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Green Technology Policies versus Carbon Pricing: An Intergenerational Perspective

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Technology policy is the most widespread form of climate policy and is often preferred over seemingly efficient carbon pricing. We propose a new explanation for this observation: gains that predominantly accrue to households with large capital assets and that influence majority decisions in favor of technology policy. We study climate policy choices in an overlapping generations model with heterogeneous energy technologies and distortionary income taxation. Compared to carbon pricing, green technology policy leads to a pronounced capital subsidy effect that benefits most of the current generations but burdens future generations. Based on majority voting which disregards future generations, green technology policies are favored over a carbon tax. Smart "polluter-pays" financing of green technology policies enables obtaining the support of current generations while realizing efficiency gains for future generations. (JEL Q54, Q48, Q58, D58, H23).

Market-based regulatory approaches to internalize the carbon dioxide (CO_2) externality, including carbon taxes and emissions trading, enjoy the long-standing and near-unanimous advocacy by economists (Coase, 1960; Montgomery, 1972; Baumol and Oates, 1988; Nordhaus, 1994; Metcalf, 2009). While carbon pricing is on the rise (World Bank, 2021), technology policies—i.e., technology mandates and performance standards—remain the most widely adopted form of actual low-carbon policy (Meckling, Sterner and Wagner, 2017). Examples for the major fossil-fuel burning sectors in most developing and developed economies around the world are abound: green quotas, clean energy standards, and subsidies for renewable energy (RE) technologies in the power sector, fuel economy and emissions intensity standards in private transportation, and energy efficiency standards in the buildings and household sector.

The economic literature offers several explanations as to why technology policy is often preferred over carbon pricing. First, direct promotion of environmentally friendly technologies exploits positive externalities associated with innovation and

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diffusion of new technologies (Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012).[1] Second, because technology policies contain implicit or explicit subsidies, they give rise to a less pronounced increase in the price for energy services (for example, electricity, distance traveled, or heating or cooling). This has two advantages: it limits negative impacts on low-income households, which spend a disproportionately large fraction of their income on energy (Landis et al., 2019), and it leads to smaller reductions in real factor returns, thereby exacerbating to a lesser extent the preexisting factor-market distortions caused by the tax system (Goulder et al., 1999; Goulder, Hafstead and Williams III, 2016). On the other hand, carbon pricing generates revenues that can be used to address distributional concerns and the superiority of technology policies based on tax interactions is rapidly diminishing as climate policy becomes more stringent (Goulder, Hafstead and Williams III, 2016). Third, there are political economy arguments which can explain a preference for technology policies.[2]

This paper adds another important explanation which has so far been overlooked: gains that predominantly accrue to households with large capital assets and that influence majority decisions in favor of technology policy over (apparently efficient) price-based climate policy. To study the economic effects of different climate policy approaches and the consequences for the well-being of different types of households, we develop a quantitative large-scale dynamic general equilibrium model with overlapping generations (OLG). The model highlights several key features which are important for the choice and design of real-world climate policy. First, "clean" energy technologies—such as wind and solar power, electric vehicles, green buildings—exhibit a substantially higher capital intensity than "dirty" conventional energy technologies. Second, the households that vote on different types of climate policies are of different ages and therefore exposed to the product and factor market effects caused by the policy in different ways. Third, in most countries, climate policy is implemented in an environment with substantial income taxation to finance government spending, which in turn requires consideration of the interactions between climate and fiscal policies.

The predominant view that carbon pricing outperforms technology policy is based either on static models or on dynamic models with infinitely-lived, representative agents.[3] Our analysis suggests a different answer. By providing incentives

[1]Obviously, carbon pricing is not the perfect instrument here—but empirical evidence suggests that it can be quite effective in triggering innovation in clean technologies through higher (carbon) tax-inclusive fuel prices (Popp, 2002; Aghion et al., 2016; Fried, 2018). Moreover, positive knowledge and adoption spillovers and information problems can further weaken the innovation incentives from technology policies (Jaffe and Stavins, 1994).

[2]Olson (1971) argues that it is easier to effectively organize special interests and narrowly focused lobby groups demanding subsidies and privileges. Austen-Smith et al. (2019) show that legislators, in particular in polarized political and volatile economic environments, agree more readily on inefficient technology standards and quotas as they are politically easier to repeal than efficient instruments.

[3]There is a comprehensive literature on instrument choice in environmental policy (for an overview, see Goulder and Parry, 2008). Carbon pricing is generally considered to be cost-effective compared to technology mandates and performance standards, regardless of policy stringency (for example, Goulder et al., 1999; Fawcett et al., 2014; Abrell, Rausch and Streitberger, 2019). An exception is Goulder,

for "clean" low-carbon energy technologies which are capital-intensive relative to "dirty" fossil-based technologies, a green technology policy largely mimics the effects of a capital subsidy. This benefits today's generations of households with relatively large capital assets (which were accumulated prior to the policy as a result of life-cycle consumption and savings decisions). Compared to a carbon pricing policy, however, technology policies provide poor incentives for energy conservation and substitution away from "dirty" energy (Holland, Hughes and Knittel, 2009). These efficiency losses in carbon abatement lead to real income losses that to a large extent have to be borne by future generations of households.

Using an OLG framework that does not obscure the potential of climate policies to deliver generational gains, this paper argues that the superiority of carbon pricing over green technology policies is not clear-cut. When social valuation is based on a utilitarian welfare perspective, we confirm the established wisdom: a carbon tax is generally preferred to a green technology policy, while pre-existing distortionary income taxes can reverse this ranking at low levels of policy stringency. If, however, the current population votes over climate policy approaches, we find large support in favor of green technology policies over carbon pricing. Importantly, the societal preference for green technology policies based on majority voting does not require the distortionary income tax argument and is independent of policy stringency.

Beyond instrument choice, we also highlight the importance of policy design. Specifically, we examine how technology policies can be better designed to improve CO_2 abatement efficiency and to gain increased approval in a majority decision. We show that the way in which policy support for green energy technologies is financed is key to very high approval rates of today's population for green technology policies over carbon pricing: a "smart" green technology policy design based on a "polluter-pays" financing of technology subsidies is preferred by 90% of the current population relative to a carbon tax.

The extent to which technology policy is favored over carbon pricing also depends on how carbon revenues are recycled. Technology policies tend to outperform carbon tax policies (in terms of majority voting), which forgo efficiency gains by using carbon revenues to reduce the tax burden on primary production factors. This includes the important case of lump sum transfers to consumers. When carbon revenues are used to lower capital income taxes, poorly designed technology policy, such as a "blunt" technology standard, is dominated by carbon pricing, which benefits both from the capital subsidy effect and efficient energy conservation and technology (input) substitution. A "polluter-pays" design of green technology policy, however, outperforms even a carbon tax policy design with a high efficiency in recycling carbon revenues.

Our findings have important implications for the design of climate policy. Since the transition to a carbon-neutral economy will inevitably involve extensive sub-

Hafstead and Williams III (2016) who find that, due pre-existing tax distortions, a technology mandate can be advantageous for sufficiently small emissions reductions.

stitution of capital for "dirty" fossil energy, the social valuation of capital effects is critical for policy design. Based on the analysis of general equilibrium and life-cycle effects of environmental regulation, we highlight that the current population may favor policy approaches which directly incentivize the use of "clean" capital. In the absence of intergenerational altruism (or strong intergenerational links through bequests), carbon pricing policies may find less social acceptance than green technology policies, even if the latter puts a price on carbon and are more efficient in a "narrow" (i.e., partial equilibrium) sense of carbon abatement.

This paper contributes to the fundamental issue of policy instrument choice and design in the vast literature in environmental and public economics (for overviews see, for example, Goulder and Parry, 2008; Phaneuf and Requate, 2017). A small and growing literature has used OLG models to assess the intergenerational effects of carbon taxes. Several studies examine the non-environmental welfare impacts of alternative revenue-neutral carbon tax policies using a life-cycle model (Rausch, 2013; Carbone, Morgenstern and Williams III, 2013).[4] Fried, Novan and Peterman (2018) also consider within age cohort income heterogeneity. Karp and Rezai (2014) consider a two-sector life-cycle model where agents live for two periods to explore the degree to which policy-induced general equilibrium changes in factor and asset prices could affect a Pareto improvement with no direct redistribution across generations. Kotlikoff et al. (2020) consider the optimal carbon tax in an OLG model with climate change damages and intergenerational redistribution.[5] Bovenberg and Heijdra (2002) find that public abatement benefits the oldest generations in terms of non-environmental welfare, whereas future generations gain most in terms of environment welfare. Surprisingly, the existing literature has not examined the intergenerational dimension of the classical issue of instrument choice and design between "command-and-control" technology regulation and market-based climate policy using carbon pricing. This paper aims to fill this gap.

Section I presents the model and Section II model calibration. Section III describes the computational experiment used to compare alternative climate policy approaches. Section IV examines the intergenerational incidence of technology and carbon pricing policies. Section V evalutes the different policy approaches from a social welfare perspective. Section VI concludes.

I. The Model

We use an infinite-horizon, multi-sector Auerbach and Kotlikoff (1987)-type general equilibrium model with overlapping generations. Sectoral output combines intermediates produced under perfect competition using physical capital, labor,

[4] Rausch and Yonezawa (2018) also consider the impacts of using carbon revenues to reduce the size of the federal debt in an OLG model.

[5] Also in a DICE-type OLG model, and abstracting from Pareto-improving policies as in Kotlikoff et al. (2020), Leach (2009) shows that a variety of carbon policies, including an approximation of the Kyoto protocol, leave early generations worse off.

and different types of energy (coal, natural gas, crude oil, refined oil, electricity). Electricity is generated from fossil-based, nuclear, hydro, and new renewable (wind and solar) technologies. Carbon emissions derive from burning fossil fuels in production and consumption. The model also includes government spending and preexisting income (and product) taxes. Life-cycle consumption and savings decisions stem from inter-temporally optimizing households with finite lifetimes.[6]

A. *Household Behavior: Overlapping Generations*

Time is discrete and extends to infinity: $t = 0, \ldots, \infty$. The economy is populated by overlapping generations where a new generation of households g is born at the beginning of year $t = g$ and exits at the end of year $t = g+N$.[7] Households are forward-looking with perfect foresight over their finite lifetime.

