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# DISCUSSION PAPER

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## Green Technology Policies Versus Carbon Pricing: An Intergenerational Perspective

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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 diffusion of new technologies (Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012).[1] Second, because technology

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[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

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 prevailing view that carbon pricing outperforms technology policy is based either on static models or on intertemporal models with infinitely-lived representative agents.[3] Our analysis suggests a different answer. By providing incentives 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.[4] This benefits today's generations of households with relatively large capital assets (which were accumulated

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

[4]Renewable power generation exhibits higher capital cost as compared to coal- and gas-fired power generation. For OECD countries, the capital cost of renewable power generation is 7 and 4 times higher than for power generation based on coal and gas, respectively (IEA, 2015). For the US, the capital cost of both onshore wind and solar power generation are estimated to be more than 3 times higher than for natural gas power generation EIA (2021). Moreover, since renewable power generation does not include much of fuel cost, capital cost become even more important. The capital cost share of renewable power generation is more than 2.5 times higher than for coal-fired generation (IEA, 2015) and 3-3.5 times higher than for gas-based generation (IEA, 2015; EIA, 2021).

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.[5]

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 substitution 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

[5]The analysis in this paper abstracts from intra-cohort household heterogeneity. A small but growing literature has examined the distributional effects by income groups of green technology policies (such as renewable energy portfolio or vehicle fuel-economy standards). Most studies fail to find that technology mandates have an advantage in achieving more progressive outcomes than energy or carbon taxes (for an overview, see Deryugina, Fullerton and Pizer, 2019) but also show that their costs are less salient (Davis and Knittel, 2019; Landis et al., 2019). Whether green technology policies are considered less or more socially favorable based on their distributional effects within a cohort remains an open question. This paper fills a gap by focusing on the inter-generational effects that have not been studied previously.

(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).[6] 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.[7] 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 environmental 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 a simple OLG model to illustrate the key mechanisms of how green technology policy and a carbon tax affect firms' responses and intergenerational incidence. Section II describes the quantitative framework, and Section III presents data and model calibration. Section IV describes the computational experiment to compare the alternative climate policy approaches. Section V examines intergenerational incidence and Section VI evaluates the different policies from a social welfare perspective. Section VII concludes.

## I. A Simple Model

This section presents a simple analytical model that illustrates the economic effects of a green technology versus a carbon pricing policy. We consider an OLG setting with two period-lived agents where energy is produced from a dirty and a clean sector. The clean sector (for example, wind or solar power) emits no emissions and is characterized by a high capital intensity compared to the dirty sector (for example, fossil-based energy). The model is a special case of our numerical model in Section II and provides some intuition for the main model mechanisms.

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

[7] 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.

## A. Economic environment

HOUSEHOLD ENDOWMENTS, PREFERENCES, AND BUDGET SETS.—Time is discrete and extends from $t = 0$ to infinity. In each period, a new generation or household[8] is born and lives for two periods. At any point in time, there is a young generation and an old generation. The initial old generation has one remaining year of life.[9] Only young generations work, inelastically supplying labor to the market at wage $w_t$. We normalize household size to $L_t = 1$ for each age cohort.

Households have preferences over consumption $c_t^y$, $c_{t+1}^o$. We assume logarithmic period utility $u(c) = ln(c)$. Households rank consumption according to:

$$\log(c_t^y) + \beta \log(c_{t+1}^o)\,, \tag{1}$$

where $\beta$ is the private discount factor.

The budget constraints in both periods of a household born in period $t$ are:

$$c_t^y + a_{t+1} = w_t + T_t^y \tag{2}$$

$$c_{t+1}^o = R_{t+1} a_{t+1} + T_{t+1}^o \tag{3}$$

where $R_{t+1} = 1 + r_{t+1}$ is the gross interest rate between period $t$ and $t+1$. Each member of the current old generation is additionally endowed with assets equal to $a_0$. $T_t^y$ and $T_t^o$ denote lump-sum transfers to young and old returning revenues from carbon pricing.

ENERGY PRODUCTION AND CLIMATE REGULATION.—Two sectors $i = \{clean, dirty\}$ produce energy services using capital in fixed proportions:

$$Y_{it} = K_{it}^{\alpha_i} L_{it}^{(1-\alpha_i)}\,. \tag{4}$$

$\alpha_i$ measures the capital intensity of energy production in sector $i$. The clean sector is more capital-intensive than the dirty sector when:

$$\alpha_{clean} > \alpha_{dirty}\,. \tag{5}$$

Capital and labor are fully mobile across sectors.

$CO_2$ emissions per unit of output in sector $i$ are $\theta_i$. Assuming that the clean sector does not generate emissions (i.e., $\theta_{clean} = 0$), economy-wide carbon emissions in period $t$ are given by: $E_t := \theta_{dirty} Y_{dirty,t}$.

$CO_2$ emissions can be regulated with a carbon tax $\tau$ or a green technology policy. The technology policy mandates that a certain fraction $0 \leq \sigma \leq 1$ has to be produced with

[8] We use "household" and "generation" interchangeably.

[9] Our model setup, except for introducing multiple sectors, $CO_2$ emissions, and different forms of climate policy, is similar to Krueger and Ludwig (2007) and Krueger, Ludwig and Villalvazo (2021).

clean energy:[10]

$$\frac{Y_{clean,t}}{\sum_i Y_{it}} \geq \sigma \,. \tag{6}$$

The same logic can be used to represent other types of quota instruments, such as efficiency and performance standards or mandates that target emissions intensity.[11]

Firms behave competitively in factor and product markets. Energy firm $i$ maximizes static profits, taking into account existing climate regulation ($\tau$,$\sigma$), the rental rate of capital $R_t$, wage rate $w_t$, output price $p_{it}$, and the energy output by other firms $Y_{-i}$. Given the technology policy constraint (6), the Lagrangians for the firms' profit maximization problems are:

$$\max_{K_{it},L_{it}} \; p_{it}Y_{it} - C(R_t, w_t, K_{it}, L_{it}) - \tau\theta_i Y_{it} + \lambda_t[Y_{clean,t} - \sigma(Y_{it} + Y_{-it})] \,, \tag{7}$$

where total factor cost are $C(R_t, w_t, K_{it}, L_{it}) = R_t K_{it} + w_t L_{it}$ and $Y_{it}$ has to satisfy production technology (4). $\lambda_t$ is the shadow value on the technology policy constraint.

Profit maximization of firms implies:

$$R_t = \tilde{p}_{it}\frac{\alpha_i Y_{it}}{K_{it}} \quad \forall i \tag{8}$$

$$w_t = \tilde{p}_{it}\frac{(1-\alpha_i)Y_{it}}{L_{it}} \quad \forall i \tag{9}$$

where $\tilde{p}_{it} = p_{it} - \tau\theta_i + \lambda_t(I_i - \sigma)$. $I_i$ is an indicator variable which is equal to one for the clean sector and zero otherwise.

FINAL GOODS, MARKETS, AND CAPITAL ACCUMULATION.—The final good which can be used for consumption and savings is a Cobb-Douglas aggregation of sectoral outputs:

$$\hat{Y}_t = \prod_i Y_{it}^{\gamma_i} \tag{10}$$

where $\sum_i \gamma_i = 1$. $\hat{Y}$ is the numeraire good. Cost-minimizing use of energy good $i$ in final good aggregation requires:

$$p_{it} = \frac{\gamma_i \hat{Y}_t}{Y_{it}} \,. \tag{11}$$

Given factor mobility across sectors, markets for rental capital and labor in a given

[10]This represents most of the regulatory approaches which have been used in the electricity sector to incentivize the adoption of RE. Prominent examples include renewable or clean energy standards in the U.S. (Holland, Hughes and Knittel, 2009; Cleary, Palmer and Rennert, 2019), renewable energy quotas in Europe, but also more broadly subsidies for renewable energy which are financed through an excise tax on electricity (for example, feed-in tariffs or market premiums in Germany and Spain (Abrell, Kosch and Rausch, 2019)).

[11]While the focus of our analytical model is on the case of a green energy quota, we explore alternative designs of green technology policies in our quantitative framework.

period clear if:

$$K_t = \sum_i k_{it} \tag{12}$$

$$L_t = 1 = \sum_i l_{it} \,. \tag{13}$$

(12) and (13) imply that at every period capital and labor inputs across sectors are priced uniformly, i.e. the marginal value products of capital and labor (see RHS of (8) and (9)), respectively, are equalized across sectors.

We assume that capital fully depreciates after its use in production. Capital thus accumulates according to:

$$K_{t+1} = a_{t+1} \,. \tag{14}$$

The market for final output clears if:

$$\hat{Y}_t = c_t^y + a_{t+1} + c_t^o \,. \tag{15}$$

We can now define the competitive equilibrium:

DEFINITION 1: *Given the initial conditions $a_0 = K_0$ and climate policies $\{\tau, \sigma\}$, a competitive equilibrium is an allocation $\{c_t^y, c_t^o, a_{t+1}, L_{it}, K_{it}\}_{t=0}^{\infty}$, prices $\{R_t, w_t, p_{it}\}_{t=0}^{\infty}$ and transfers $\{T_t^y, T_t^o\}_{t=0}^{\infty}$ such that*

1) *given prices $\{R_t, w_t, p_{it}\}_{t=0}^{\infty}$ and transfers $\{T_t^y, T_t^o\}_{t=0}^{\infty}$ for each, $t \geq 0$ $(c_t^y, c_t^o, a_{t+1})$ maximizes (1) subject to (2) and (3);*
2) *consumption $c_0^o$ of the initial old satisfies (3): $c_0^o = R_0 a_0 + T_0^o$;*
3) *given prices $\{R_t, w_t, p_{it}\}_{t=0}^{\infty}$ and policies $\{\tau, \sigma\}_{t=0}^{\infty}$ for each $t \geq 0$, $(L_{it}, K_{it})$ maximizes (7) subject to (4);*
4) *prices satisfy equations (8), (9), and (11);*
5) *the government budget constraint is satisfied in every period: $T_t = T_t^y + T_t^o = \tau E_t$ for all $t \geq 0$;*
6) *markets (12), (13), (14), and (15) clear.*

### *B. Analysis*

FIRMS' RESPONSES TO CLIMATE REGULATION.—To see how a green technology standard and carbon pricing affect the economy, consider first firms' output decisions (in partial equilibrium with given factor prices). Solving (7) with respect to $Y_{it}$ yields:

$$p_{it} = C'_{it} + \underbrace{\tau\theta_i}_{\substack{\text{Costs of}\\ \text{carbon tax}}} + \underbrace{\lambda_t \sigma}_{\substack{\text{Implicit tax}\\ \text{due to green}\\ \text{technology standard}}} - \underbrace{\lambda_t I_i}_{\substack{\text{Implicit subsidy}\\ \text{due to green}\\ \text{technology standard}}} \tag{16}$$

where $C'_{it} := \partial C(r_t, w_t, K_{it}, L_{it})/\partial Y_{it}$ denotes the marginal costs of energy output.

