidies by the electricity tax based on the carbon content. However, carbon pricing with the reduction of distorting income taxes is still more efficient than the RE subsidies. That said, we find that the RE support policies could be a politically viable option.

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Appendix A: Additional Figures

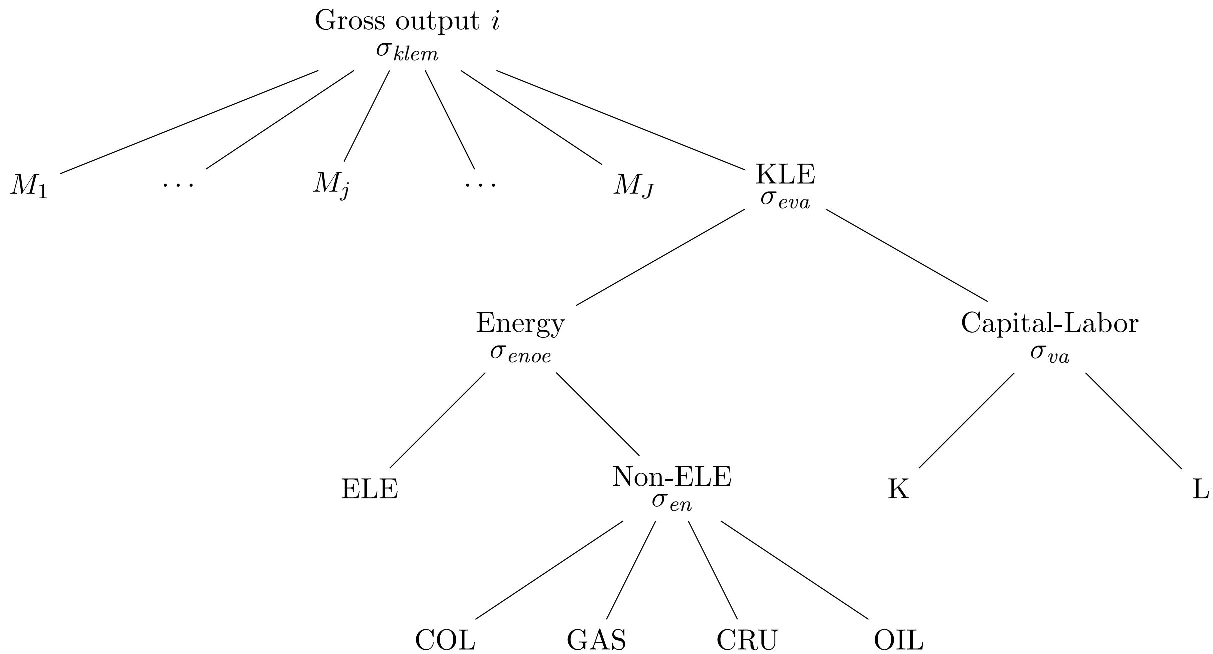

Figure A1. Structure of production for $i \in \{$AGR,EIS,TRN,SRV,MAN$\}$.

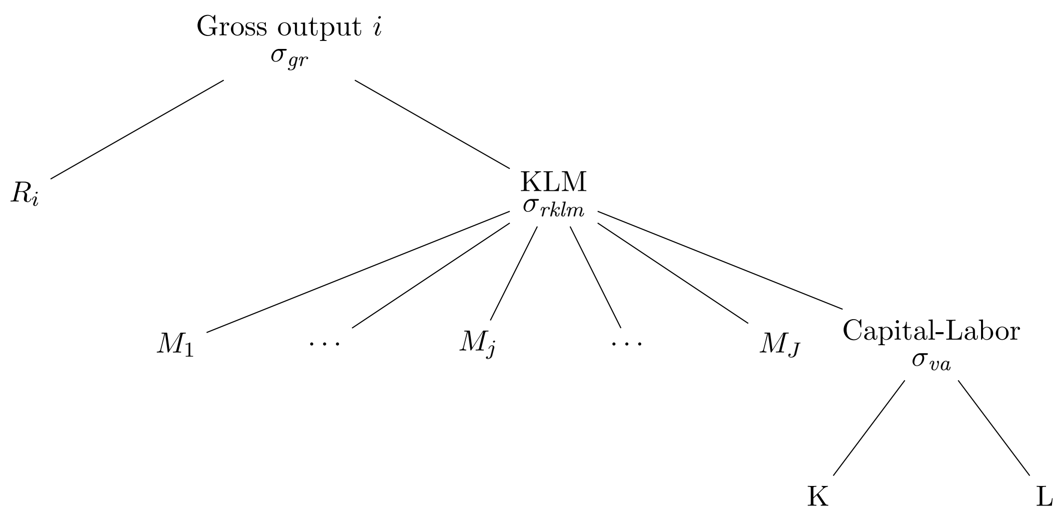

Figure A2. Structure of primary energy sectors $i \in \{\text{COL,CRU,GAS}\}$.