Lifetime utility of generation g, u_g, is of the constant-intertemporal-elasticity-of-substitution form (and thus additively separable over time):

$$u_g(z_{gt}) = \sum_{t=g}^{g+N} \left(\frac{1}{1+\hat{\rho}}\right)^{t-g} \frac{z_{gt}^{1-1/\sigma}}{1-1/\sigma} \tag{1}$$

where full consumption z_{gt} is a CES aggregate of leisure time and consumption:

$$z_{gt} = \left(\alpha c_{gt}^{\nu} + (1-\alpha)\,\ell_{gt}^{\nu}\right)^{\frac{1}{\nu}} .$$

$\hat{\rho}$ is the subjective utility discount factor, σ 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. c_{gt} is an CES aggregate of final Armington goods A_{it} with corresponding price index $p_t^C = [\sum_i c_i (p_{it}^A)^{1-n}]^{1/1-n}$, where c_i and n are share and elasticity of substitution parameters, respectively.[8]

In each period during the life-cycle, a household allocates its time between labor and leisure:

$$\ell_{gt} \leq \omega_g . \tag{2}$$

The generation g is endowed with $\omega_{g,t} = \omega\,(1+\gamma)^g$ units of time in each period, where γ denotes the effective population growth rate (including labor-augmenting technological progress).[9]

The lifetime budget constraint requires that the total value of consumption

[6]We abstract from all sources of uncertainty at the aggregate and individual level.
[7]We use "household" and "generation" interchangeably.
[8]Figure A1 in the Appendix depicts the nested CES structure for material consumption.
[9]ω is a constant income scaling factor, which is determined in the initial calibration procedure to reconcile household behavior with the aggregate benchmark data.

cannot exceed lifetime income from different sources:

$$\sum_{t=g}^{g+N} p_t^C c_{gt} \leq \underbrace{p_0^K \overline{k}_g}_{\substack{=\text{Initial}\\ \text{assets}}} + \sum_{t=g}^{g+N} \underbrace{\Omega_{gt}}_{\text{Periodic income}} \tag{3}$$

where

$$\Omega_{gt} = \underbrace{w_t\,(1-\tau_l)\,\pi_{gt}\,(\omega_g - \ell_{gt})}_{\substack{=\text{Net-of-tax labor}\\ \text{income}}} + \underbrace{\sum_{i\in P\cup U} \theta_{ig} p_{it}^R R_{it}}_{\substack{=\text{Resource}\\ \text{income}}} + \underbrace{p_t^C\,\Delta_{gt}}_{\substack{=\text{Transfer}\\ \text{income}}} \; .$$

$\overline{k}_g$ denotes the capital holdings of generation g at the beginning of life and p_0^K the purchase price of capital at time $t = 0$. Initial old generations, i.e. generations born prior to period zero, are endowed with a non-zero amount of capital which represents claims on the initial capital stock, i.e. $K_0 = \sum_{g=-N}^{0} \overline{k}_g$. We abstract from intergenerational bequests and assume that newborn households enter the economy with zero capital assets, i.e. $\overline{k}_g = 0$, $\forall\, g \geq 0$.

τ_l is a tax rate on labor income, and π_{gt} is an index of labor productivity over the life cycle. θ_{ig} is the ownership share of generation g in income derived from resource of type i, where incomes at time t are fully distributed among generations alive at t. Δ_{gt} denotes income from government transfers, including potential rebates from carbon tax revenues.

Each generation chooses optimal life-cycle paths of consumption $\{c_{gt}\}_{t=g}^{t=g+N}$ and leisure $\{\ell_{gt}\}_{t=g}^{t=g+N}$ to maximize lifetime utility (1) subject to time endowment (2) and lifetime budget (3) constraints. Utility-maximizing behavior of generation g is reflected by the lifetime budget constraint (3) and the household-level Euler equation:

$$\frac{z_{gt+1}}{z_{gt}} = \left(\frac{1 + r_{t+1}}{1+\hat{\rho}}\right)^{\sigma} . \tag{4}$$

Using this condition and the budget constraint, we can derive the fraction of periodic income Ω_{gt} saved or invested by generation g in period t, $s_{gt}(r)$, as:

$$s_{gt}(r_{t+1}) = \frac{(1 + r_{t+1})^{(\sigma-1)}}{(1+\hat{\rho})^{\sigma} + (1 + r_{t+1})^{(\sigma-1)}} . \tag{5}$$

B. *Firm Behavior: Finals Goods and Energy Resource Sectors*

Sectors are indexed with $i, j \in I$. We distinguish two main types of sectors: energy-supplying resource sectors $p \in P \subset I$ and sectors producing final goods $n \in N \subset I$. There are two types of resource sectors. Resource sectors $f \in F \subset P$ extract coal, crude oil, or natural gas resources from the Earth's crust and resource sectors $r \in R \subset P$ generate electricity from nuclear, hydro, and intermittent "new renewable" (for example, wind and solar) resources. Final goods include non-energy sectors $g \in G \subset N$ (such as energy-intensive and non-energy intensive manufacturing, services, transportation, agriculture), the refining of crude oil $c \in C \subset N$, and the generation of electricity from fossil resources $l \in L \subset N$.

ENERGY RESOURCE SECTORS AND RENEWABLES (WIND AND SOLAR).—The output of energy resource and renewables sector p at time t, Y_{pt}, is subject to decreasing returns to scale and is characterized by the following nested constant-elasticity-of-substitution (CES) production function which combines a sector-specific resource R_{pt}, intermediate inputs B_{ipt}, $i \neq p$, from other sectors, capital K_{pt}, and labor L_{pt}:

$$(6)\quad Y_{pt} = [\epsilon_p \underbrace{R_{pt}}_{\text{Resource input}}{}^{\rho_p^R} + (1-\epsilon_p)\min\{\underbrace{B_{1pt},\ldots,B_{ipt},\ldots,B_{Ipt}}_{\text{Intermediate material inputs}},\underbrace{V_{pt}(K_{pt},L_{pt})}_{\text{Capital-labor composite}}\}^{\rho_i^R}]^{\frac{1}{\rho_p^R}}$$

where V_{pt} is a Cobb-Douglas aggregate of capital and labor, ϵ is a share parameter, and $\sigma_p^R = 1/(1-\rho_p^R) > 0$ is the elasticity of input substitution.

The representative resource-extracting or renewable energy firm in sector p maximizes static profits at time t under perfect competition:

$$(7)\qquad \max_{K_{pt},L_{pt},R_{pt},B_{ipt}} (p_{pt}^Y + s_t)Y_{pt} - r_t K_{pt} - w_t L_{pt} - p_{pt}^R R_{pt} - \sum_{i \neq p} p_{it}^B B_{ipt}$$

subject to (6) and taking prices of output p^Y, capital r, labor w, and resource p^R and material p^B inputs as given. s_t is an output subsidy (used to represent technology policies, see Section III).

To control for potential intermittency issues related to the resource-varying nature of wind and solar energy, we assume that the "new renewable" technology is backed up with a 100 percent of natural gas. This combined, synthetic technology can be considered fully dispatchable and can be thus treated as a perfect substitute for conventional, base-load technologies (Joskow, 2011; Rausch and Karplus, 2014), and thus enables modelling electricity generated from different sources as a homogeneous good.[10]

FINAL GOODS SECTORS.—Final output Y_{nt} in sector n at time t is characterized by a two-stage KLEM production process (see, for example, Bovenberg and Goulder, 1996; Paltsev et al., 2005*b*) in which inputs of capital, labor, energy, and materials are combined. At the first stage, inputs B_{int} from other sectors $i \neq n$

[10]The extreme (conservative) assumption of a 100 percent backup most likely leads us to overestimate the actual costs of energy supplied from wind and solar power. This is innocuous, however, considering that our focus is on *relative* comparisons of different climate policy instruments.

are combined with a sector-specific capital-labor-energy composite Q_{nt}:

$$(8)\quad Y_{nt} = [\phi_n \min_{i \in I \setminus E} (\underbrace{B_{1nt}, \ldots, B_{int}, \ldots, B_{Int}}_{\text{Non-energy material inputs}})^{\xi_n} + (1-\phi_n)(\underbrace{Q_{nt}}_{\text{Capital-labor-energy composite}})^{\xi_n}]^{\frac{1}{\xi_n}}$$

where $E = \{$*coal, natural gas, refined oil, electricity*$\} \subset I$ denotes the set of energy inputs used at the second stage of production. ϕ_n are share parameters and $\sigma_n^Y = (1-\xi_n)^{-1} > 0$ denotes the elasticity of input substitution. In the case of the refining sector ($n = c$), the crude oil "feedstock" enters in the Leontief nest together with the other non-energy materials inputs. Final good producers at time t maximize static profits under perfect competition:

$$(9)\qquad \max_{Q_{nt}, B_{nt}} p_{nt}^Y Y_{nt} - p_{nt}^Q Q_{nt} - \sum_{i \in I \setminus E} p_{it}^B B_{int}$$

subject to (8) and taking output and input prices as given.

At the second stage of sectoral production, Q_{nt} is produced by combining capital, labor, and energy E according to:

$$(10)\qquad Q_{nt} = [\theta_n (K_{nt}^{\beta_n} L_{nt}^{1-\beta_{nt}})^{\nu_n} + (1-\theta_n) E_{nt}^{\nu_n}]^{\frac{1}{\nu_n}}$$

where θ_n and β_n are share parameters and $\sigma_n^Y = (1-\nu_n)^{-1} > 0$ is the elasticity of substitution. E_{nt} is an aggregate energy input which combines different types of energy:

$$(11)\qquad E_{nt} = (\xi_n \tilde{Z}_{nt}^{\mu_n} + (1-\xi_n)[\sum_e \vartheta_{en} (Z_{ent})^{\omega_n}]^{\frac{1}{\omega_n}})^{\frac{1}{\mu_n}}$$

where Z_{ent} and $\tilde{Z}_{nt}$ are the quantities of thermal (fossil-based) and electric energy used in sector n at time t, respectively. ξ_n and ϑ_{en} are share parameters. $\sigma_n^E = (1-\mu_n)^{-1} > 0$ and $\sigma_n^Z = (1-\omega_n)^{-1} > 0$ denote elasticity of substitution parameters between electric and aggregate thermal and within-thermal energy, respectively. Figure A2 in the Appendix summarizes the production structure for n-type sectors. The profit maximization problem of intermediate goods producer n at time t solves:

$$(12)\qquad \max_{K_{nt}, L_{nt}, Z_{ent}} p_{nt}^Q Q_{nt} - r_t K_{nt} - w_t L_{nt} - \sum_e (p_{et}^A + \lambda_t) Z_{ent}$$

subject to (10) and (11) taking commodity and factor prices as given. λ_{et} is an input tax levied on fossil fuel e used in sector n, Z_{ent}. The carbon emissions which result from combusting one unit of fossil fuel e is given by κ_e.

