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Green tax reform, endogenous innovation and the growth dividend

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Abstract

We study theoretically and numerically the effects of an environmental tax reform using endogenous growth theory. In the theoretical segment, mobile labor between manufacturing and R&D activities, and elasticity of substitution between labor and energy in manufacturing lower than unity allow for a growth dividend, even if we consider preexisting tax distortions. The scope for innovation is reduced when we consider direct financial investment in the lab, or elastic labor supply. We then apply the core theoretical model to a real growing economy and find that a boost in economic growth following such a carbon policy is a possible outcome; all the more when substitution away from CO2-intensive energy is possible. Redistribution of additional carbon tax revenue by lowering capital taxation performs best in terms of efficiency measured by aggregate welfare. In terms of equity among social segments the progressive character of lump-sum redistribution fails when we consider very high emissions reduction targets.

Keywords: Climate Policy, Green Tax Reform, Induced Innovation, Endogenous Growth, Numerical Modelling
JEL classification: C63, E62, O44, Q43, Q48

1. Introduction

The purpose of this paper is to explore theoretically and computationally the existence of the growth dividend of an environmental tax reform (ETR) in a real growing economy.[1] There are three social and economic dividends associated: The first one relates to the environmental quality improvement. The second is an enhancement in welfare by reducing distorting taxation, using polluting emission tax revenues. The third one relates to the Porter hypothesis (Porter, 1991), an extension to environmental policies of the Hicks induced innovation hypothesis (Hicks, 1932). According to this hypothesis a change in factor prices will stimulate innovation to economize the use of the factors that have become relatively more expensive.

Existing empirical evidence supports the Porter hypothesis of induced innovation in emissions reduction activities by increases in the consumer price of energy on firm – or sector – level: Newell et al. (1999) show that following the oil price shocks in the 70's, air conditioners became more energy efficient; Popp (2002) provides systematic evidence of price-induced improvements in energy efficiency by using U.S. patent data; Lanoie et al. (2011) study 4,200 companies in seven OECD countries and find strong evidence of environmental innovations due to stricter environmental policies; Aghion et al. (2016) document that

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[1]We define the term "environmental tax reform", or "green tax reform", as the tax reform that attempts to reduce the burden of welfare distorting taxation by redistributing back to consumers revenues from taxation on environmentally damaging activities.

car manufacturers tend to innovate more in clean technologies when they face higher tax-inclusive fuel prices. An important concern regarding policy-induced innovation activities is that low emission R&D might crowd-out resources from other R&D sectors, and thus act negatively on growth on an economy-wide level. In that respect, Gerlagh (2008), calibrates a simple model of endogenous growth with a climate module and three R&D sectors – a dirty energy-producing, a neutral manufacturing, and an energy-saving sector – and finds that, following an environmental policy, energy-saving R&D increases to a greater extend at the expense of dirty energy R&D. Similar crowding-out effects that lead to greater clean over dirty energy innovation can be found in an econometric study with patent data by Popp and Newell (2012), although the authors note that it is due to profit-maximizing changes in research effort, rather than financial constraints that limit the total amount of R&D possible. Accordingly, even though evidence of crowding-out exists, studies suggest that it is rather dirty R&D that gets reduced to make room for higher clean R&D activity, thus supporting the growth dividend hypothesis even on the aggregate level (Dechezleprêtre and Popp, 2015).