From (16) it is straightforward to see that with a carbon tax firms' output decisions accurately reflect the carbon content ($\theta_i$) of energy production. Per unit of output the dirty sector incurs higher costs than the clean sector ($\tau\theta_{dirty} > \tau\theta_{clean} = 0$). In contrast, a green technology standard distorts output decisions by introducing a wedge between the price of energy (equal in equilibrium to its marginal benefit) and its marginal costs. It effectively subsidizes the production of clean energy and taxes the production of dirty energy: production costs of the dirty sector reflect an implicit tax equal to $\lambda_t\sigma$ whereas the clean sector in addition receives an implicit subsidy such that the effective change in production costs for the clean sector is equal to $\lambda_t(\sigma - I_i)$. Intuitively, if the stringency of the green standard is low (small $\sigma$), the technology constraint does not bind and $\lambda_t = 0$.[12] The larger $\sigma$, the more binding becomes the standard, in turn increasing $\lambda_t$ and the wedge $\lambda_t(\sigma - I_i)$. Hence, relative to a carbon tax, a green technology standard increases the production of clean energy output and decreases dirty energy output.

IMPACT ON RELATIVE FACTOR PRICES AND INTERGENERATIONAL INCIDENCE.—To develop an intuition for the intergenerational incidence of a green technology policy compared to a carbon tax, it is helpful to adopt a partial equilibrium perspective. The ratio of the capital rental rate to wage is then given by (see Appendix A for the derivation):

$$\frac{R_t}{w_t} = \mu \left( \frac{p_{dirty,t} - \tau\theta_{dirty} - \lambda_t\sigma}{p_{clean,t} + \lambda_t(1-\sigma)} \right)^{\frac{1}{\alpha_{dirty} - \alpha_{clean}}} \tag{17}$$

where $\mu > 0$ is a parameter.

How does a green technology policy affect $R/w$ compared to a carbon tax? From expression (17) it is straightforward to see that a green technology policy increases $R/w$ relative to a carbon tax if the clean energy good is more capital-intensive than the dirty energy good, i.e. $\alpha_{clean} > \alpha_{dirty}$ as in (5). The intuition is that by implicitly subsidizing capital-intensive clean energy and taxing labor-intensive dirty energy, a green technology standard increases (decreases) demand for capital (labor) compared to a carbon tax. Consequently, $R/w$ increases after the adoption of a green technology standard.

How a green technology standard compares to a carbon tax on the intergenerational incidence between current old, current young, and future generations follows from the change in $R/w$ and the OLG household structure. The current old generations (i.e., those alive in the first model period when the climate regulation is introduced) earn no labor income and derive their capital income from a pre-determined endowment of assets ($a_0$). As $R/w$ increases with a green technology policy, these generations benefit from a positive "capital appreciation effect" relative to a carbon tax which enables an increase in old-age consumption $c_0^o$ (see budget constraint (3)). In contrast, the initial young and future generations potentially benefit from higher savings income, while their labor income declines relative to capital income. The overall utility impact for the initial young and future generations is, however, ambiguous.

[12] The complementary slackness condition associated with (7) is: $\lambda_t[Y_{clean,t} - \sigma \sum_i Y_{it}] = 0$. If $Y_{clean,t} > \sigma \sum_i Y_{it}$, then $\lambda_t = 0$. When $\lambda_t > 0$, then $Y_{clean,t} = \sigma \sum_i Y_{it}$.

## II. Quantitative Model

MOTIVATING THE QUANTITATIVE OLG FRAMEWORK.—To quantify the intergenerational incidence of green technology policy relative to a carbon tax, we extend the analytical model in several ways. While the fundamental intuition for the capital appreciation effect is unchanged, the key question is how strong this effect is relative to the other channels through which policy affects lifetime utility of current and future generations. First, we need to consider the full general equilibrium effects of the capital-wage ratio over time (including income effects which were ignored in the analysis of the simple model in Section IB). Second, the capital appreciation effect is not clear-cut under a more realistic demographic structure in the OLG setting in which households live for more than two periods: the amount of initial capital varies with age (due to accumulation prior to the introduction of the climate policy), and current old generations living beyond the introduction of the policy will have to bear some of the cost of the policy in later periods of their lifetime. Third, assessing climate policy choices in a real-world economy needs to consider interactions with distortionary capital income taxation: to the extent that a green technology policy implicitly subsidizes capital (through decreasing the relative costs of the capital-intensive clean energy sector), efficiency losses from capital income taxation can be mitigated more than under a carbon tax policy. Fourth, the extent to which capital income tax distortions can be lowered under a carbon tax policy depends on the design of carbon revenue recycling: lowering distortionary income taxes instead of recycling revenues through lump-sum transfers has a first-order impact on the comparison between green technology and carbon pricing policies. Fifth, in real-world economies "dirty" energy derives from multiple fossil fuels with heterogeneous carbon intensities. A simple model with only one "dirty" energy sector underestimates the efficiency costs of a green technology policy that fails to differentiate the implicit input tax by carbon content. Considering multiple fossil energy sources also opens the space to go beyond the instrument choice question (e.g., a green technology mandate vs. a carbon tax) and analyze alternative design options for green technology policy. In summary, these considerations motivate the use of a quantitative OLG model to further investigate the hypothesis (1) that a green technology policy is preferred over a carbon tax by today's older generations and (2) that the preference of today's generations may influence majority decisions in favor of green technology policy over carbon pricing.

MODEL OVERVIEW.—We develop 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, 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 and no bequests.

### A. *Household Behavior: Overlapping Generations*

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 $t = g + N$.

Households are forward-looking with perfect foresight over their finite lifetime. Each generation chooses optimal life-cycle paths of consumption $c_{gt}$ and leisure $\ell_{gt}$ to maximize lifetime utility subject to time endowment, period budget, and investment technology constraints. Lifetime utility of generation $g$, $u_g$, is of the constant-intertemporal-elasticity-of-substitution form:

$$u_g\left(z_{gt}\right) = \sum_{t=g}^{g+N} \left(\frac{1}{1+\hat{\rho}}\right)^{t-g} \frac{z_{gt}^{1-1/\sigma}}{1-1/\sigma} \tag{18}$$

where full consumption $z_{gt}$ is a constant-elasticity-of-substitution (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, $\sigma$ the intertemporal elasticity of substitution, $\sigma_{cl} = 1/(1-\nu)$ is the elasticity of substitution between consumption and leisure, and $\alpha$ 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.[13]

At any point in time, a household chooses to allocate its time between labor and leisure:

$$\ell_{gt} \leq \omega_g\,. \tag{19}$$

$\omega_{g,t} = \omega\,(1+\varsigma)^g$ denotes the time endowment of generation $g$ at $t$ and $\varsigma$ is the effective population growth rate (including labor-augmenting technological progress).[14]

The household period budget constraint requires that the total spending on consumption and savings cannot exceed income from different sources:

$$p_t^C c_{gt} + i_{gt} \leq \Omega_{gt} \tag{20}$$

where

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

Households have access to a storage technology: they can use one unit of the output good to obtain one unit of the capital good next period:

$$k_{gt+1} \leq (1-\delta)k_{gt} + i_{gt} \tag{21}$$

where $i_{gt}$ denotes household investment into this technology and $\delta$ the annual capital

[13] Figure B2 in the Appendix B depicts the nested CES structure for material consumption.

[14] $\omega$ is a constant income scaling factor, which is determined in the initial calibration procedure to reconcile household behavior with the aggregate benchmark data (see Rasmussen and Rutherford, 2004).

depreciation rate.[15]

$w_t$ denotes the nominal wage rate, $\tau_l$ is the tax rate on labor income, and $\pi_{gt}$ is an index of labor productivity over the life cycle. $r_t$ denotes the nominal interest rate and $\tau_r$ is the tax rate on capital income. $\theta_{ig}$ 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 $t$. $\Delta_{gt}$ denotes income from government transfers, including potential rebates from carbon tax revenues.

### *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 characterized by the following nested 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 $L_{pt}$:

$$Y_{pt} = [\epsilon_p \underbrace{R_{pt}}_{\substack{\text{Resource}\\ \text{input}}}{}^{\rho_p^R} + (1-\epsilon_p) \min\{\underbrace{B_{1pt}, \ldots, B_{ipt}, \ldots, B_{Ipt}}_{\substack{\text{Intermediate material}\\ \text{inputs}}}, \underbrace{V_{pt}(K_{pt}, L_{pt})}_{\substack{\text{Capital-labor}\\ \text{composite}}}\}^{\rho_i^R}]^{\frac{1}{\rho_p^R}} \tag{22}$$

where $V_{pt}$ is a Cobb-Douglas aggregate of capital and labor, $\epsilon$ 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:

$$\max_{K_{pt}, L_{pt}, R_{pt}, B_{ipt}} (p_{pt}^Y + s_t) Y_{pt} - r_t K_{pt} - w_t L_{pt} - p_{pt}^R R_{pt} - \sum_{i \neq p} p_{it}^B B_{ipt} \tag{23}$$

subject to (22) 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 IV).[16]

[15] Initial old generations, i.e. generations born prior to period zero, are endowed with a non-zero amount of capital: $k_{g0} = \bar{k}_g > 0$ for $g = -N, \ldots, -1$. These asset holdings by initial old generations represent claims on the aggregate capital stock at $t = 0$, i.e. $K_0 = \sum_{g=-N}^{0} \bar{k}_g$. We abstract from intergenerational bequests and assume that newborn households, i.e. those born at t=0 or later, enter the economy with zero capital assets.