C. International Trade and Supply of Final Goods

All sectoral goods are tradable. Sector-specific bilateral international trade is represented following the standard Armington (1969) approach where goods produced at different locations are treated as imperfect substitutes. We adopt a small-open economy perspective where the price of the foreign goods is denominated by the foreign exchange rate p^f_t.[11]

The amount of final good i supplied at time t, A_{it}, is thus given by a CES composite of sectoral varieties produced domestically D_i and imported from abroad M_i:

$$A_{it} = \left[\psi^m_i \, D^{\rho^m_i}_{it} + \xi^m_i \, M^{\rho^m_i}_{it}\right]^{1/\rho^m{}_i} \tag{13}$$

ψ^m and ξ^m denote the share coefficients and the Armington substitution elasticity between domestic and imported varieties is $\sigma^m_i = 1/(1 - \rho^m_i)$. The final goods supplier i at time t maximizes profits taking prices as given according to:

$$\max_{D_{irt}, M_{it}} p^A_{it} A_{it} - p^Y_{it} D_{it} - p^f_t M_{it} \tag{14}$$

subject to (13).

Domestically produced goods, Y_i, are transformed into exports, X_i, and domestic supply, D_i, according to a constant elasticity-of-transformation (CET) function:

$$\left[\psi^x_i \, D^{\rho^x_i}_{it} + \xi^x_i \, X^{\rho^x_i}_{it}\right]^{1/\rho^x{}_i} = Y_{it} \tag{15}$$

where ψ^x and ξ^x denote the share coefficients and $\sigma^x_i = 1/(1 + \rho^x_i)$ is the transformation elasticity between domestic and exported varieties. The supplier of exports and domestic goods of variety i at time t maximizes profits taking prices as given according to:

$$\max_{D_{irt}, M_{it}} p^Y_{it} D_{it} + p^f_t X_{it} - p^Y_{it} Y_{it} \tag{16}$$

subject to (15).

D. Aggregate Investments and Capital Accumulation

Next period's capital stock of the aggregate economy depends on and last periods (net of depreciation) capital stock and the aggregate of individuals' savings

[11] 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.

behavior according to:

$$K_{t+1} = (1 - \delta_t)K_t + I_t \tag{17}$$

where δ is the capital depreciation rate. Savings are carried out by buying an aggregate investment good I_t which is produced by combining final goods A_{it} in fixed proportions. The total demand for aggregate investment at time t is thus given by the sum of savings from generation alive at this point in time:

$$I_t = \sum_{g=t-N}^{t} s_{gt}(r_{t+1})\Omega_{gt} \,. \tag{18}$$

E. Markets and Pricing

To characterize equilibrium prices, we define additional market clearing and pricing conditions. Markets for sectoral output clear, determining p^Y_{it}, if:

$$Y_{it} = D_{it} + X_{it} \,. \tag{19}$$

Final goods can be used for consumption, as inputs in the production of sectoral output and the aggregate investment good. The price for final goods, p^A_{it}, is then determined by the following market clearing condition:

$$A_{it} = \sum_{g=t-N}^{t} c_{gt} + \sum_j B_{jit} + I_t \,. \tag{20}$$

Electricity generated from dirty and clean power technologies is a homogeneous good implying that aggregate electricity output is given by:

$$Y_{st} = \sum_{i \in F \cup R} Y_{it} \tag{21}$$

where the production structure of conventional, fossil-based electricity is similar to (8). Figures A3 and A4 in the Appendix summarize the production structure for sectors of type p, f, and r. Labor is treated as perfectly mobile between sectors but not internationally. Accordingly, the wage rate w_t is determined on the national labor market:

$$\sum_i L_{it} = \sum_{g=t-N}^{t} \pi_{gt} \left(\omega_g - \ell_{gt}\right) . \tag{22}$$

Given an exogenous supply of natural or renewable resources $\overline{R}_{it}$, resource markets clear if:[12]

$$\overline{R}_{it} = R_{it}\,. \tag{23}$$

The price of foreign exchange p^f_t is determined by balancing the total value of exports and imports:

$$\sum_i (M_{it} - X_{it}) = 0\,. \tag{24}$$

II. Data and Model Calibration

A. Matching Social Accounting Matrix Data

We use social accounting matrix (SAM) data for the US economy to parametrize the multi-sectoral economic structure as well as the international trade flows. This study makes use of SAM data from the Global Trade Analysis Project (Aguiar, Narayanan and McDougall, 2016) which provides a consistent set of global accounts of production, consumption, and bilateral trade as well as physical energy flows differentiated by primary and secondary energy carrier. We use version 9 of the GTAP database and the base year 2011. Table 1 shows the sectors and primary factors of the model. We follow the standard calibration procedure in multi-sectoral numerical general equilibrium modeling (see, for example, Rutherford, 1995; Harrison, Rutherford and Tarr, 1997; Böhringer, Carbone and Rutherford, 2016) according to which production and consumption technologies are calibrated to replicate a single-period reference equilibrium consistent with the SAM data in the base year.

B. External Parameters

ELASTICITIES OF SUBSTITUTION PARAMETERS.—The choice of values for the elasticity of substitution parameters σ follows closely the MIT EPPA model (Paltsev et al., 2005*a*; Chen et al., 2015), a numerical general equilibrium model which has been widely used for climate policy analysis. We use the econometrically estimated substitution parameters parameters for Armington trade provided (Aguiar, Narayanan and McDougall, 2016). Table A1 in the Appendix provides the parameter values.

AGE-SPECIFIC LABOR PRODUCTIVITY.—To describe labor productivity over the life-cycle, we use an age-related productivity profile according to:

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

[12] We thus model natural resources as flow variables (as opposed to stock variables), and we abstract from the issue of optimal endogenous extraction of natural resource stocks.

Table 1. Model resolution: sectors and primary production factors.

Sectors	**Primary production factors**
Energy resource sectors ($f \in F \subset P$)	Capital
Coal	Labor
Crude oil	*Natural resources*
Natural gas	Coal
	Natural gas
Secondary energy sectors	Crude oil
Refined oil products $c \in C \subset N$	Nuclear
Electricity	Hydro
Fossil-based (coal, natural gas, refined oil)	
Nuclear	
Hydro	
Wind and solar	
Non-energy sectors	
Energy-intensive industries	
Other manufacturing	
Agriculture	
Transportation	
Services	

Notes: Sectoral classifications shown above are many-to-one aggregations of the 57 sectors contained in the GTAP9 database (Aguiar, Narayanan and McDougall, 2016). The sectoral mapping is available on request from the authors.

where the parameters of this function are selected to minimize the difference from the profile arising by taking the average of multiple income groups as discussed in Altig et al. (2001). The coefficients used are: $\lambda_0 = 1.0785$, $\lambda_1 = 0.0936$, $\lambda_2 = -0.0015$, and $\lambda_3 = 7 \times 10^{-6}$.

C. *Calibration of Balanced Growth Path*

We calibrate the model to a steady-state baseline extrapolated from the base-year SAM data using exogenous assumptions on the growth rate of output, the interest rate, the intertemporal elasticity of substitution, and capital depreciation rate $\{\bar{\gamma}, \bar{r}, \theta, \delta_t\}$. The choice of the annual interest rate is important for the results of a long-term analysis like the present one. We use a value of $\bar{r} = 0.05$ for the net of tax return.[13] The annual capital depreciation rate is set to 0.07. $\bar{\gamma}$ is set to 0.02 reflecting roughly an annual average of U.S. economic growth experience between 2004 and 2011. To calibrate the model to the SAM, it is necessary that the solution to the maximization problems of OLG households is consistent with the base-year value for aggregate private consumption and income. We employ a steady-state calibration procedure for OLG models described in Rasmussen and Rutherford (2004) which imposes two additional constraints on individuals' maximization problems by endogenously solving for the time en-

[13] Altig et al. (2001) argue for using a value around 7-8% based on the historical real rate of return to capital, while others (e.g., Fullerton and Rogers, 1993) use a much smaller rate around 3-4%. With no account for risk in this model it is not clear which value should be used. Also it should be kept in mind that with these kind of models there is no "correct" value.

dowment parameter ω and the utility discount rate $\hat{\rho}$.[14] $\hat{\rho}$ is calibrated to ensure that the model is on a balanced growth path: given a constant interest rate $\overline{r}$, the Keynes-Ramsey rule gives the growth rate of the economy along a balanced growth, i.e. $g = [(1+\overline{r}))/(1+\hat{\rho})]^{(1/\sigma)}$, from which we can infer $\hat{\rho}$. Lastly, given $\{\bar{r}, \bar{\gamma}, \delta_t\}$ we use data on base-year capital earnings from the SAM data (Altig et al., 2001) to infer the capital stock at $t = 0$.

D. Computational Strategy

Following Mathiesen (1985) and Rutherford (1995), we formulate the model as a mixed complementarity problem associating quantities with zero-profit and prices with market-clearing conditions. To approximate the infinite horizon global economy by a finite-dimensional computational problem, we use state-variable targeting (Lau, Pahlke and Rutherford, 2002). We use the General Algebraic Modeling System (GAMS) software and the GAMS/MPSGE higher-level language (Rutherford, 1999) together with the PATH solver (Dirkse and Ferris, 1995) to compute the equilibrium. We solve the model for 150 years ($T = 150$) and assume that the lifespan of households is 50 years ($N = 49$).[15]