The theoretical literature initially failed to confirm positive results associated with an ETR partly due to the static nature of the models used.Bovenberg and De Mooij (1994) using a static model of general equilibrium, examine the effect of environmental levies in the presence of preexisting distorting taxes where the government uses pollution tax revenues to lower distorting taxation. Using comparative statics they find that, due to preexisting distortions, "..environmental taxes typically exacerbate, rather than alleviate preexisting tax distortions...". There are two effects in a static setting that indicate whether the welfare cost of an environmental tax reform is positive or negative in an economy with various goods and factors of production: the positive *revenue recycling effect*, and the negative *tax interaction effect*. The former arises by employing the environmental tax revenues to cut distortionary taxes. This leads to an alleviation of inefficiencies in the existing tax system and can increase disposable income, labor supply, and welfare. The latter, however, arises because typically an environmental tax drives up firm production costs, which reduces the real household wage, and discourages labor supply; this reflects the fact that shifting the tax burden from a wide tax base, as in the case of income and capital tax, to a narrow one, like the energy input, is likely to further increase rather than reduce preexisting tax distortions, (Parry, 1998; Bovenberg and Goulder, 2002). Which effect dominates depends on three main conditions that allow the exploitation of a potentially inefficient tax system: i) the burden of the environmental tax should fall on factors with relatively low marginal efficiency costs, ii) the revenue should be used to reduce taxes on factors with relatively high marginal efficiency costs and iii) the tax base of the environmental tax should be large and subject to low demand elasticities (Goulder, 1995). This strand of literature tended to reject the second dividend of such a tax reform. An exception is Bento and Jacobsen (2007) where the authors show that a double dividend is likely to occur by incorporating a fixed-factor in the production of the polluting good.[2]

Contrary to that, and in favor of using dynamic settings when examining such policies, Bovenberg and De Mooij (1997), using a growth model of Barro (1990), with a pollution externality, however without labor or research, show that higher welfare and growth is an option – even though unlikely – and determine the conditions for it. Hettich (1998) using a modified Uzawa-Lucas model with elastic labor supply finds that

[2]The term "partly" at the beginning of the paragraph refers to the fact that the first strand of theoretical literature on the double dividend hypothesis focused on the income tax distortions at the labor/leisure margin. However, income taxes cause a wide range of distortions on other margins of behavior beyond those in factor markets. An example of a higher labor income tax is shifting economic activity to the informal sector. As stated in Saez et al. (2012), these issues can be addressed by calculating the elasticity of taxable income, which is much larger than the factor market elasticity. This can capture all the responses to taxation, and thereby increase the scope for a greater welfare improvement from the tax revenue redistribution, i.e. a larger revenue recycling effect from an ETR. We provide an estimate of this elasticity for our scenarios in foonote (26) in section 3, which allows us to compare the relative efficiency gains between policies.

a higher pollution tax might boost long term economic growth and that a tax reform which cuts distorting taxation can further increase this boost. However in the case of that contribution the polluting factor is the capital itself, an ever-increasing tax base, and no substitution possibilities away from this input arise, a rather unrealistic assumption. Positive growth effects arise also in Oueslati (2014) who uses a similar framework with a convex capital adjustment cost. Using a multi-sector model of endogenous growth with R&D, Bretschger (1998) shows that, in an economy with no preexisting distortions, an increase in the price of energy has a first order effect: it leads to sectoral reallocation and pushes more labor to the R&D sector, which boosts growth. Structural change helps sustain research investments also in Bretschger and Smulders (2012). Kronenberg (2010) using a directed technical change framework with clean and dirty goods, based on the model of Smulders and de Nooij (2003), finds a support for the second dividend, but no for the third one. Finally, Kruse-Andersen (2016) using an endogenous growth framework with research in both production and pollution abatement technologies shows that a stricter environmental policy increases the scope for research in abatement at the expense of research into production methods. He also notes in favor of endogenous growth settings that "even small changes in growth rates [due to environmental policy changes] have large level effects in the long-run", and "[...] static models and exogenous growth models (like the DICE model) leave out an important welfare effect of environmental policy."

Our study comprises of both a theoretical and a numerical segment, the latter studying an environmental tax reform in a real growing economy. The analytical model extends the theoretical part of Bretschger and Ramer (2012) in several directions.[3] First, we include both preexisting labor and energy taxation. This feature allows us to study a revenue neutral environmental tax reform where the additional energy tax revenue is redistributed by lowering labor income taxation. Second, we include leisure in the model. Since input reallocation towards innovative activities – and hence towards capital formation – will be crucial for our results, adding leisure to the model might decrease both employment in the manufacturing sector but also in the lab when policy is implemented. This acts negatively on growth and welfare. Third, we allow for a combination of scientific labor employment and direct investment in the lab.