[16] 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-

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 $i \neq n$ are combined with a sector-specific capital-labor-energy composite $Q_{nt}$:

$$Y_{nt} = [\phi_n \min_{i \in I \setminus E}(\underbrace{B_{1nt}, \ldots, B_{int}, \ldots, B_{Int}}_{\text{Non-energy material inputs}})^{\xi_n} + (1-\phi_n)(\underbrace{Q_{nt}}_{\text{Capital-labor-energy composite}})^{\xi_n}]^{\frac{1}{\xi_n}} \tag{24}$$

where $E = \{$*coal, natural gas, refined oil, electricity*$\} \subset I$ denotes the set of energy inputs used at the second stage of production. $\phi_n$ 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:

$$\max_{Q_{nt}, B_{nt}} p_{nt}^Y Y_{nt} - p_{nt}^Q Q_{nt} - \sum_{i \in I \setminus E} p_{it}^B B_{int} \tag{25}$$

subject to (24) 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:

$$Q_{nt} = [\theta_n (K_{nt}^{\beta_n} L_{nt}^{1-\beta_{nt}})^{\nu_n} + (1-\theta_n) E_{nt}^{\nu_n}]^{\frac{1}{\nu_n}} \tag{26}$$

where $\theta_n$ and $\beta_n$ 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:

$$E_{nt} = (\iota_n \tilde{Z}_{nt}^{\mu_n} + (1-\iota_n)[\sum_e \vartheta_{en} (Z_{ent})^{\omega_n}]^{\frac{1}{\omega_n}})^{\frac{1}{\mu_n}} \tag{27}$$

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. $\iota_n$ and $\vartheta_{en}$ 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 B3 in the Appendix B summarizes the production structure for $n$-type sectors. The profit maximization problem of intermediate goods producer $n$ at time $t$ solves:

$$\max_{K_{nt}, L_{nt}, Z_{ent}} p_{nt}^Q Q_{nt} - r_t K_{nt} - w_t L_{nt} - \sum_e (p_{et}^A + \lambda_{et}) Z_{ent} \tag{28}$$

subject to (26) and (27) taking commodity and factor prices as given. $\lambda_{et}$ is an input tax levied on fossil fuel $e$ used in sector $n$, $Z_{ent}$. The carbon emissions which result from

load technologies (Joskow, 2011; Rausch and Karplus, 2014), and thus enables modelling electricity generated from different sources as a homogeneous good.

combusting one unit of fossil fuel $e$ is given by $\kappa_e$.

### 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 $p_t^f$.[17]

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 $M_i$:

$$A_{it} = \left[\psi_i^m \, D_{it}^{\rho_i^m} + \xi_i^m \, M_{it}^{\rho_i^m}\right]^{1/\rho^m{}_i} \tag{29}$$

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

$$\max_{D_{irt}, M_{it}} p_{it}^A A_{it} - p_{it}^Y D_{it} - p_t^f M_{it} \tag{30}$$

subject to (29).

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:

$$\left[\psi_i^x \, D_{it}^{\rho_i^x} + \xi_i^x \, X_{it}^{\rho_i^x}\right]^{1/\rho^x{}_i} = Y_{it} \tag{31}$$

where $\psi^x$ and $\xi^x$ denote the share coefficients and $\sigma_i^x = 1/(1+\rho_i^x)$ 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:

$$\max_{D_{irt}, M_{it}} p_{it}^Y D_{it} + p_t^f X_{it} - p_{it}^Y Y_{it} \tag{32}$$

subject to (31).

### D. Capital Accumulation and Aggregate Investment

Aggregate capital accumulates according to

$$K_{t+1} = (1-\delta_t)K_t + I_t \tag{33}$$

[17] 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.

where $\delta$ is the capital depreciation rate. Given intergenerational heterogeneity, the following feasibility conditions have to be satisfied:

$$K_t = \sum_{g=t-N}^{t} k_{gt} \,. \tag{34}$$

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:

$$I_t = \sum_{g=t-N}^{t} i_{gt} \,. \tag{35}$$

### *E. Markets and Pricing*

Markets for sectoral output clear, determining $p_{it}^{Y}$, if:

$$Y_{it} = D_{it} + X_{it} \,. \tag{36}$$

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, $p_{it}^{A}$, is then determined by the following market clearing condition:

$$A_{it} = \sum_{g=t-N}^{t} c_{gt} + \sum_{j} B_{jit} + I_t \,. \tag{37}$$

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

$$Y_{st} = \sum_{i \in F \cup R} Y_{it} \tag{38}$$

where the production structure of conventional, fossil-based electricity is similar to (24).[18] Labor is perfectly mobile between sectors but not internationally. Accordingly, the nominal wage rate $w_t$ is determined on the national labor market:

$$\sum_{i} L_{it} = \sum_{g=t-N}^{t} \pi_{gt} \left(\omega_g - \ell_{gt}\right) . \tag{39}$$

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

[18] Figures B4 and B5 in the Appendix B summarize the production structure for sectors of type $p$, $f$, and $r$.

if:[19]

$$\overline{R}_{it} = R_{it}\,. \tag{40}$$

The price of foreign exchange $p_t^f$ is determined by balancing the total value of exports and imports:

$$\sum_i (M_{it} - X_{it}) = 0\,. \tag{41}$$

## III. Data and 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. We use 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 carriers. 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 $\sigma$ 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 for Armington trade provided (Aguiar, Narayanan and McDougall, 2016).[20]

CAPITAL COST SHARE OF POWER GENERATION TECHNOLOGIES.—Based on GTAP data (Aguiar, Narayanan and McDougall, 2016), the calibrated capital cost share for fossil-based electricity is 0.21 and for renewable (wind and solar) is 0.58. That the capital cost share for renewables is about three times higher than for fossil-based electricity is consistent with empirical evidence for OECD countries (IEA, 2015) and the US (EIA, 2021).

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

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

[19] 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.

[20] Table B1 in the Appendix B provides the parameter values.

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.

For parametrization, we use the estimates from Altig et al. (2001) taking an average across income groups (i.e., $\lambda_0 = 1.0785$, $\lambda_1 = 0.0936$, $\lambda_2 = -0.0015$, 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 $\{\bar{\varsigma}, \bar{r}, \theta, \delta_t\}$. We use a value of $\bar{r} = 0.05$ for the net of tax return.[21] The annual capital depreciation rate is set to 0.07. $\bar{\varsigma}$ is set at 0.02, which is broadly in line with the annual average of U.S. economic growth from 2004-2011. 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 follow the calibration procedure by Rasmussen and Rutherford (2004), imposing two additional constraints on individuals' maximization problems by endogenously solving for the time endowment parameter $\omega$ and the utility discount rate $\hat{\rho}$.[22] $\hat{\rho}$ is calibrated to ensure that the model is on a balanced growth path: given a constant interest rate $\bar{r}$, the Keynes-Ramsey rule gives the growth rate of the economy along a balanced growth, i.e. $g = [(1+\bar{r}))/(1+\hat{\rho})]^{(1/\sigma)}$, from which we can infer $\hat{\rho}$. Lastly, given $\{\bar{r}, \bar{\varsigma}, \delta_t\}$ we use data on base-year capital earnings from the SAM data (Aguiar, Narayanan and McDougall, 2016) to infer the initial capital stock.

[21] 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.

[22] Note that $\omega$ is a simple scaling factor with no economic significance. $\rho$ is selected as the second calibration parameter as there is little evidence on what would constitute an appropriate value.

### 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 ($N = 49$).[23]

### E. Calibrated Life-Cycle Behavior

Panel (a) of Figure B1 in Appendix B 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 B1 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.

## IV. The Computational Experiment

Table 2 provides an overview of the various climate policy designs analyzed in the computational experiments. Appendix C provides algebraic detail on the model-based representation of climate policies in the quantitative OLG model.

GREEN TECHNOLOGY POLICIES.—We analyze the set of green technology policies $\mathcal{T}$, which includes:

- *"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"* represents most of the regulatory approaches which have been used in the electricity sector to incentivize the expansion of RE. Such

[23]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.

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

| | Input tax $\lambda$ | Output subsidy $s$ | Recycling of carbon revenues |
|---|---|---|---|
| Technology policies $\mathcal{T}$ | | | |
| *Technology standard* | Not proportional to $CO_2$ ($\lambda_{et} = \gamma p_t^{Credits}, \forall e$) | $s_t = (1-\gamma)p_t^{Credits}$ | None |
| *Emissions intensity standard* | Proportional to $CO_2$ ($\lambda_{et} = \gamma \kappa_e p_t^{Credits}$) | $s_t = p_t^{Credits}$ | None |
| Carbon tax policies $\mathcal{C}$ | | | |
| *Flat recycling* | $CO_2$ price ($\lambda_{et} = \kappa_e \tau_C$) | None | Per capita transfers |
| *Labor tax recycling* | $CO_2$ price ($\lambda_{et} = \kappa_e \tau_C$) | None | Labor income tax |
| *Capital tax recycling* | $CO_2$ price ($\lambda_{et} = \kappa_e \tau_C$) | 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. $\tau_C$ denotes a carbon tax. Appendix C provides algebraic detail on the model-based representation of the climate policies shown above.

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 (Helfand, 1991; 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.[24]

The policy category *"Emissions intensity standard"* considers a refined technology policy in which the regulator requires that $CO_2$ emissions be offset or compensated by a certain amount of energy from RE sources. Notably, such a 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; it can also be conceived as a system of tradable certificates for "green" electricity (Abrell, Rausch and Streitberger, 2019).