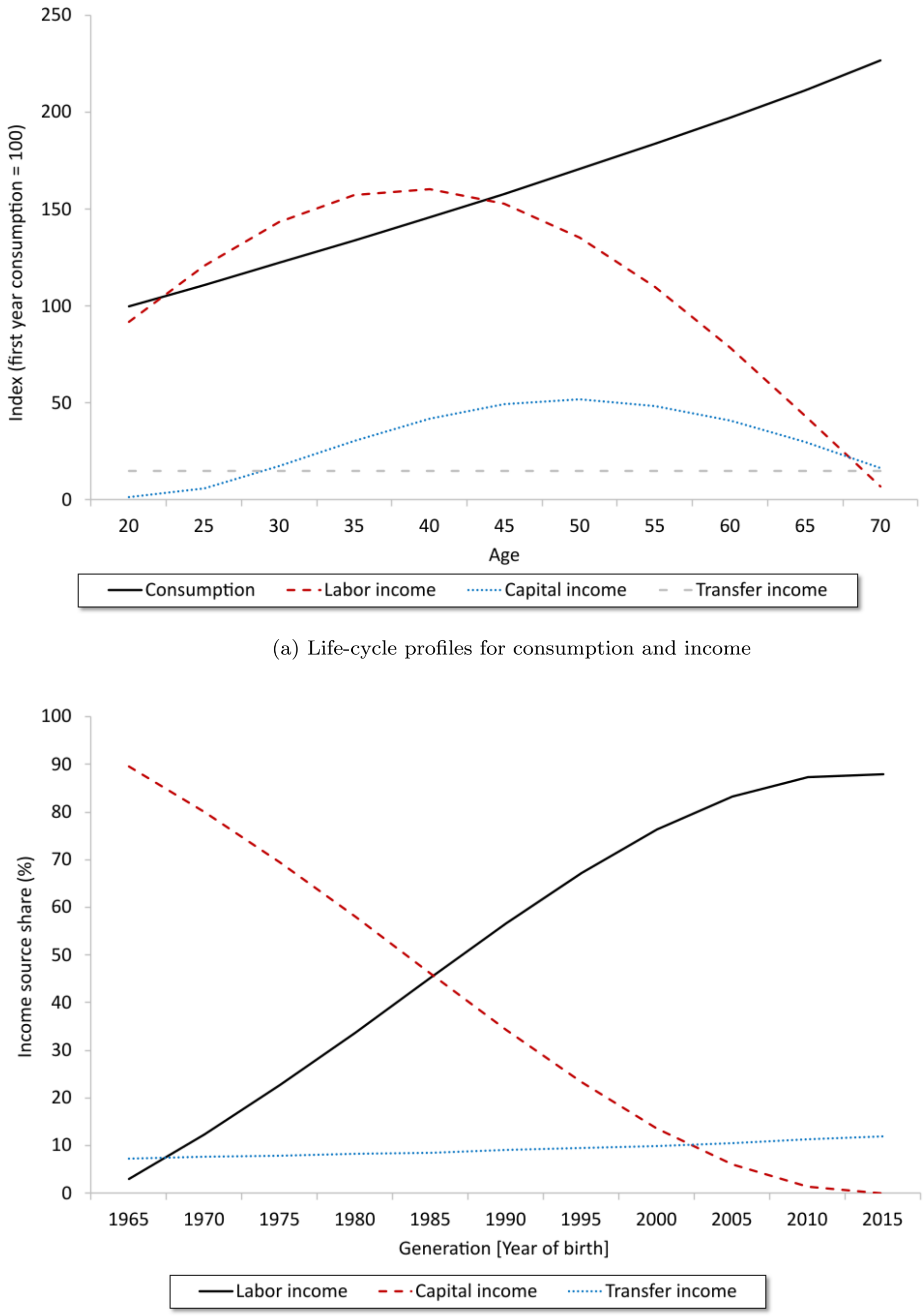
E. Calibrated Life-Cycle Behavior

Panel (a) of Figure 1 shows the calibrated profiles for consumption and income over the life-cycle. Given a hump-shaped labor productivity profile over the life cycle and the desire to smooth consumption over the life span, households derive a high share of their income from labor at a young age and accumulate savings that are then consumed as labor productivity declines with age. Panel (b) of Figure 1 shows that this translates into substantial heterogeneity in terms of the composition of income by source. If the climate policy is implemented in 2015, generations born in or just before 2015 will derive most of their income from labor, while older generations will have a high share of capital income and a low share of labor income.

This has important consequences for the intergenerational impact of climate policy, which affects the relative price of capital and labor. Carbon pricing induces a shift from "dirty" fossil fuels to "clean" capital, raising the relative price of capital. Green technology policies that effectively subsidize capital-intensive "clean" energy technologies thus benefit today's old generations with high shares of capital income even more.

[14]Note that ω is a simple scaling factor with no economic significance. ρ is selected as the second calibration parameter as there is little evidence on what would constitute an appropriate value.

[15]Solving the model for longer time horizons does not produce different results, thus indicating that the model has been given enough time to settle on a new balanced growth path. To reduce computational complexity, we solve the model with a five-year time step.



(a) Life-cycle profiles for consumption and income

(b) Income shares by source for different generations

Figure 1. Calibrated life-cycle profiles and income source shares along steady-state reference path for current generations, i.e. born before the introduction of the climate policy.

Table 2. Overview of alternative technology and carbon tax policy designs

	Input tax λ	Output subsidy s	Recycling of carbon revenues
Technology policies $\mathcal{T}$			
Technology standard	Not proportional to CO_2 ($\lambda_t = \gamma p_t^{Credits}$)	$s_t = (1-\gamma)p_t^{Credits}$	None
Emissions intensity standard	Proportional to carbon ($\lambda_t = \gamma\kappa_e p_t^{Credits}$)	$s_t = p_t^{Credits}$	None
Carbon tax policies $\mathcal{C}$			
Flat recycling	CO_2 price ($\lambda_t = \kappa_e\tau_C$)	None	Equal per capita transfers
Labor tax recycling	CO_2 price ($\lambda_t = \kappa_e\tau_C$)	None	Labor income tax
Capital tax recycling	CO_2 price ($\lambda_t = \kappa_e\tau_C$)	None	Capital income tax

Notes: Technology policies $\mathcal{T}$ aimed at promoting "green" RE technologies comprise two types: a technology standard and an emissions intensity standard. Both standards are essentially a blending constraint which translates into an implicit input tax ($\tau^{\mathcal{T}}$) and output subsidy ($s^{\mathcal{T}}$) levied on energy firms. τ_C denotes a carbon tax.

III. The Computational Experiment

We compare carbon pricing and technology policies to a "no-climate policy" baseline under which CO_2 emissions are determined by the decentralized equilibrium decisions of firms and consumers without imposing any climate policy constraints. Table 2 provides an overview of the alternative climate policy designs we consider.

TECHNOLOGY POLICIES.—We consider two categories of technology policies $\mathcal{T}$ which are representative of sectoral policies typically enacted as "command-and-control" regulation in real-world policy. Focusing on the case of decarbonization of the electricity sector, where technology policy seeks to promote "green" RE technologies, the elements {*Technology standard*, *Emissions intensity standard*} $\in \mathcal{T}$ are defined as:

- *"Technology standard"*: mandates that a certain share of electricity must be generated from RE.
- *"Emissions intensity standard"*: mandates that every ton of CO_2 emissions must be offset by a minimum amount of electricity generated from RE.

The policy category *"Technology standard"* thus represents most of the regulatory approaches which have been used in the electricity sector to incentivize the expansion of RE. Such standards are essentially blending constraints which translate into implicit output subsidies for RE technologies and implicit input taxes in energy production to finance RE subsidies (Holland, Hughes and Knittel, 2009). By design, they are revenue neutral and entail a redistribution of economic rents from fossil-based to RE producers. Prominent examples include renewable or clean energy standards in the U.S., renewable energy quotas in Europe, but also more broadly subsidies for renewable energy which are financed through an excise tax on electricity.[16]

Consider the case of an RE quota which mandates that at each point in time t a certain share γ_t of total electricity supplied has to come from RE (wind and solar) resources—adding the following constraint to the equilibrium model described in Section I:

$$\underbrace{\sum_{p \in \{Wind,Solar\}} Y_{pt}}_{=\text{Supply of RE credits}} \geq \underbrace{\gamma_t \sum_{i \in \{Electricity, Wind, Solar\}} Y_{it}}_{=\text{Demand for RE credits}} \qquad (p_t^{Credits}) \,. \tag{25}$$

The RE quota can be conceived as a system of tradable credits where $p_t^{Credits}$ corresponds to the post-trading equilibrium price of a credit determined by credit supply and demand.

A tradable RE standard is by definition revenue-neutral: expenses for RE subsidies are fully financed through implicit input taxes $\tau_t^{Technology\ standard}$ on energy producers. Output subsidies are paid to RE firms which receive one credit valued at price $p_t^{Credits}$ for each unit of electricity produced. From (25) it then follows that the implicit per-unit tax under an RE quota, which enters in the firm optimization problem (12), is:

$$\lambda_t^{Technology\ standard} = \gamma p_t^{Credits} \,. \tag{26}$$

The interpretation is that all energy firms have to hold γ credits for each unit of electricity produced. Because RE firms also receive one credit per unit of electricity, their effective net support per unit of electricity produced, which enters in the firm optimization problem (7), is:

$$s_t^{Technology\ standard} = p_t^{Credits} - \gamma p_t^{Credits} = (1-\gamma) p_t^{Credits} \,. \tag{27}$$

The second policy category *"Emissions intensity standard"* considers a more refined type of technology policies which entails the idea that the regulator mandates that CO_2 emissions have to be compensated or offset by a certain amount of energy supplied from RE sources. Such a technology policy is an RE support scheme with "polluter-pays refinancing": the expenses for RE subsidies are entirely refinanced by levying production input taxes on fossil-based electricity firms which are proportional to the carbon intensity (Abrell, Rausch and Streitberger, 2019).

It can also be conceived as a system of tradable certificates for "green" electricity

[16]For example, feed-in tariffs or market premiums in Germany and Spain (Abrell, Kosch and Rausch, 2019). While these technology policies support categories of technologies that are considered "clean" or carbon-neutral (e.g., wind and solar power plants), they are "blunt" instruments when it comes to mitigating CO_2 emissions because they do not differentiate between the CO_2 intensity of "dirty" electricity technologies. For example, a coal-fired power plant is implicitly subject to the same input tax as a much cleaner natural gas-fired power plant (Abrell, Rausch and Streitberger, 2019).

(offsets) according to:

$$(28) \qquad \underbrace{\sum_{p \in \{Wind, Solar\}} Y_{pt}}_{=\text{Supply of green offsets}} \geq \underbrace{\gamma_t \sum_{n \in \{Electricity} \sum_e \kappa_e Z_{ent}}_{=\text{Demand for green offsets}} \qquad (p_t^{Credits}) \; .$$

γ represents here the "offset intensity", i.e. the minimum amount of green energy required to offset overall CO_2 emissions from fossil-based electricity production, which is chosen by the regulator. Here, $p_t^{Credits}$ indicates the value of a tradable green offset certificate. In an energy system where RE is relatively abundant, $p^{Credits}$ is small; it is zero if all energy comes from green sources. If fossil fuels are still the dominant sources of energy supply, $p_t^{Credits}$ is large and provides an incentive for RE producers to increase their supply.

Analogously to the case of an RE quota, the implicit input tax per MWh of electricity produced with fossil fuel e under a revenue-neutral green offset standard is:

$$(29) \qquad \tau_{et}^{Intensity\ standard} = \gamma \kappa_e p_t^{Credits} \; .$$

A green offset policy is thus an RE support scheme with polluter-pays refinancing: the expenses for RE subsidies are entirely refinanced by levying production input taxes on fossil-based electricity firms which are proportional to the carbon intensity. This implies that RE firms with zero emissions receive a net support equal to the credit price:

$$(30) \qquad s_t^{Intensity\ standard} = p_t^{Credits} \; .$$

DIRECT CARBON PRICING AND REVENUE RECYCLING.—We consider carbon tax policies $\mathcal{C}$ that involve a constant carbon tax over time under the following alternative ways of recycling the additional revenues from the tax increase. Let $\mathcal{R}$ denote the set of revenue-recycling options:

- *"Flat recycling"*: annual revenues are returned lump-sum in equal amounts per capita to every household alive in that year.
- *"Labor tax recycling"*: annual revenues are returned by lowering the labor income tax rate in that year.
- *"Capital tax recycling"*: annual revenues are returned by lowering the capital income tax rate in that year.