We then bring our theory to the data. Using a fully dynamic multi-sectoral general equilibrium model of endogenous growth, which keeps the core components of our theory, we examine numerically the effects of a green tax reform in Switzerland, which has recently agreed upon implementing an environmental tax reform from 2021. The numerical model extends the structure of the model developed in Bretschger et al. (2011) in the following ways. First, while the aforementioned contribution abstracts from preexisting taxation, we consider a detailed representation of the Swiss fiscal system. Second, we include several heterogeneous households, instead of one representative household, which allows us to study heterogeneous welfare effects. Third, in the more complex computational model labor is freely mobile not only within manufacturing and R&D, but also between these sectors, thus opening up a new channel of input reallocation towards innovation.[4] Fourth, we examine different redistribution schemes for the carbon tax implemented and show the results in terms of growth and welfare, in aggregate, but also for each household group.

Our contribution to the literature is twofold. In the theoretical part we identify the modeling conditions

[3]Bretschger and Ramer (2012) extend the increasing variety model of Romer (1990) to include energy in the intermediate good firms and examine how the substitutability between labor and energy might affect economic growth when the price of the latter increases. In their case – as in ours – each intermediate firm holds a blueprint, or patent, that allows it to produce. This is the costly result of intentional R&D and constitutes the capital of the economy.

[4]Labor inputs for manufacturing and R&D are not perfectly substitutable in the short-run. Since it takes years to educate new scientists and engineers, it is logical to assume that the expansion of labor input in the R&D sector cannot occur in an instant. This concern is not warranted in this paper for two reasons: first, we focus on the long-run effects of environmental policy on innovation; second, in the numerical simulation we are using a ten-year time step. Both conditions justify the assumption of freely mobile labor.

that can lead to higher economic growth due to an increase in energy taxation. We show that when the energy tax increases, mobile labor between manufacturing and research, and limited substitution possibilities in manufacturing between labor and energy inputs, can lead to enhanced growth: higher energy taxes reduce the demand for the energy good; with limited substitutability between inputs this reduces also the demand for labor in manufacturing and pushes it towards innovation. A positive *growth effect*. Contrary to the general consensus, this occurs even in the case of preexisting tax distortions. Exactly the same environmental policy is detrimental for growth in the typical case where new capital formation is the result of foregone consumption ("lab equipment model"): part of the final output is used as direct financial investments in the lab; as its demand declines due to an increase in the energy tax, so does investment activity into new forms of capital. A negative *level effect*. The scope for investment and subsequent higher growth gets further reduced if labor is mobile within the manufacturing sector, or if a leisure option exists. In general the effect of an environmental tax reform on induced innovation and growth is ambiguous.

Turning to the numerical segment, related to the crowding-out effects underlined above, we show that when considering limited substitution possibilities away from polluting energy sources, low to medium CO2 emissions reduction targets can induce innovation and higher growth in the long-run if the tax proceedings are used to reduce preexisting capital taxation. When the tax on polluting energy steadily increases over time, to achieve a very ambitious target, the positive growth effects are outweighed by negative level effects in the long-run: increasing energy taxes increasingly suppress output each period, leaving less room for investment; this reduces growth. An environmental tax reform is always growth-promoting – although marginally – even at very stringent CO2 emissions reduction targets when substitution away from CO2-intensive energies is possible.

Efficiency considerations in terms of aggregate welfare speak in favor of redistributing additional tax revenue by lowering capital taxation. In general shifting the tax burden from a large and ever increasing tax base – like capital – to a small and shrinking one – polluting energy – is inefficient when the first dividend of the green tax reform is not monetized. On the other hand lump-sum redistribution is the least efficient option since in this case the positive revenue recycling effect is absent. The results on equity are not straightforward: low emissions reduction targets follow the consensus in the literature and speak in favor of lump-sum redistribution; the results turn, however, regressive when one considers a very stringent emissions reduction, exposing the inherently regressive character of carbon taxation. In our reference scenario with limited substitution possibilities away from polluting energy and for a stringent target of 60% emissions reduction in 2050 compared to 2010, the carbon tax increases from 107\$/tonCO2 in 2020 to 1'710 \$/tonCO2. Overall welfare cost amounts to about 2.2% of GDP over time, while raised revenue to 1.5% of GDP in 2020 up to 10% of GDP in 2050.

In the next section we present the theoretical model which allows us to identify the sufficient conditions for higher growth inspite of higher energy taxes. The computational model is presented in section 3. Section 4 analyzes different redistribution scenarios in Switzerland in terms of efficiency, equity and growth. Section 5 concludes by giving the appropriate policy recommendations.