DIRECT CARBON PRICING AND REVENUE RECYCLING.—We consider carbon tax policies $\mathcal{C}$ that involve a constant carbon tax over time under alternative ways of recycling the additional revenues from the tax increase. Let $\mathcal{R}$ denote the set of revenue-recycling options:[25]

- *"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

[24]For example, feed-in tariffs or market premiums in Germany and Spain are in this category (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).

[25]We refer to a carbon tax with flat recycling as a "plain vanilla" carbon pricing option (which is representative of what has already been implemented in a number of countries (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).

tax rate in that year.

- *"Capital tax recycling"*: annual revenues are returned by lowering the capital income tax rate in that year.

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 $\tau_C$, 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 $\mathcal{C} = \mathcal{R} \times \mathcal{S}$.

EXOGENOUS $CO_2$ TARGETS AND EQUAL-YIELD CONSTRAINT.—The logic of our computational experiments is to compare both carbon tax and green technology policies to a to a "no-climate policy" baseline, where $CO_2$ emissions are determined by the decentralized equilibrium decisions of firms and consumers, without any climate policy constraints imposed. Our analysis does not consider the benefits of averted damages from climate change. Instead, we focus on cost-effectiveness, i.e. how to achieve a given environmental target at least cost using alternative climate policy approaches. To enable a meaningful welfare comparison between climate policies, we require that technology policies achieve the same year-on-year emissions reductions as carbon pricing policies.

Since 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) to satisfy this revenue equality constraint.

## V. 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 1 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 wage reduction is larger than the reduction of capital rental rate (see Figure 2).[26] It is the current

[26] A carbon tax with flat recycling includes the lump-sum transfer, which is not reflected in wage and capital rental rate. The welfare effect of the flat lump-sum transfer is lower for today's older generations because they are richer.

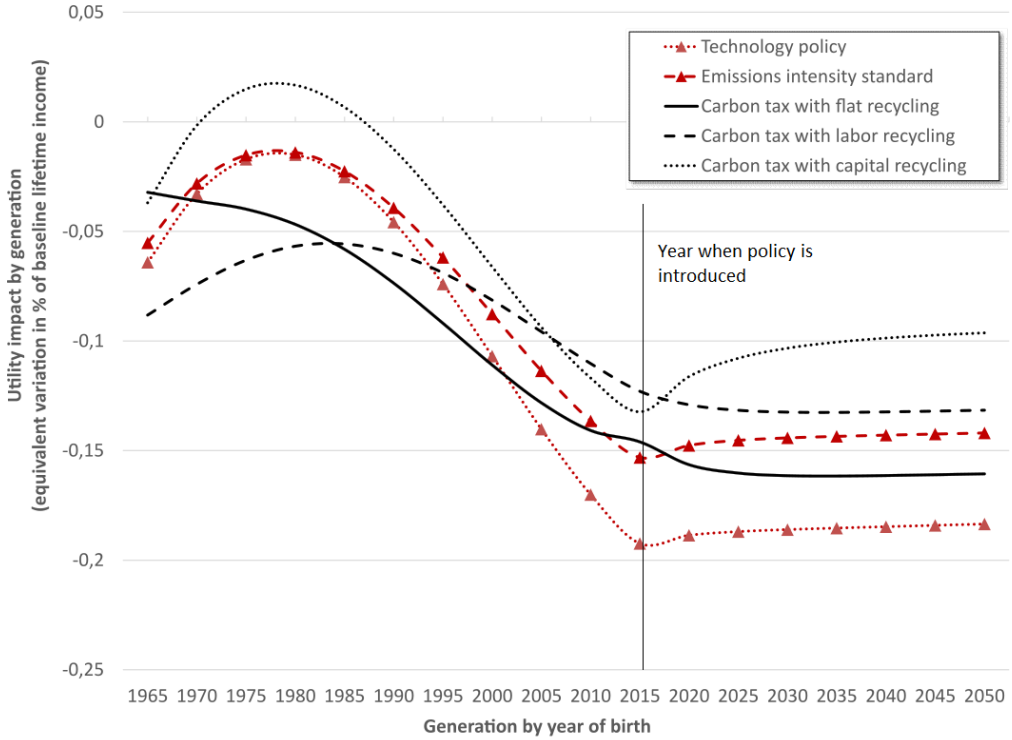
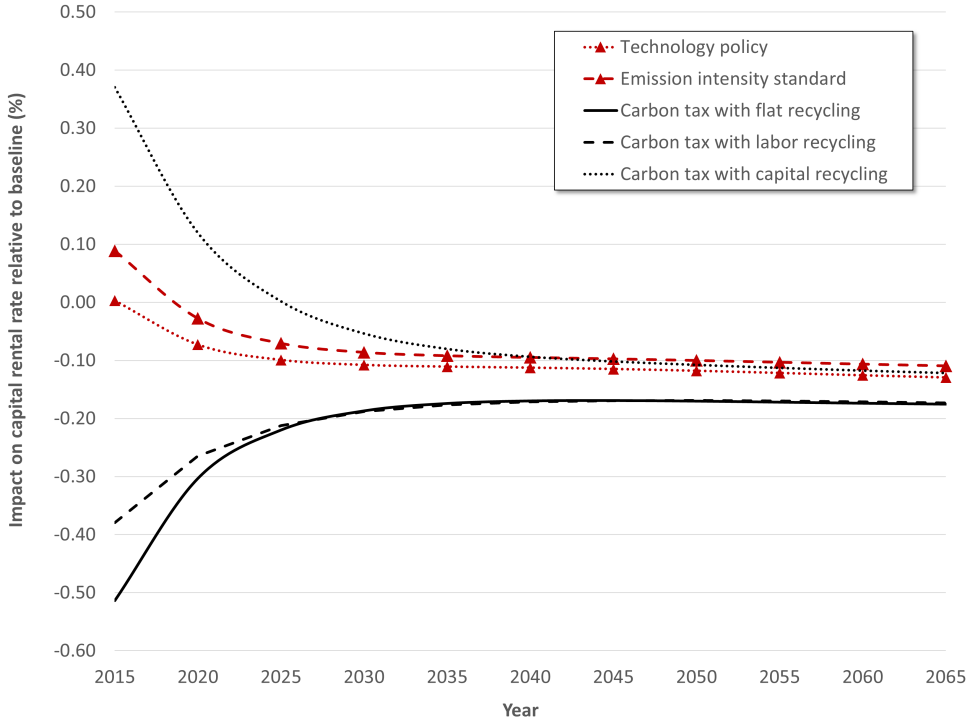



Figure 1. Utility impact by generation for a \$50 carbon tax and alternative technology policies with identical year-on-year emissions reductions.

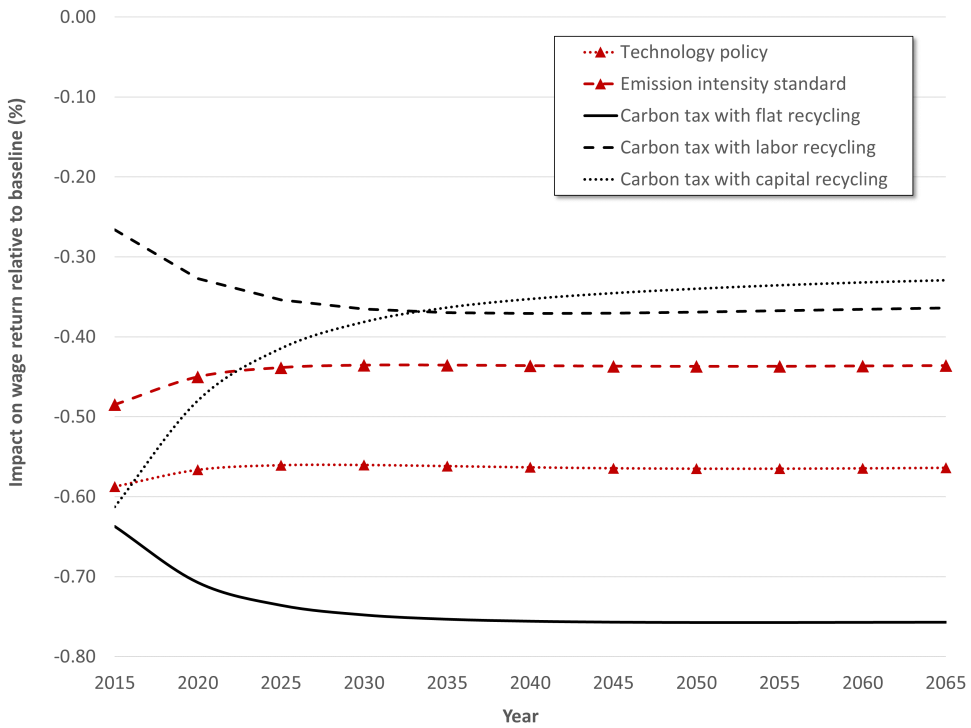
*Notes:* The figure shows the utility change by generation, identified by birth year, for alternative climate policy designs measured as the equivalent change in percent of lifetime income without climate policy. The results presented assume that a constant carbon tax of \$50 per ton of $CO_2$ emissions 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.

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 B1). 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 leads to a smaller reduction in wage (see Figure 2, Panel b). This means that today's middle-aged generations, the young generations, and future generations are less burdened, while today's older generations are worse off. The reason is that today's elderly receive little labor income and therefore do not benefit as much from the reduction in after-tax wages. With capital income tax recycling, the impact on the capital rental rate is positive (Figure 2, Panel a). Since current generations have capital assets (i.e., claims on the initial capital endowment; see $\overline{k}_g$ in (20)), they are better off. 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




(a) Impact on capital return




(b) Impact on wage

Figure 2. Impact on capital return and wage over time relative to baseline.

on labor income, as this would leave today's old generations worse off.

*Carbon pricing with capital tax recycling produces similar intergenerational incidence as a 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. Figure 2, Panel (a), shows that the capital rental rate is increased for green technology policies and carbon pricing with capital tax recycling compared to carbon pricing with flat recycling. 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. Economic growth leads to an increase in wage over time as investment and capital flows adjust gradually. These effects compound over time, so that future generations benefit more than today's young people, who experience the first decade in which the wage increase (compared to the carbon pricing with flat recycling) does not fully materialize.