We refer to a carbon tax with flat recycling as a "plain vanilla" carbon pricing option as it is representative of what has already been implemented or is broadly discussed in a large number of countries either (see, for example, World Bank, 2021). Revenue recycling options based on a reduction in income tax rates have so far been discussed intensively, but mainly in the academic literature (Goulder, 1995; Bovenberg and Goulder, 1996; Goulder et al., 1999; Barrage, 2020).

POLICY STRINGENCY.—An important dimension of our analysis is to investigate how the policy comparison depends on the level of policy stringency. We consider different carbon tax rates τ_C, expressed in 2012 US$ per ton of CO_2, of $\{5, 25, 50, 75, 100, 125\} \in \mathcal{S}$ which correspond to $\{3, 12, 20, 27, 31, 35\}$ percent of annual economy-wide CO_2 emissions reductions relative to the "no-climate policy" baseline, respectively. The set of carbon tax policies is thus given by $\mathcal{C} = \mathcal{R} \times \mathcal{S}$. The carbon tax rate enters the firm optimization problem in (12) according to:

$$\lambda_t^{Carbon\ tax} = \kappa_e \tau_C \,. \tag{31}$$

EXOGENOUS CO_2 TARGETS AND EQUAL-YIELD CONSTRAINT.—As we do not value the benefits from changes in environmental quality (i.e. CO_2 emissions), and focus exclusively on the economic costs of climate change mitigation, we require that technology policies achieve the same year-on-year emissions reductions as are achieved under carbon pricing. This enables a meaningful welfare comparison between technology and carbon pricing policies.

Given that government spending is exogenous in our model, we use an equal-yield constraint for each period that requires real government spending to be maintained at its baseline level. We endogenously determine the equilibrium value of the recycling instrument (i.e. lump-sum transfers or income taxes) in each period to satisfy this equal-yield constraint.

IV. Green Technology vs. Carbon Pricing Policies: Intergenerational Welfare Effects

This section examines and compares the intergenerational incidence of carbon pricing and green technologies. We first focus on the impacts of a carbon tax under alternative revenue recycling options and then compare it to green technology policies.

A. Alternative Carbon Tax Policy Designs

Figure 2 shows the utility change by generation, identified by birth year, for alternative climate policy designs measured as the equivalent variation expressed in percent of remaining lifetime income (including leisure) in the absence of climate policy. The following key findings emerge:

"Plain vanilla" carbon tax places much lower burden on the current than on future generations: For a "plain vanilla" carbon tax with flat recycling, current old generations incur the lowest welfare costs, while the lifetime welfare cost for subsequent generations steadily increase: today's middle-aged and young generations are worse off compared to the today's old, and future generations experience even greater welfare losses. A carbon tax induces a switch towards capital-intensive RE technologies and hence implies that the relative price of capital to labor increases.

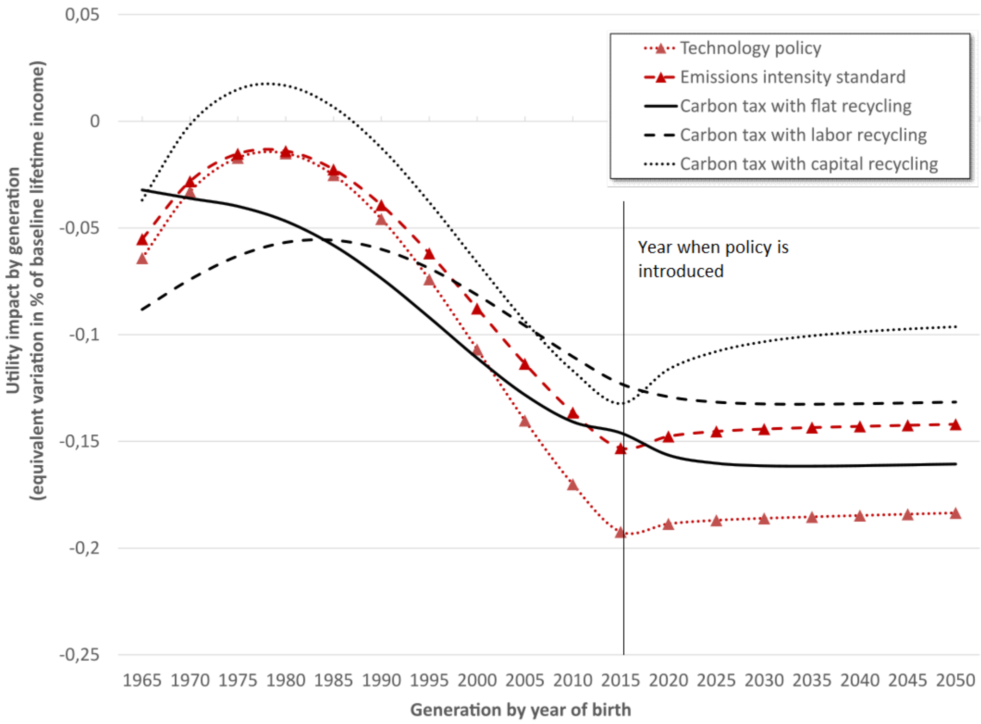


Figure 2. Utility impact by generation for a $50 carbon tax and alternative technology policies with identical year-on-year emissions reductions.

Notes: The figure shows the utility change by generation, identified by birth year, for alternative climate policy designs measured as the equivalent change in percent of lifetime income without climate policy. The results presented assume that a constant carbon tax of $50 per ton of CO_2 emissions is implemented in the electricity sector starting in model year 2015. Technology policies are specified so that the same year-on-year emissions reductions are achieved. Results are for the model with pre-existing income tax distortions.

It is the current old with relatively large capital assets, accumulated through life-cycle savings, who benefit more from this effect than the current middle-age and young generations with smaller savings and higher shares of labor income (compare also with Figure 1). Future generations are worse-off as they do not benefit from this initial "capital endowment effect".

Efficiency gains from income tax recycling make current and future generations better off: The importance of heterogeneity in age-specific income composition becomes even more apparent when carbon tax recycling is varied. A carbon tax with recycling via lower labor income taxes places the least burden on today's middle-aged generations, while leaving today's elderly and future generations worse off. The reason for this is that, unlike today's middle-aged generations, today's elderly receive little labor income and therefore do not benefit as much from the reduction in after-tax wages. At the same time, all current generations hold capital assets (i.e., claims on the initial capital endowment; see $\overline{k}_g$ in (3)). This means that they are better off compared to future generations when the relative price of capital increases. The efficiency gains from using carbon revenues to reduce distortionary income taxes result therefore in most current and future generations being better off. The exception, however, is the use of taxes on labor income, as this would leave today's old generations worse off.

Carbon pricing with capital tax recycling produces similar intergenerational incidence as green technology policy: A carbon tax with capital income tax recycling results in a similar pattern (but not level) of intergenerational incidence as green technology policies: today's old and middle generations bear lower welfare costs, while today's young and future generations bear higher welfare costs. Because RE production is capital intensive, green technology policies act as an effective subsidy to capital, which creates the same effects as a reduction in the capital income tax. The current old and middle generations enjoy the direct benefits because they derive a large portion of their income from capital assets and thus enjoy the appreciation of those capital assets. The indirect benefit comes from increased investment, as a reduction in the capital income tax stimulates investment and reduces the existing income tax distortion associated with capital, which in turn increases efficiency and economic growth. These effects compound over time, so that future generations benefit more than today's young people, who do not live long enough to reap the longer-term benefits of effectively subsidizing capital.

B. Green Technology Policies vs. Carbon Pricing

Figures 3 and 4 provide, in addition to Figure 2, a comparison of the intergenerational incidence of technology and carbon pricing policies for different levels of policy stringency. Each figure shows the utility change by generation relative to the "plain vanilla" carbon tax with flat recycling. A value below one means that the utility loss (gain) for a given generation and climate policy is smaller (larger) than under the "plain vanilla" carbon tax.

It is evident that there is a large heterogeneity in utility impacts which depends on four main factors: the design of the technology policy, the choice of recycling revenues under a carbon tax policy, policy stringency, and the birth year of the household. The following summary of key findings substantiates this broader insight:

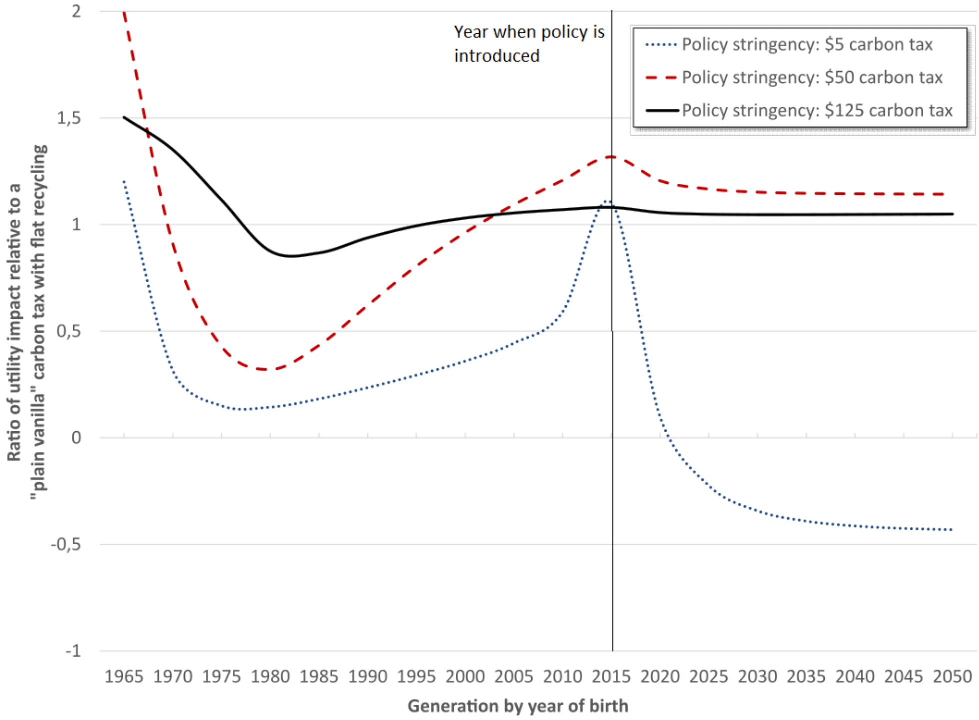
Similar outcomes at high policy stringency: With a high degree of policy stringency, all policy approaches yield a broadly similar pattern of intergenerational incidence (see the black solid lines corresponding to a carbon tax of $125 per ton of CO_2). The reason is two-fold. At high CO_2 emission reductions, the relevant substitution margin is between RE and fossil fuels, but not between fossil fuels with different CO_2 intensities (for example, coal and natural gas). Fossil fuels are increasingly replaced by RE. Hence, the advantage of a direct carbon price to alter the relative prices between different types of fossil fuels diminishes, while a technology subsidy can affect the relative price between fossil fuels and renewables just as much. Moreover, with higher emissions reductions, carbon revenues available for recycling purposes decrease, dampening the carbon price option's advantage of generating efficiency gains from reducing distortionary income taxes.