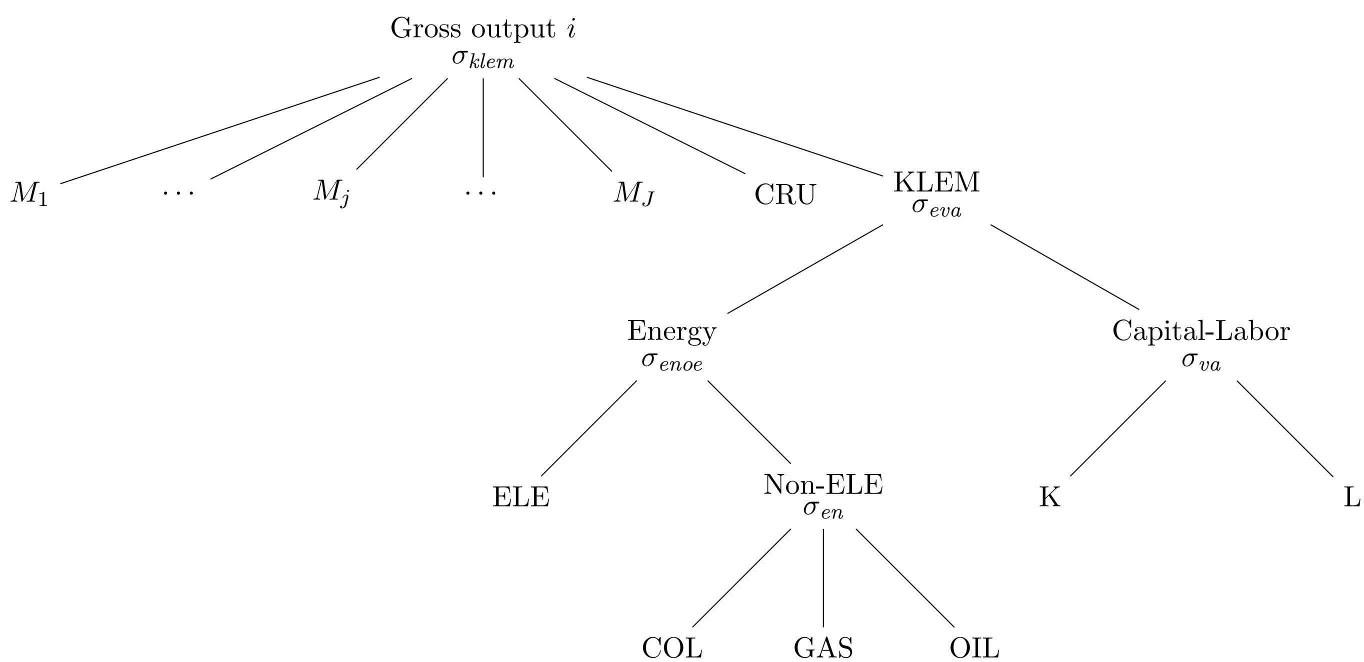

Figure A3. Structure of production for $i \in \{\text{OIL}\}$.