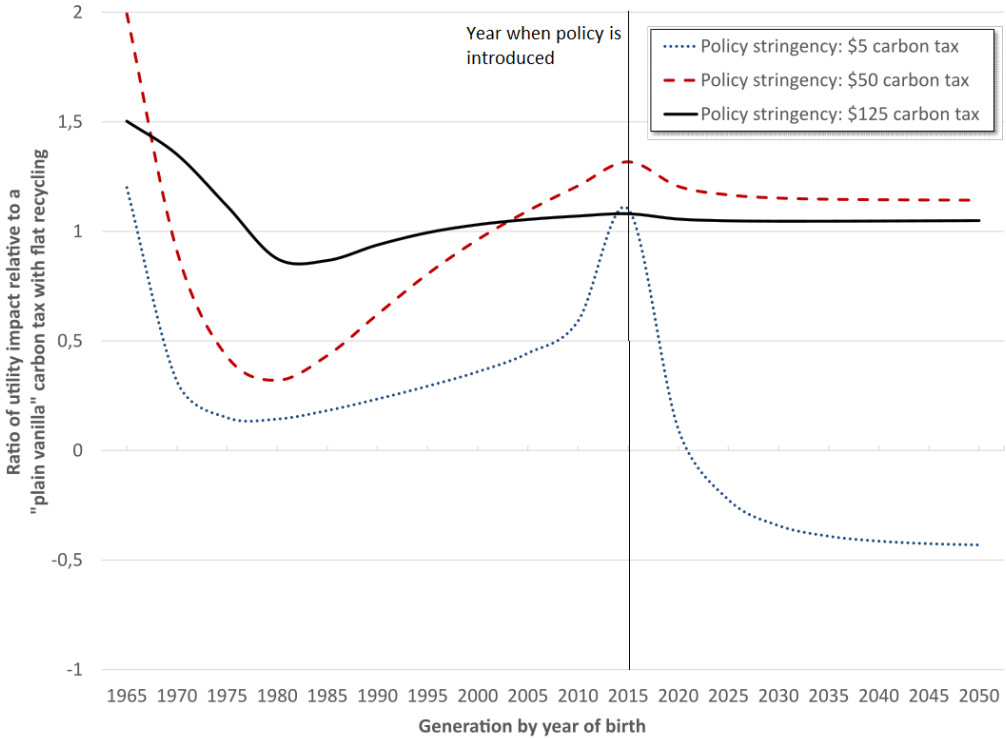
### *B. Green Technology Policies vs. Carbon Pricing*

Figures 3 and 4 provide, in addition to Figure 1, 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.

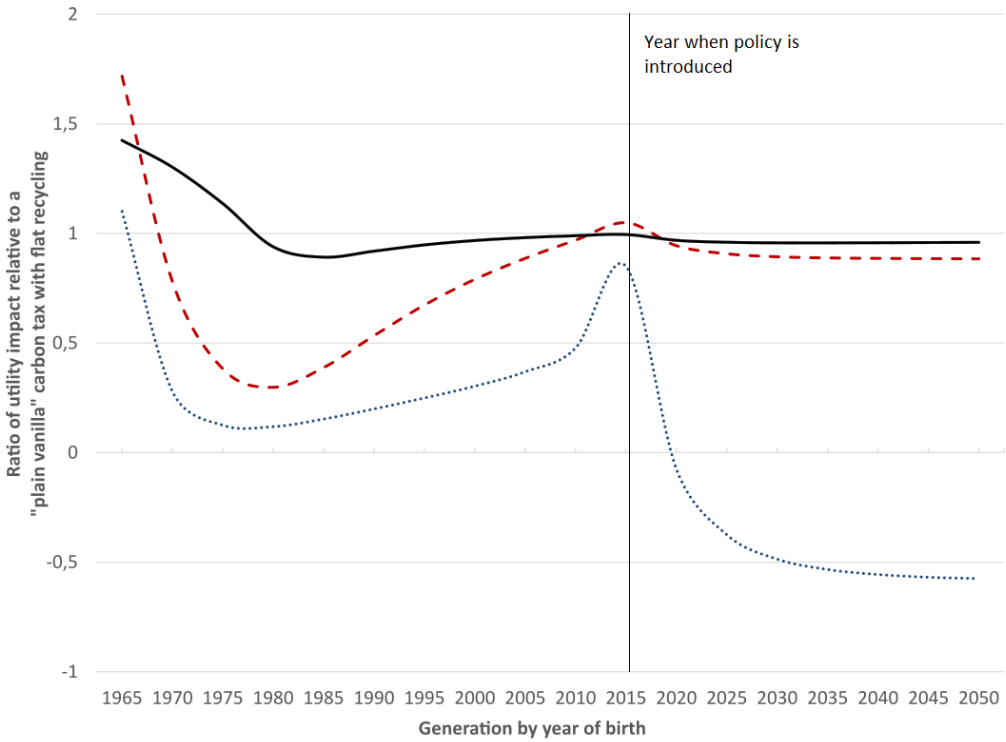
It is evident that there is a large heterogeneity in utility impacts which depends on four main factors: the design of the technology policy, the choice of recycling revenues under a carbon tax policy, policy stringency, and the birth year of the household. The following summary of key findings substantiates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

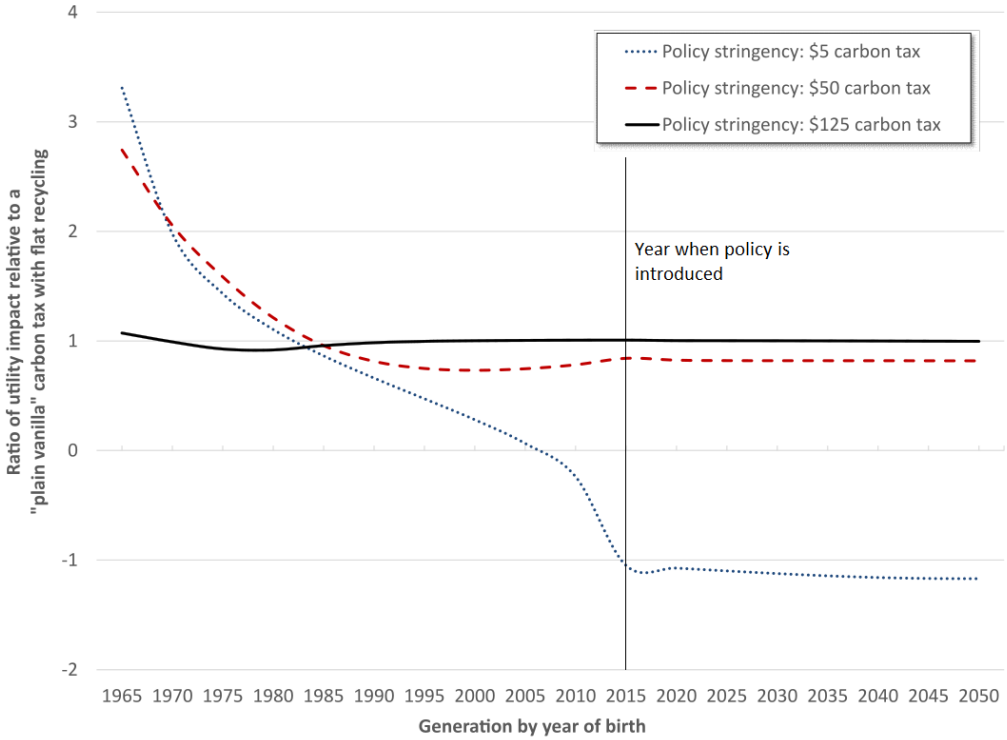



(a) Technology standard.

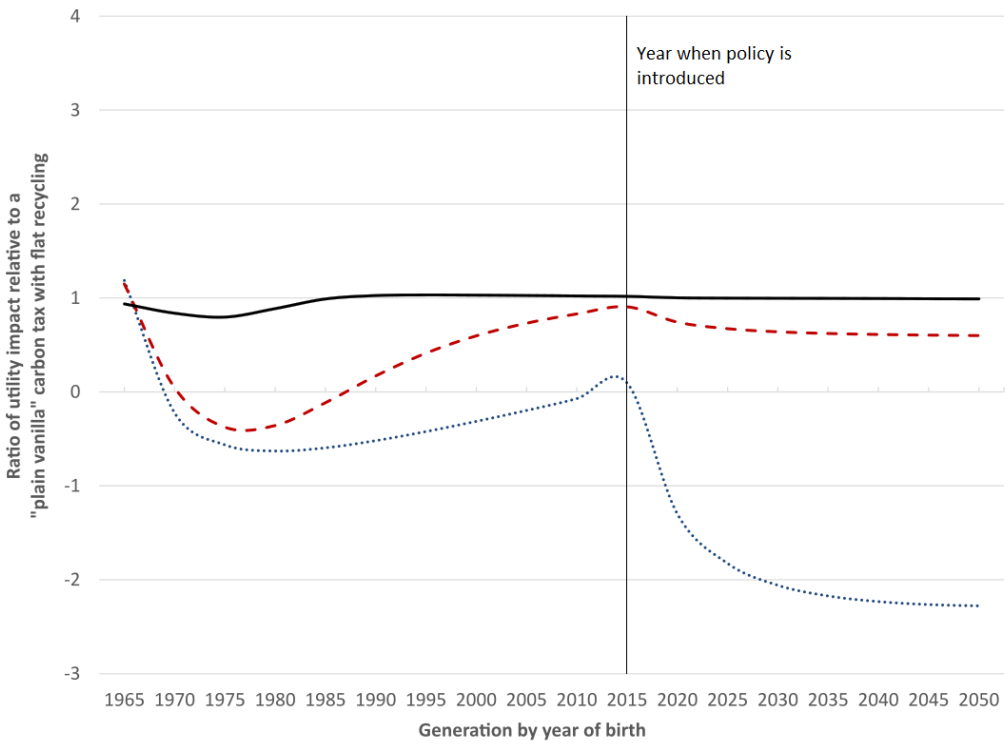



(b) Emissions intensity standard.