Gains for current population under green technology policy at low to medium policy stringency: At low to medium policy stringency, green technology policies significantly outperform a "plain vanilla" carbon tax on the basis of welfare effects for current generations (see panels (a) and (b) in Figure 3 and the blue dashed and red dotted lines corresponding to a carbon tax of \$5 and \$50 per ton of CO_2, respectively). Such climate policies promote capital-intensive green technologies, thus effectively subsidizing the use of capital. This, in turn, boosts the capital demand and increases after-tax returns to capital owners. Since current generations, and especially the current old, own a disproportionate amount of capital, the gains from such a policy accrue predominantly to these households, making them better off compared to a "plain-vanilla" carbon tax, where the gains are less concentrated on capital.[17]

Design of green technology policy matters for medium to high policy stringency: Whether and to what extent future generations benefit from a green technology policy compared to a "plain-vanilla" carbon tax depends on two factors. On the one hand, the benefit of a green technology policy that offsets pre-existing distortions associated with capital income taxation is large if the policy stringency is sufficiently low (i.e., a carbon tax of \$5 per ton of CO_2). Both technology policies then perform better for each generation (see Figure 3). On the other hand, the more stringent the policy, the smaller the efficiency gain from reducing this tax distortion. In this case, the design of the green technology is important: future generations are better off compared to a "plain vanilla" carbon tax only with an emissions intensity standard. The technology standard results in higher welfare losses for future generations compared to the carbon tax because it does not provide sufficient incentives for fuel switching from coal to natural gas. A smart design which incorporates a polluter-pays principle thus contributes to the attractiveness of of green technology policy for the current population.

Carbon pricing with capital tax recycling dominates green technology policy for current and future generations, but labor tax recycling creates ambiguity: A comparison of Figures 3 and 4 shows that a carbon tax with capital income tax recycling outperforms technology policies for all generations. However, when carbon revenue recycling is done through the labor income tax channel, the picture is mixed: current generations would prefer a technology policy over a carbon tax, while future generations would be better off with a carbon tax.

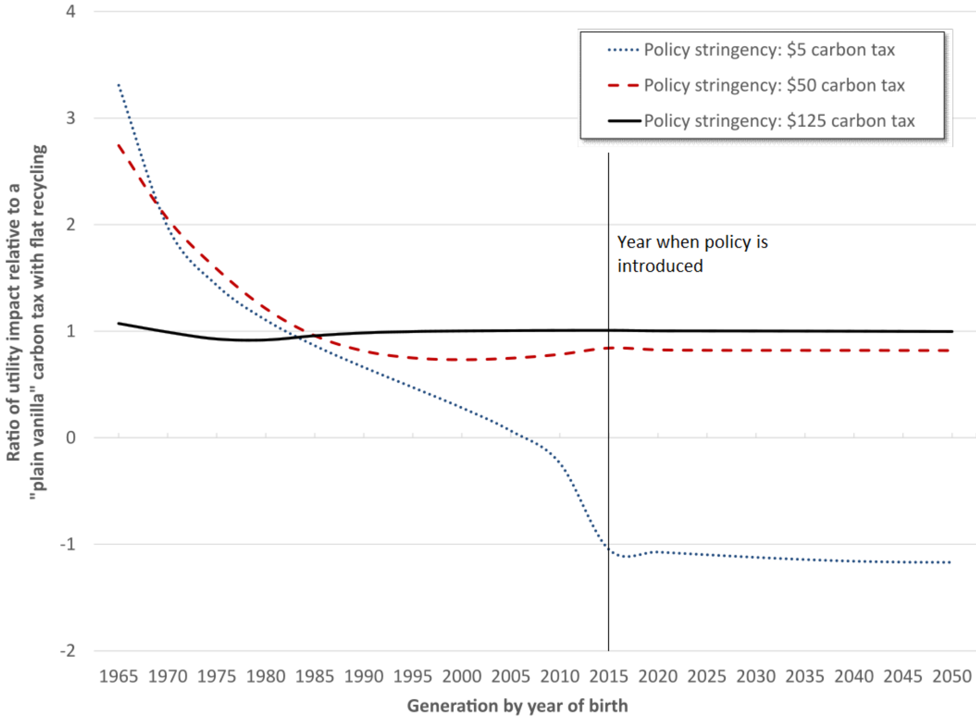
[17]At low stringency, future generations are also better off under a green technology policy because such a policy reduces factor market distortions due to pre-existing income taxes. This is consistent with the results of Goulder, Hafstead and Williams III (2016) in a Ramsey growth model with infinitely-lived agents.



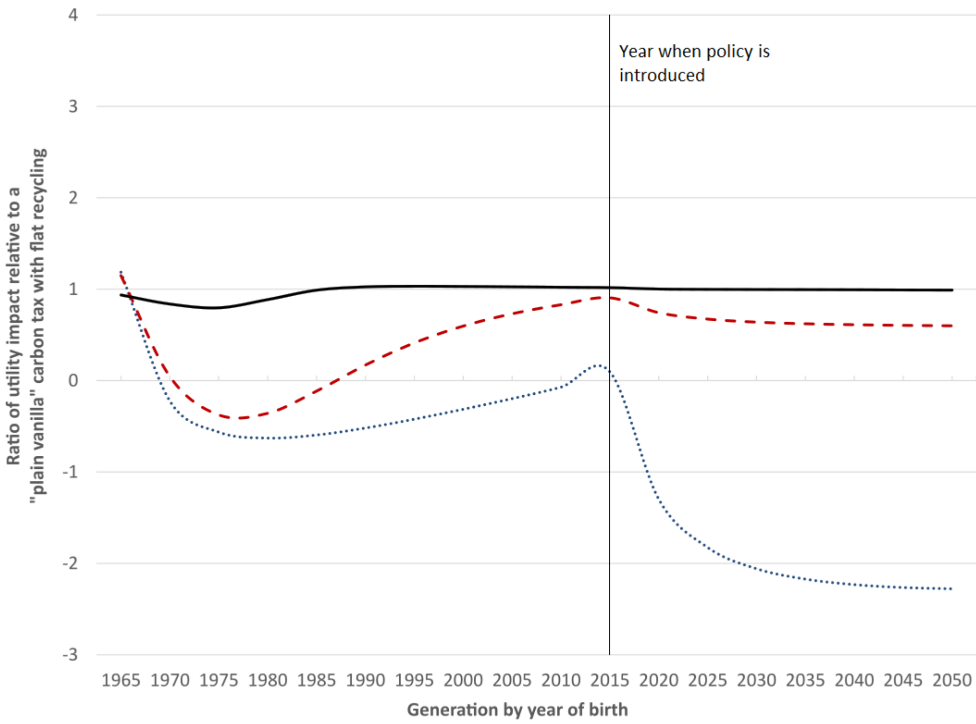
(a) Technology standard.

(b) Emissions intensity standard.

Figure 3. Utility impact by generation for alternative technology policies & stringency relative to "plain vanilla" carbon tax with flat recycling.



(a) Carbon tax with labor recycling.



(b) Carbon tax with capital recycling.

Figure 4. Utility impact by generation for alternative carbon tax policies & stringency relative to "plain vanilla" carbon tax with flat recycling.

V. Green Technology Policies vs. Carbon Pricing: Two Social Welfare Perspectives

Based on the intergenerational distribution of utility impacts, we next compare the alternative climate policy designs from a social welfare perspective. First, we consider a utilitarian social welfare perspective which aggregates the utility impact of each generation with equal weights. Second, we look at the societal preference for alternative policy approaches through the lens of majority voting. We assume that at a given point in time each generation alive can cast a vote for or against a policy based on his expected utility from the remaining lifetime. This second perspective emphasizes that the acceptance for a particular policy approach is based solely on how it affects the well-being of the current population.

A. *Utilitarian Social Welfare Perspective*

Figure 5 compares the green technology and alternative carbon tax policies adopting a utilitarian social welfare perspective. Formally, we follow Jensen and Rutherford (2002) and define social welfare as:

$$\mathcal{W} = \left(\sum_{g=-N}^{\infty} \bar{Y}_g u_g^{\rho} \right)^{1/\rho}$$

where $\bar{Y}_g$ is the remaining lifetime full-income at present value in the "no-climate policy" baseline and ρ is an social inequality aversion parameter. The weights $\bar{Y}_g$ account for population growth and the market interest rate but do not entail additional social discounting. The utilitarian case corresponds to $\rho = 1$. Policy performance is shown relative to the "plain vanilla" carbon tax with flat recycling for different levels of policy stringency. The following insights emerge:

Without distortionary income taxation, carbon pricing is always preferred to green technology policies: Technology policy measures (i.e., the gray solid and dashed lines) always lead to higher welfare costs in an environment without income taxation, regardless of the stringency of the measures. This is not surprising, since technology policies work by subsidizing capital but do not put an explicit price on carbon. Thus, in the absence of tax distortions in capital and labor markets, a carbon tax minimizes the utilitarian social welfare costs of reducing CO_2 emissions. The emissions intensity standard performs better than the technology standard because it finances the implicit production subsidies for RE technologies through an implicit input tax on "dirty" production that is proportional to CO_2 emissions. CO_2 emissions.