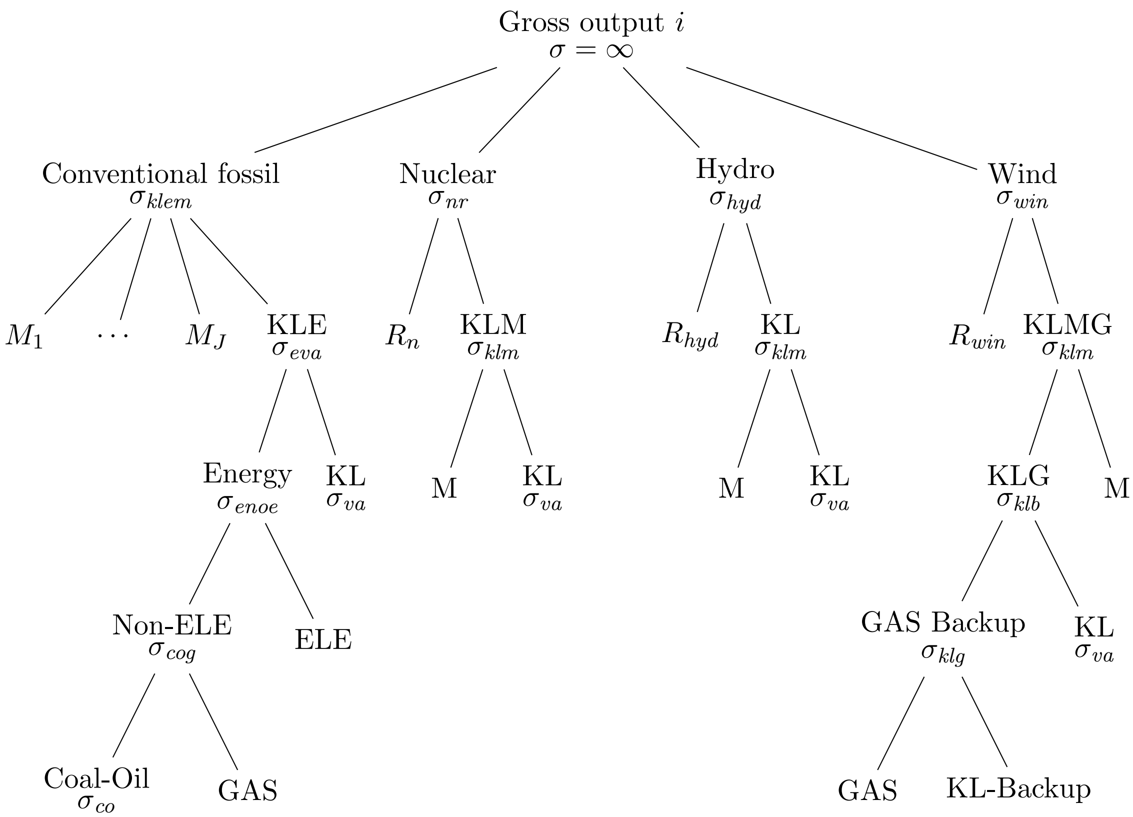

Figure A4. Structure of electricity production $i \in \{\text{ELE}\}$.

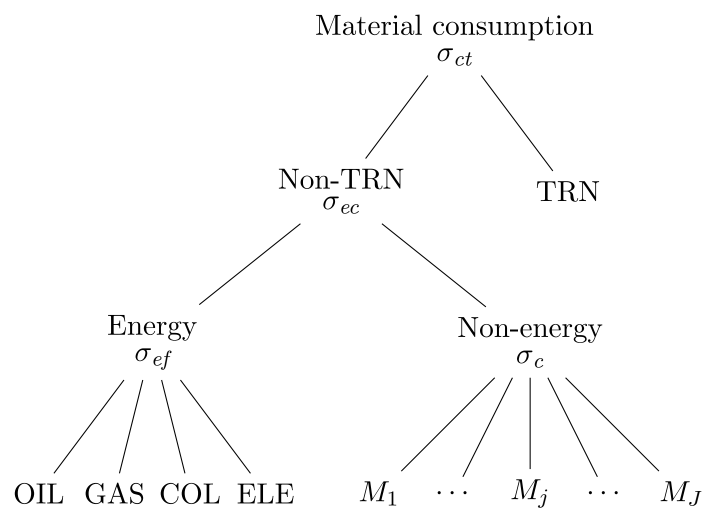

Figure A5. Structure of private material consumption.

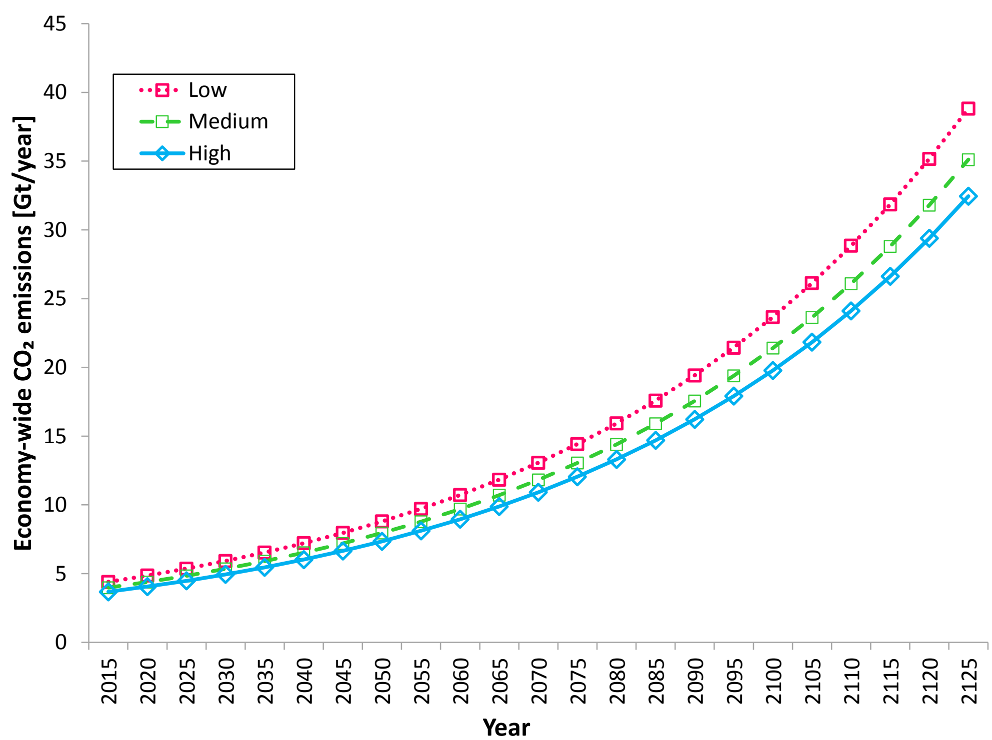

Figure A6. Economy-wide CO_2 emissions over time for different policy stringency.