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.

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.[27]

*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.

## VI. Can Green Technology Policies Outperform Carbon Pricing?

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.

[27] 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. Utilitarian Social Welfare Perspective

To evaluate generational utility impacts, we adopt a social welfare function as in Jensen and Rutherford (2002):

$$\mathcal{W} = \left( \sum_{g=-N}^{\infty} \bar{Y}_g u_g^{\rho} \right)^{1/\rho} \tag{42}$$

where $\bar{Y}_g$ is the remaining lifetime full-income at present value in the "no-climate policy" baseline and $\rho$ is an social inequality aversion parameter. The weights $\bar{Y}_g$ account for population growth and the market interest rate. The utilitarian case corresponds to $\rho = 1$.

Figure 5 compares the green technology and alternative carbon tax policies adopting a utilitarian social welfare perspective. Policy performance is shown relative to the "plain vanilla" carbon tax with flat recycling for different levels of policy stringency. The following insights emerge:[28]

*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.

*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, 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 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

[28] As $\rho$ approaches $-\infty$, a higher social weight is placed on future generations, who suffer higher utility losses (see Figure 1). Therefore, for a given climate policy approach, social welfare becomes somewhat lower as $\rho$ decreases. However, the comparison of social welfare costs between alternative policy approaches (as in Figure 5) is largely insensitive to $\rho$. While a technology policy leads to a larger dispersion of intergenerational welfare effects compared to a simple carbon tax (i.e., the current generations experience smaller and the future generations larger utility losses), the relative valuation of social welfare deteriorates only slightly for very high levels of social inequality aversion (i.e., large negative values of $\rho$).

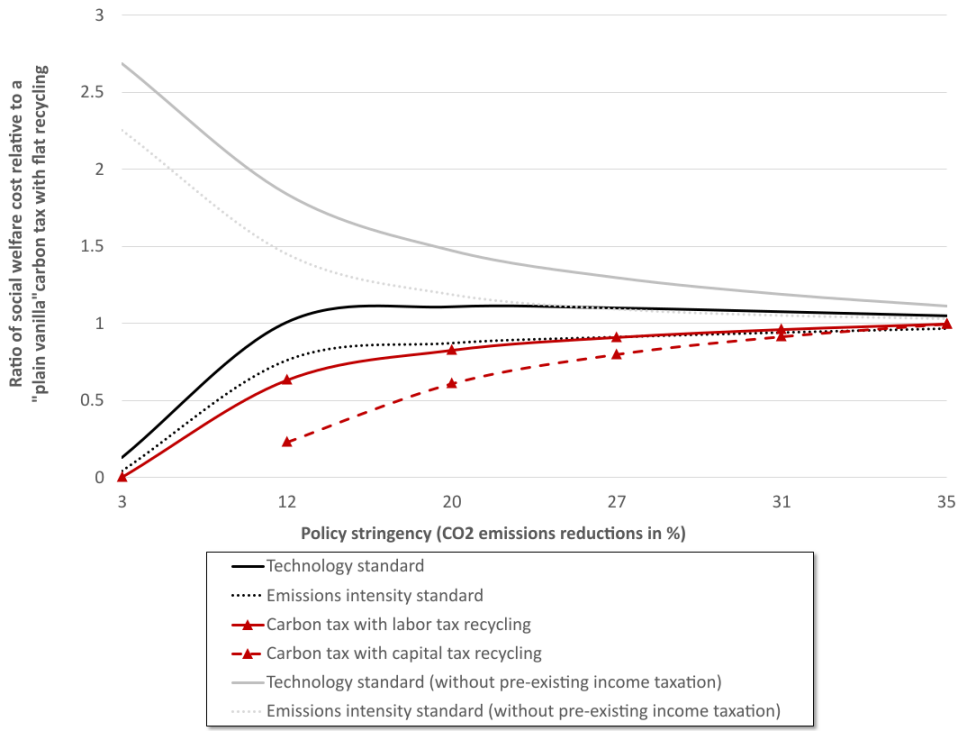



Figure 5. Utilitarian social welfare comparisons of alternative climate policies $\mathcal{T}$ and $\mathcal{C}$.

*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.

(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 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. Majority Voting*

In the U.S. (and the vast majority of other countries), climate policy must find support in political systems based on majority voting. As individual preferences through voting can only be expressed by households or generations who are currently alive, the social preferences are largely shaped by how alternative policy choices affect the well-being of the current population. We thus examine societal preference for green technologies versus carbon pricing policies based on a hypothetical referendum that embodies the principle of

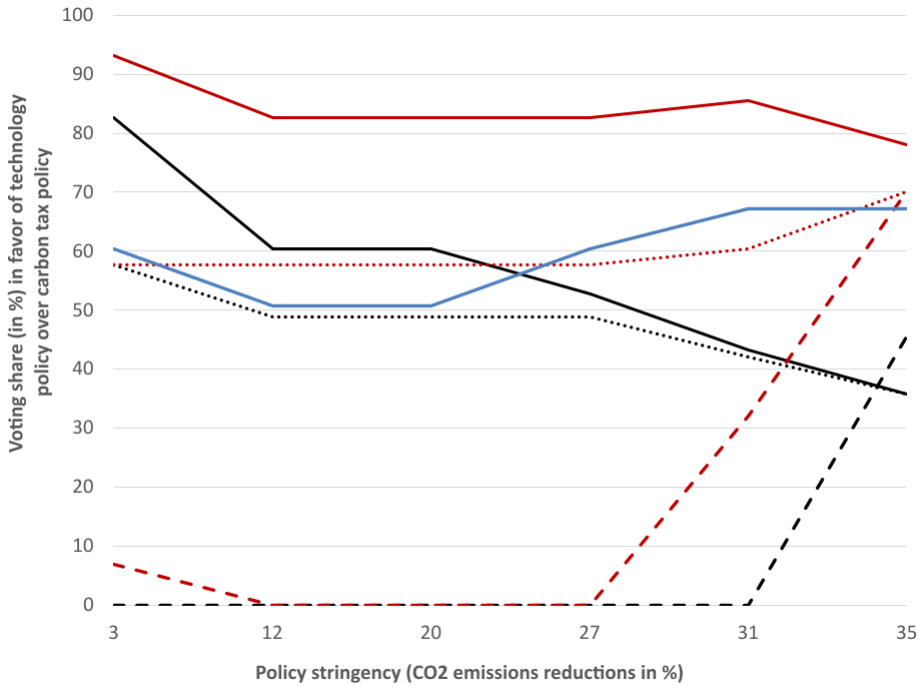



Figure 6. Share of votes by current generations for technology policies over carbon tax policies.

*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.

majority voting and takes the utility impacts derived from our model as the main input.[29]

Let $p, p' \in \mathcal{P} = \{\mathcal{T}, \mathcal{C}\}$ denote the set of alternative policy designs. Policy $p$ is preferred over policy $p'$ if it receives the simple majority of votes compared to $p'$:

$$\sum_{g=-N}^{\tilde{t}} V_g^{p,p'} > \sum_{g=-N}^{\tilde{t}} V_g^{p',p} \,. \tag{43}$$

$\tilde{t}$ denotes the time of the potential introduction of the policy, and we assume that only generations alive at $\tilde{t}$ can participate in the vote. Whether policy $p$ as compared to $p'$

[29]Our social welfare assessment is "ex-post", i.e. it does not consider potential feedbacks from voting behavior (i.e., outcomes) to economic decision-making. For example, Habla and Rieder (2017) show that the chosen level of mitigation in a political equilibrium with a distortionary tax system may be inefficiently high. Extending our equilibrium concept to political economy considerations that may affect, for example, the menu of available policy options is an intriguing question for future research.

receives the support by generation $g$ depends on a comparison of her expected (remaining) lifetime utility under the competing policy options:

$$V_g^p = \begin{cases} \Xi_g & \text{if} \quad u_g^p > u_g^{p'} \\ 0 & \text{otherwise}\,, \end{cases} \tag{44}$$

where $\Xi_g$ is a weight which adjusts for population size and age-specific voter turnout (based on information from the (U.S. Census, 2016)).[30,31]

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 following insights emerge:

*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

[30]For example, if all generations were of equal population size and had the same voter turnout, then $\Xi_g = 1$, $\forall g$. Adjusting for voter turnout takes into account the empirical fact that young U.S. citizens often do not exercise their right to vote compared to older ones (Macdonald, 2020).

[31]In light of the support for climate protection measures among younger generations in recent years, as clearly evidenced through the Fridays for Future movement, one could argue that younger generations are generally more supportive of climate action. However, the evidence for differences in the preference for alternative climate policy designs is less clear. Moreover, this paper is not about climate policy support per se, but rather about understanding the intergenerational distributional impacts of climate mitigation measures, which then determine support for or against a particular policy measure.

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:* 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.

## VII. 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 has shown that it is critical to consider the general equilibrium and life-cycle effects of climate policy on capital income for the economic assessment of market-based decarbonization strategies.