Distortionary income taxes reverse the policy ranking at low policy stringency: Consistent with previous studies, a technology standard (black solid line) can achieve the same amount of emissions reductions at a lower welfare cost in an environment with distortionary income taxes (Goulder, Hafstead and Williams III,

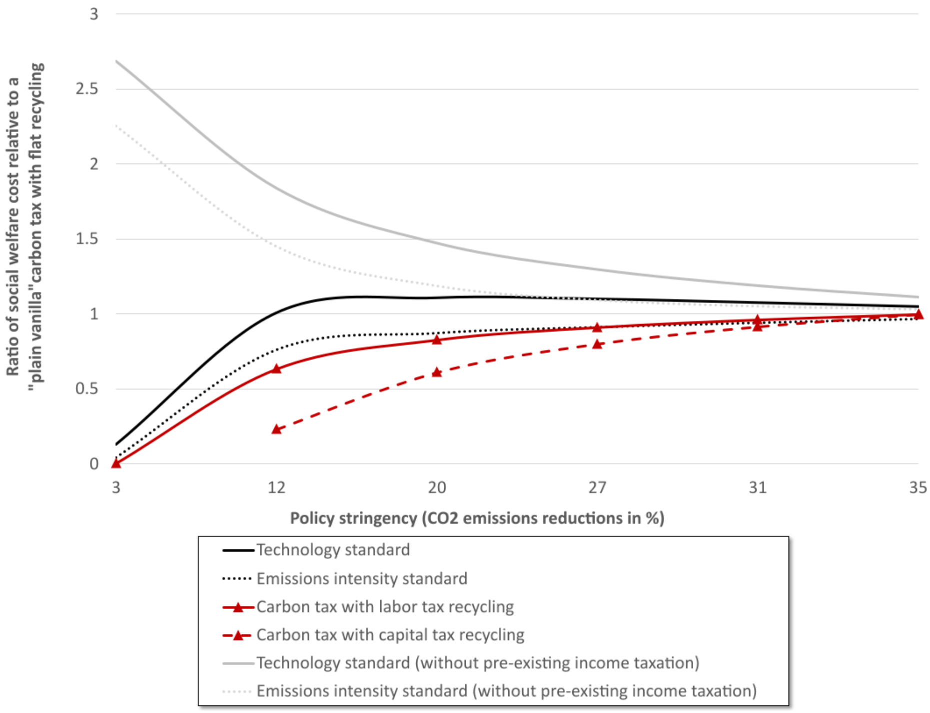


Figure 5. Utilitarian social welfare comparisons of alternative climate policies $\mathcal{T}$ and $\mathcal{C}$.

Notes: The figure shows the welfare cost ratio which is defined as the percentage change in utilitarian welfare under a particular policy relative to the percentage change in utilitarian welfare under a carbon tax with flat recycling (i.e., no income tax recycling). A ratio lower (higher) than 1 means that a policy is less (more) costly than a carbon tax with flat recycling. The alternative levels of policy stringency $\mathcal{S} = \{5, 25, 50, 75, 100, 125\}$ correspond to the different carbon tax rates, expressed in 2012US$. Technology policies $\mathcal{T}$ are designed to deliver the same year-on-year emissions reductions to ensure comparability. Unless otherwise specified, the cases shown here refer to the model with pre-existing income taxation.

2016). By effectively subsidizing capital, the technology standard mitigates the deadweight loss of income taxation, which outweighs the direct and higher carbon abatement costs of using only an indirect instrument if emissions reductions are sufficiently small. This relationship reverses under a more stringent policy if the efficiency loss from not directly pricing carbon outweighs the gains from reducing income tax distortions.

"Polluter-pays" design of of green technology policies increases social welfare: Smarter design of technology policy based on the polluter-pays principle can further reduce welfare costs and ensure that technology policy works better than a "plain-vanilla" carbon tax. However, based on the utilitarian welfare perspective, the emissions intensity standard (black dotted line) does not perform better than a carbon tax policy that uses carbon revenues to capture the benefits from income tax recycling-regardless of the stringency of the policy. The intuition is clear: on

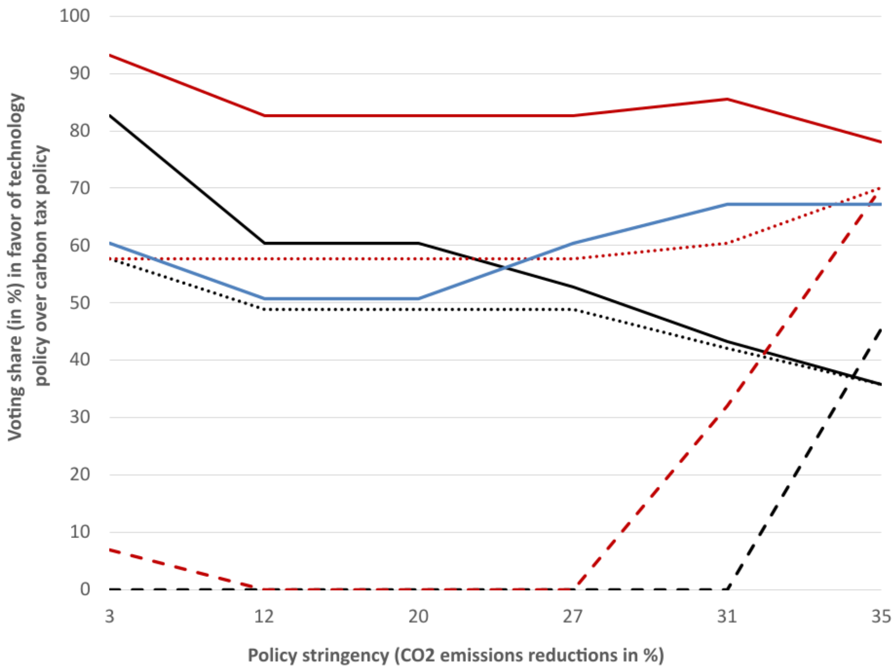


Figure 6. Share of votes by current generations for technology policies over carbon tax policies.

Notes: The figure shows the share of votes by current generations, adjusted for population size and age-specific voter turnout (U.S. Census, 2016), in favor of a particular technology policy over alternative carbon tax policy designs based on utility impacts of current generations for alternative levels of policy stringency. For any pair of policies $(\mathcal{C}, \mathcal{T})$, the generation vote is given to the policy that provides a higher benefit. Color code indicates the technology policy $\mathcal{T}$: **black**=*Technology standard*, **red**=*Emissions intensity standard*. The dash type indicates the type of revenue recycling associated with the carbon tax policy $\mathcal{R}$: ——=*Flat recycling*, ⋯⋯=*Labor tax recycling*, - - -=*Capital tax recycling*. All cases shown refer to the model with pre-existing income taxation, with the exception of the **blue line** which summarizes the case of both technology policies in a setting without distortionary income taxation.

the carbon pricing side, the emissions intensity standard cannot do better than an explicit carbon tax, and the constraint on mixing production subsidies and input taxes also means that the benefits from mitigating income tax distortions are smaller.

B. Societal Preferences for Climate Policy Approaches based on Majority Voting

Figure 6 shows the share of votes of generations alive at the time of the policy's introduction that favor a particular technology policy relative to the carbon tax policy. The vote for each generation is adjusted for population size and age-specific voter turnout (U.S. Census, 2016). For any policy pair $(\mathcal{C}, \mathcal{T})$, a vote in favor of either policy is given if it yields higher (remaining lifetime) utility.

Societal preference for green technology policies based on majority voting (in *contrast to utilitarian perspective):* It is evident that technology policies, even those which perform poor in terms of a utilitarian welfare perspective, can have a large support in the current population. The level of support, however, depends on the specific design aspects of technology policy and carbon tax policy, as well as the stringency of the policy. Consider emissions reductions up to 20%. The main insight here is that, unless a carbon tax policy is combined with capital income tax recycling (dashed lines), all technology policies are supported by voting shares of 50% and higher. The voting shares range between 60-90% if a technology policy is compared to a "plain-vanilla" carbon tax which forgoes efficiency gains from revenue recycling, and slightly decrease if carbon revenues are recycled through labor income taxes (dotted lines). A "smart" polluter-pays design of technology policies which implicitly taxes carbon (red lines) significantly increases the voting share relative to a "blunt" technology standard as it enhances the carbon abatement efficiency.

Policy design matters more than instrument choice at high policy stringency: For higher levels of policy stringency (i.e., emissions reductions in excess of 20%), Figure 6 underscores the point that not instrument choice but policy design matters. As emissions reductions increase, the efficiency costs of a badly designed technology policy, i.e. the technology standard, increasingly dominate for current generations the benefits from implicitly subsidizing capital income. Thus, comparing the technology standard to a carbon tax policy with flat or labor income tax recycling (black solid and dotted lines), it loses support. Instead, supporting RE technologies through a "smart" polluter-pays policy design, establishes an implicit carbon price signal while still subsidizing clean capital, which translates into high voting shares of 60-80% (red solid and dotted lines). Notably, such a technology policy compares favorably to a carbon tax policy that uses carbon revenues to reduce the high burden of capital taxation (red dashed line). This is because as policy stringency increases, the revenue available for recycling under a carbon tax policy decreases, effectively limiting the scope for exploiting efficiency gains from lowering capital income taxes.

Green technology policy is socially preferred over carbon pricing in an environment without distortionary income taxation: Figure 6 bears out another important insight. Even in the absence of pre-existing income tax distortions, technology policies can be superior to a carbon tax, if the societal assessment is based on majority voting. The blue line summarizes the case which compares both technology policies $\mathcal{T}$ to a carbon tax with flat recycling. Regardless of policy stringency, both technology policies receive support rates in the 50-70% range. For high emissions reductions of about 30%, all types of carbon tax policies as well as "blunt" technology standard are outperformed by a "smart" polluter-pays design of green technology policy. Again, this is in stark contrast to a policy assessment which adopts a utilitarian welfare perspective.

VI. Conclusions

This study revisited the issue of policy instrument choice between "command-and-control" technology policies and carbon pricing for climate change mitigation in an overlapping generations framework. The established view is that a carbon price is the most cost-effective approach, preferable to a green technology policy. This contrasts with the popularity of green technology policy in real-world policymaking. Our analysis provided a novel explanation for this observation: gains that predominantly accrue to households with large capital assets and that influence majority decisions in favor of technology policy over carbon pricing.

We have argued that the established view that carbon pricing is superior requires a utilitarian social welfare perspective that values the welfare of future generations. The policy ranking is much less clear-cut when selfish generations care only about their own well-being and not that of their descendants. We demonstrated that the majority of the population alive when the climate policy is put in place prefers green technology policies over carbon pricing. Importantly, this societal preference for green technology policies does not depend on the presence of distortionary income taxes (an argument which has been made before to rationalize green technology policy).

Instrument choice is ultimately instrument design, so the policy ranking naturally depends on how the particular regulatory approach is fleshed out. We showed that "poorly" designed green technology policies that provide inadequate incentives for carbon abatement result in large utility losses for the current population compared to carbon tax policies that are highly efficient at recycling carbon revenues (for example, through reducing distortionary income taxes). "Smart" policy designs, however, which finance the subsidies for green energy technologies based on the the "polluter-pays" principle receive very high support (about 90%) among the current population.