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## Appendix A: Derivation of capital rental rate-wage ratio

To see how the equilibrium capital rental rate to wage ratio depends on climate regulation parameters, first use the FOC of the "dirty" energy firm with respect to labor input to obtain:

$$p_{dirty,t}\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}} - \frac{\partial C_{dirty,t}}{\partial L_{dirty,t}} - \tau\theta_{dirty}\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}} - \lambda_t\sigma\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}} = 0\,. \tag{A1}$$

Since $\frac{\partial C_{dirty,t}}{\partial L_{dirty,t}} = w_t$:

$$w_t = (p_{dirty,t} - \tau\theta_{dirty} - \lambda_t\sigma)\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}} = \tilde{p}_{dirty,t}\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}}\,. \tag{A2}$$

Similarly, for the "clean" energy firm:

$$w_t = (p_{clean,t} + \lambda_t(1-\sigma))\frac{\partial Y_{clean,t}}{\partial L_{clean,t}} = \tilde{p}_{clean,t}\frac{\partial Y_{clean,t}}{\partial L_{clean,t}}\,. \tag{A3}$$

From this it follows that:

$$\frac{\tilde{p}_{dirty,t}}{\tilde{p}_{clean,t}} = \frac{\frac{\partial Y_{clean,t}}{\partial L_{clean,t}}}{\frac{\partial Y_{dirty,t}}{\partial L_{dirty,t}}}\,. \tag{A4}$$

From (8) and (9), we obtain:

$$\frac{K_{it}}{L_{it}} = \frac{\alpha_i}{1-\alpha_i}\frac{w_t}{R_t}\,. \tag{A5}$$

Inserting $\frac{\partial Y_{it}}{\partial L_{it}} = (1-\alpha_i)\left(\frac{K_{it}}{L_{it}}\right)^{\alpha_i}$ and (A5) into (A4), we obtain:

$$\frac{\tilde{p}_{dirty,t}}{\tilde{p}_{clean,t}} = \frac{(1-\alpha_{clean})\left(\frac{\alpha_{clean}}{1-\alpha_{clean}}\frac{w_t}{R_t}\right)^{\alpha_{clean}}}{(1-\alpha_{dirty})\left(\frac{\alpha_{dirty}}{1-\alpha_{dirty}}\frac{w_t}{R_t}\right)^{\alpha_{dirty}}}\,, \tag{A6}$$

which, after further rearranging, yields expression (17):

$$\frac{R_t}{w_t} = \mu\left(\frac{p_{dirty,t} - \tau\theta_{dirty} - \lambda_t\sigma}{p_{clean,t} + \lambda_t(1-\sigma)}\right)^{\frac{1}{\alpha_{dirty}-\alpha_{clean}}} \tag{A7}$$

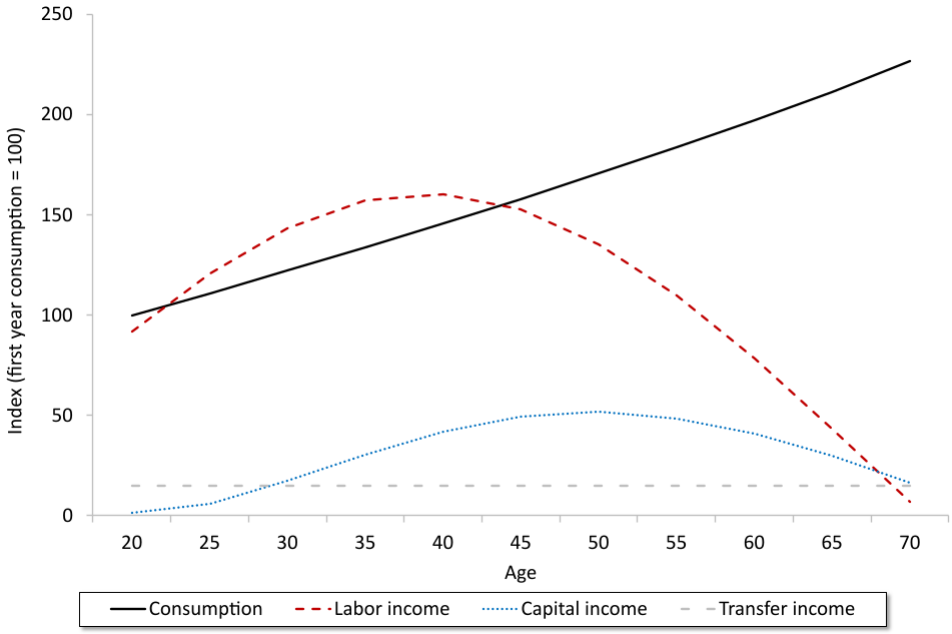
where $\mu = \left[\frac{1-\alpha_{clean}}{1-\alpha_{dirty}}\left(\frac{\alpha_{clean}}{1-\alpha_{clean}}\right)^{\alpha_{clean}}\left(\frac{1-\alpha_{dirty}}{\alpha_{dirty}}\right)^{\alpha_{dirty}}\right]^{\frac{1}{\alpha_{dirty}-\alpha_{clean}}} > 0$.

# Appendix B: Additional Tables and Figures

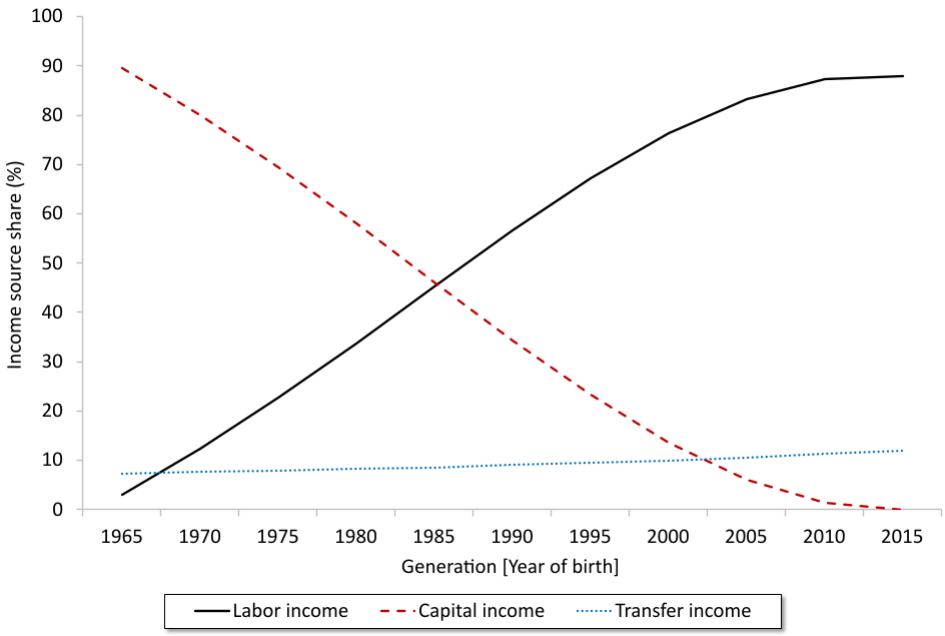
Table B1. Elasticity of substitution parameters for production and consumption technologies.

| Parameter | Substitution margin | Value |
|---|---|---|
| $\sigma_{en}$ | Energy (excluding electricity) | $1.0^a$ |
| $\sigma_{enoe}$ | Energy—electricity | $0.5^a$ |
| $\sigma_{eva}$ | Energy/electricity—value-added | $0.5^a$ |
| $\sigma_{va}$ | Capital—labor | $1.0^a$ |
| $\sigma_{klem}$ | Capital/labor/energy—materials | $0^a$ |
| $\sigma_{cog}$ | Coal/oil—natural gas in ELE | $1.0^a$ |
| $\sigma_{co}$ | Coal—oil in ELE | $0.3^a$ |
| $\sigma_{rnw}$ | Resource—Capital/labor/energy/materials in renewable ELE | *Calibrated* |
| $\sigma_{nr}$ | Resource—Capital/labor/energy/materials in nuclear ELE | *Calibrated* |
| $\sigma_{am}$ | Materials in AGR | $0^a$ |
| $\sigma_{ae}$ | Energy/electricity—materials in AGR | $0.3^a$ |
| $\sigma_{er}$ | Energy/materials—land in AGR | $0.6^a$ |
| $\sigma_{erva}$ | Energy/materials/land—value-added in AGR | $0.7^a$ |
| $\sigma_{rklm}$ | Capital/labor/materials—resource in primary energy | $0^a$ |
| $\sigma_{gr}$ | Capital/labor/materials—resources | *Calibrated* |
| $\sigma_{govinv}$ | Materials—energy in government and investment demand | $0.5^a$ |
| $\sigma_{ct}$ | Transportation—Non-transport in private consumption | $1.0^a$ |
| $\sigma_{ec}$ | Energy—Non-energy in private consumption | $0.25^a$ |
| $\sigma_{c}$ | Non-energy in private consumption | $0.25^a$ |
| $\sigma_{ef}$ | Energy in private consumption | $0.4^a$ |
| $\sigma_i^D$ | Foreign—domestic | GTAP, version 9 |
| $\sigma_i^M$ | Across foreign origins | GTAP, version 9 |
| $\sigma$ | Intertemporal elasticity of substitution | 0.5 |
| $\sigma_{cl}$ | Leisure—material consumption | 0.8 |
| $\alpha$ | Weight on material consumption in full consumption | 0.6 |
| $\hat{\rho}$ | Calibrated subjective utility discount factor | 0.012 |

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




(a) Life-cycle profiles for consumption and income




(b) Income shares by source for different generations

Figure B1. 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.

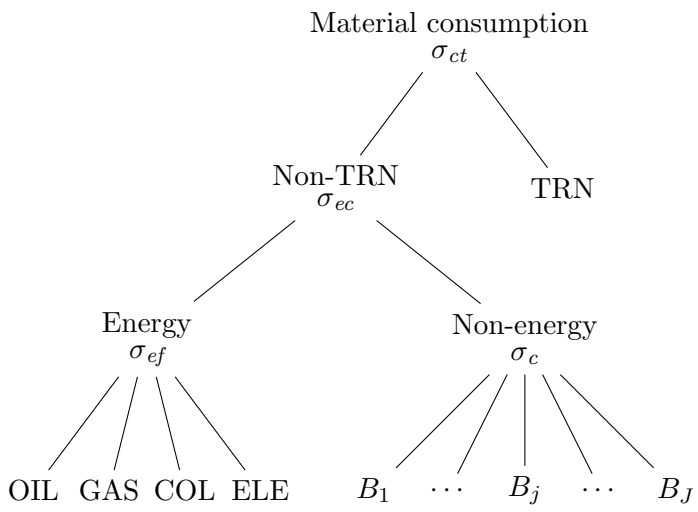



Figure B2. Structure of private material consumption.