We argued that our findings have important implications for the design of climate policy. Since the transition to a carbon-neutral economy will inevitably involve extensive substitution of "clean" capital for "dirty" fossil energy, it is critical for climate policy to consider the social valuation of utility impacts created through effects on capital income. If the current society does not care (enough) about future generations, our analysis suggests that climate policy approaches which directly incentivize the use of "clean" capital, rather than penalizing the use of "dirty" fossil energy through a carbon price, might find easier support. In any case, the choice and design of policy instruments for climate change mitigation requires going beyond a mere partial equilibrium concept of carbon abatement efficiency. This paper showed that it is of paramount importance to consider the general equilibrium and life cycle effects of climate policy on capital income.

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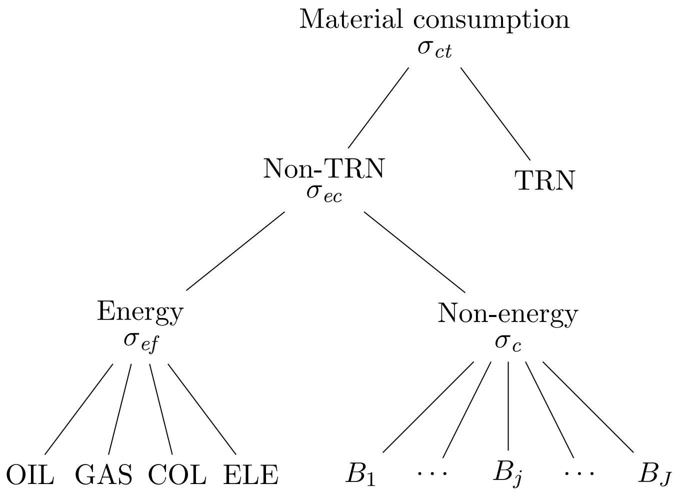

Figure A1. Structure of private material consumption.

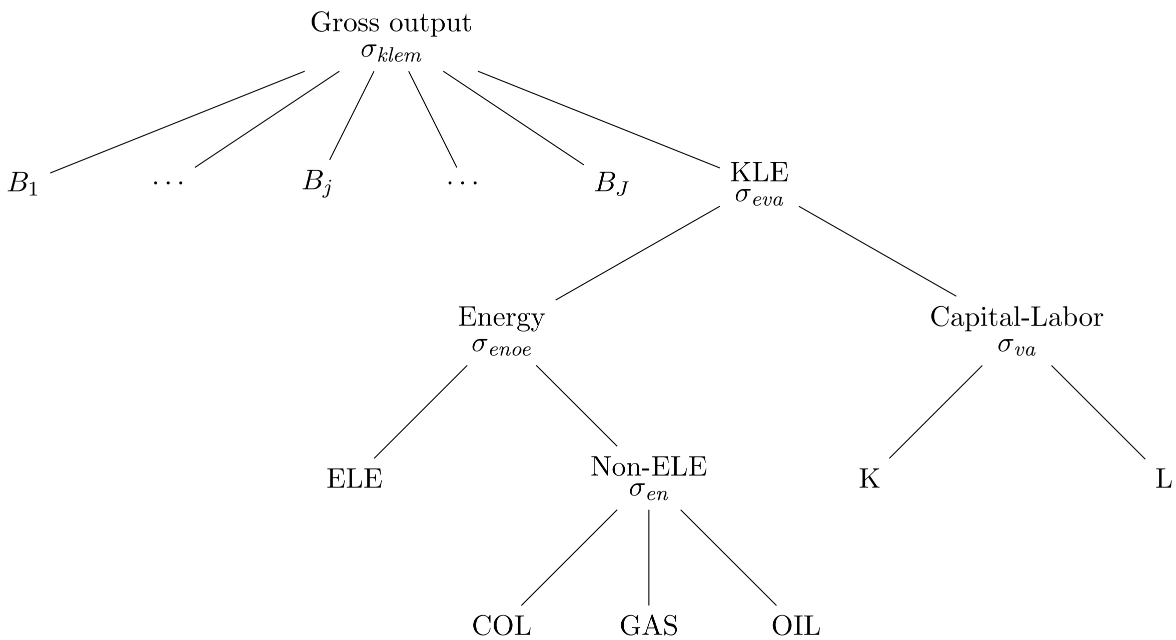

Figure A2. Production structure for final goods non-energy sectors $g \in G =\{$AGR,EIS,TRN,SRV,MAN$\}$ and refining of crude oil $c \in C =\{$OIL$\}$.

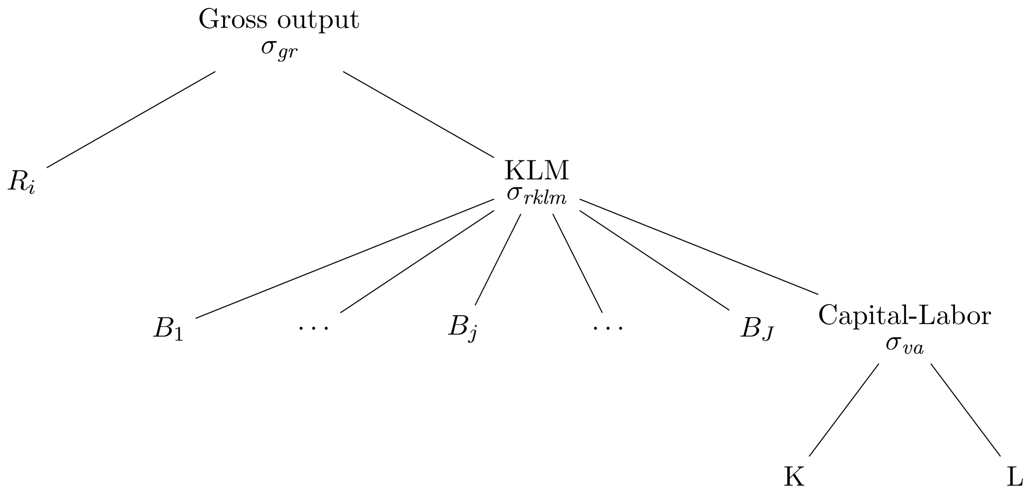

Figure A3. Production structure of energy resource sectors $f \in F \subset P\{$COL,CRU,GAS$\}$.

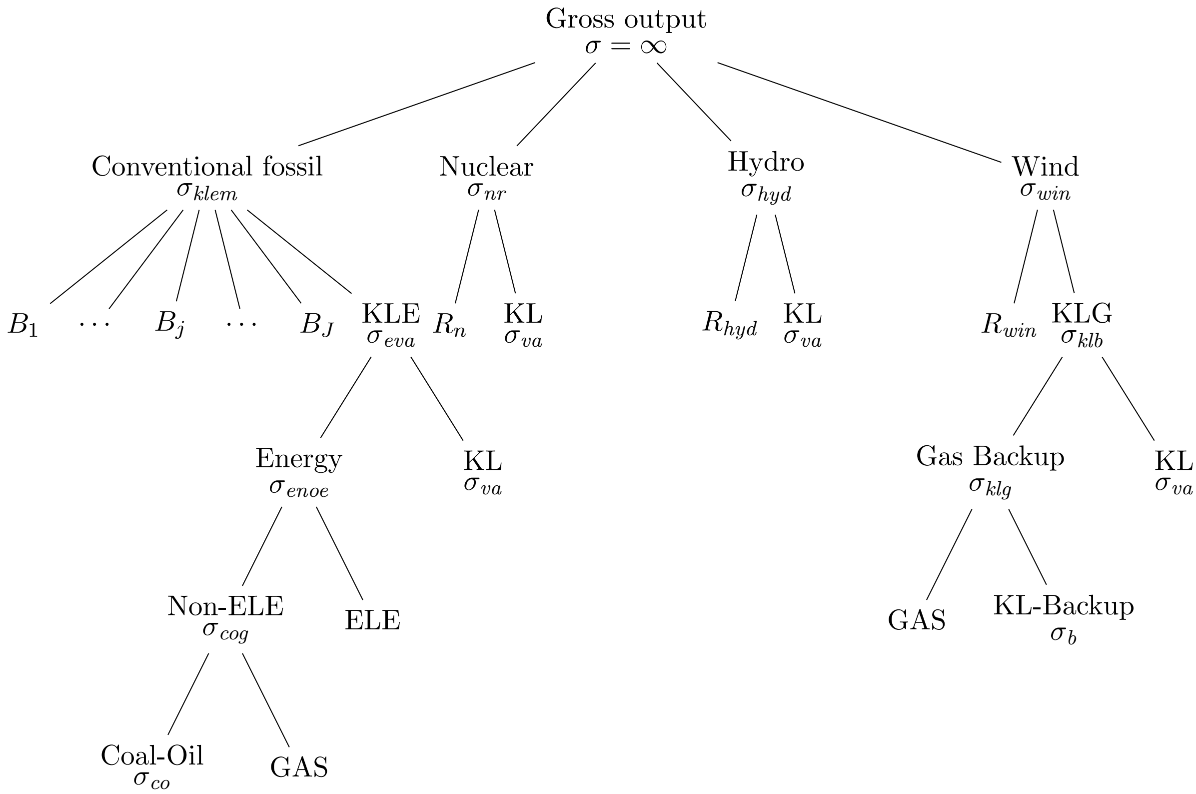

Figure A4. Production structure of fossil-based electricity $l \in L =\{$ELE$\}$ and electricity generation from nuclear, hydro, and wind and solar resources $r \in R \subset P$.

Table A1. Elasticity of substitution parameters 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_{rnw}	Resource—Capital/labor/energy/materials in renewable ELE	*Calibrated*
σ_{nr}	Resource—Capital/labor/energy/materials in nuclear ELE	*Calibrated*
σ_{am}	Materials in AGR	0[a]
σ_{ae}	Energy/electricity—materials in AGR	0.3[a]
σ_{er}	Energy/materials—land in AGR	0.6[a]
σ_{erva}	Energy/materials/land—value-added in AGR	0.7[a]
σ_{rklm}	Capital/labor/materials—resource in primary energy	0[a]
σ_{gr}	Capital/labor/materials—resources	*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	GTAP, version 9
σ_i^M	Across foreign origins	GTAP, version 9
σ	Intertemporal elasticity of substitution	0.5
σ_{cl}	Leisure—material consumption	0.8
α	Weight on material consumption in full consumption	0.6

Note: [a]Parameter values are taken from Paltsev et al. (2005*b*).

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