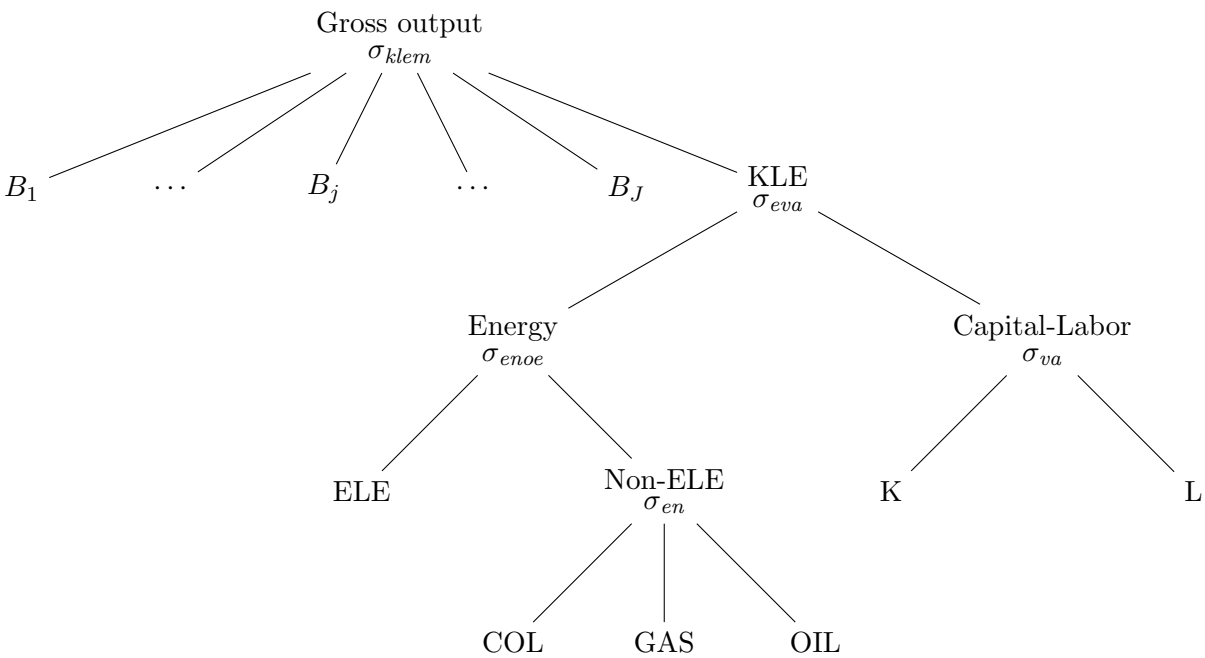



Figure B3. Production structure for final goods non-energy sectors $g \in G =$\{AGR,EIS,TRN,SRV,MAN\} and refining of crude oil $c \in C =$\{OIL\}.

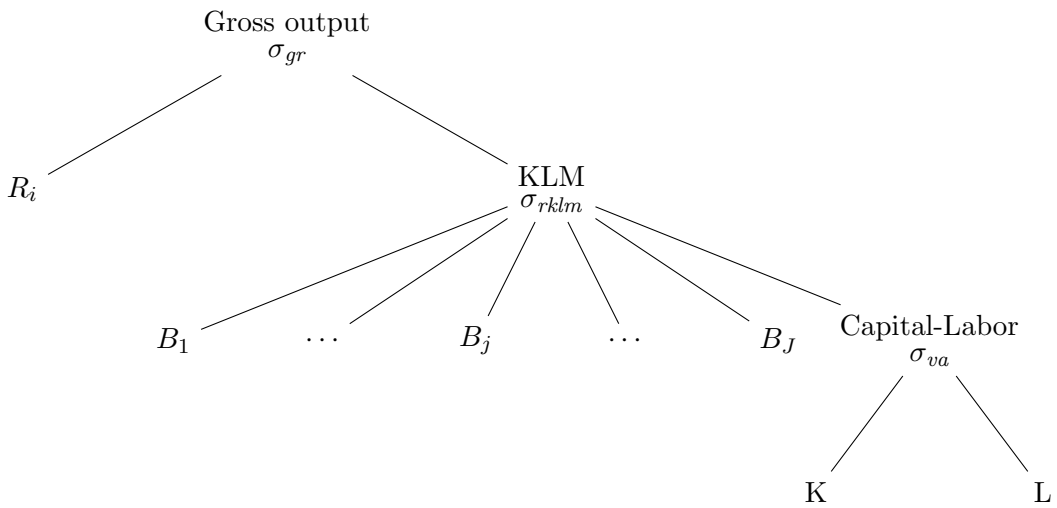



Figure B4. Production structure of energy resource sectors $f \in F \subset P\{\text{COL,CRU,GAS}\}$.

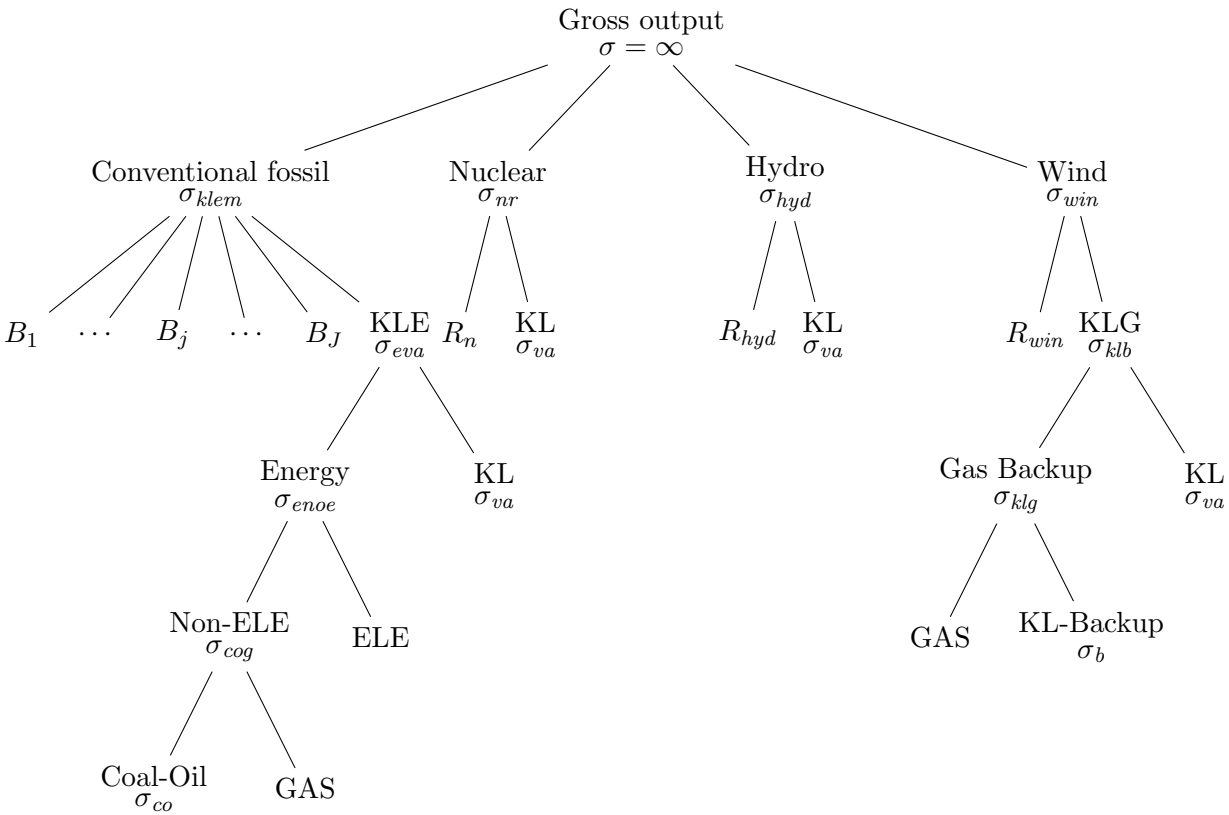



Figure B5. Production structure of fossil-based electricity $l \in L = \{\text{ELE}\}$ and electricity generation from nuclear, hydro, and wind and solar resources $r \in R \subset P$.

## Appendix C: Model-based representation of different climate policies

To see how a green *"Technology standard"* is represented in the quantitative model (i.e., the analogue to (6) in the simple model in Section I), consider the case of an RE quota which mandates that at each point in time $t$ a certain share $\gamma_t$ of total electricity supplied has to come from RE (wind and solar) resources—adding the following constraint to the equilibrium model described in Section II:

$$\text{(C1)} \qquad \underbrace{\sum_{p\in\{Wind,Solar\}} Y_{pt}}_{=\text{Supply of RE credits}} \geq \underbrace{\gamma_t \sum_{i\in\{Electricity,Wind,Solar\}} Y_{it}}_{=\text{Demand for RE credits}} \qquad (p_t^{Credits}) \ .$$

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 (C1) it then follows that the implicit per-unit tax under an RE quota, which enters in the firm optimization problem (28), is:

$$\text{(C2)} \qquad \lambda_{et}^{Technology\ standard} = \gamma p_t^{Credits} \ .$$

The interpretation is that all energy firms have to hold $\gamma$ 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 (23), is:

$$\text{(C3)} \qquad s_t^{Technology\ standard} = p_t^{Credits} - \gamma p_t^{Credits} = (1-\gamma) p_t^{Credits} \ .$$

An *"Emissions intensity standard"* can also be conceived as a system of tradable certificates for "green" electricity (offsets) according to:

$$\text{(C4)} \qquad \underbrace{\sum_{p\in\{Wind,Solar\}} Y_{pt}}_{=\text{Supply of green offsets}} \geq \underbrace{\gamma_t \sum_{n\in\{Electricity\}} \sum_{e} \kappa_e Z_{ent}}_{=\text{Demand for green offsets}} \qquad (p_t^{Credits}) \ .$$

$\gamma$ 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:

$$\text{(C5)} \qquad \lambda_{et}^{Intensity\ standard} = \gamma \kappa_e p_t^{Credits} \ .$$

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:

$$\text{(C6)} \qquad s_t^{Intensity\ standard} = p_t^{Credits} \ .$$

The carbon tax rate enters the firm optimization problem in (28) according to:

$$\text{(C7)} \qquad \lambda_{et}^{Carbon\ tax} = \kappa_e \tau_C \ .$$

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