2. Green tax reform in a model of endogenous growth

The growth dividend of a green tax reform, based on the Hicks hypothesis, should be the result of induced entrepreneurial activity leading to higher innovation. Accordingly, we propose an endogenous growth framework in the spirit of Romer (1990) and Grossman and Helpman (1991) as modified in Bretschger and Ramer (2012) to include energy inputs subject to environmental regulation; here we go one step further by considering preexisting distorting labor and energy taxes, direct investment as additional input in R&D, and elastic labor supply. In what follows we present the theoretical foundations of the more complex and more detailed computational model and explore the conditions that could lead to a positive growth dividend.

2.1. Demographics, preferences and technologies

Consider an infinite-horizon economy in continuous time admitting a representative household with preferences

$$\int_0^\infty (\log C_t + \theta \log L_{Ut})\, e^{-\rho t} dt, \tag{1}$$

with t being the time index, C representing the flow of consumption, L_U leisure, ρ the intertemporal discount rate and $\theta \geq 0$.[5] [6] We normalize total labor supply to 1 and no population growth is considered. Agents allocate their unit time budget between manufacturing L_X, research L_J, and leisure L_U. Labor market clears:

$$L_X + L_J + L_U = 1. \tag{2}$$

We also assume that the representative household owns all the assets in this economy. The supply side of the economy features two sectors: manufacturing and R&D. The unique consumption good Q is ensembled from a continuum of intermediate goods x_j produced in the manufacturing sector in a Dixit-Stiglitz fashion:

$$Q = \left(\int_0^N x_j^\beta dj \right)^{1/\beta}, \tag{3}$$

where $\beta \in (0, 1)$ and N is the number of different intermediate varieties available to the production of the final good in each time instant. Following the tradition in new growth theory, each intermediate variety corresponds to a patent held by one firm in the manufacturing sector so that N is also the number of intermediate firms. As each firm is the owner of one patent, the value of knowledge capital embodied in it constitutes the value of the firm, an asset in this economy. The number of varieties is determined endogenously in the model. Notice that final good producers take the number of varieties as given. Moreover for given N, equation (3) exhibits constant returns to scale. Therefore, final good producers are competitive and their production possibilities set can be represented by this aggregate production function. Gross output can be used to meet the demand for consumption by households, investment by R&D firms, and energy imports by firms in the manufacturing sector, i.e.

$$p_Q Q = p_Q C + p_Q I + p_E E, \tag{4}$$

with p_Q the price of the final good and p_E the – exogenous – world's price of energy. Each firm j in the manufacturing sector has to buy a patent that allows it to produce according to the same technology. The intermediate goods follow a constant returns to scale function described by $x_j = f(l_{Xj}, e_j)$, with l_{Xj} and e_j labor and energy demand. We thus specify:

$$x_j = \left[\alpha_X l_{Xj}^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1 - \alpha_X) e_j^{\frac{\epsilon_X - 1}{\epsilon_X}} \right]^{\frac{\epsilon_X}{\epsilon_X - 1}}, \tag{5}$$

[5] In the theoretical part we use logarithmic utility for ease of exposition. We will be using the more general CRRA function in the numerical exercise.

[6] We will suppress the time index when no confusion arises. In general, unless stated otherwise, all variables are time-dependent.

with $\alpha_X \in [0,1]$ and ϵ_X the elasticity of substitution between labor and energy in manufacturing. In a symmetric equilibrium each manufacturer of intermediates will demand the same amount of labor and energy inputs, i.e. $l_{Xj} = l_X$ and $e_j = e$, and will produce the same quantity per variety, i.e. $x_j = x$. In this case equation (3) will read

$$Q = N^{\frac{1-\beta}{\beta}} X, \tag{6}$$

with $X \equiv \int_0^N x_j dj = Nx$, the aggregate demand of intermediates and the exponent $(1-\beta)/\beta$ reflecting gains from diversification. Thus, the aggregate production of intermediate goods will follow:

$$X = \left[\alpha_X L_X^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1-\alpha_X) E^{\frac{\epsilon_X - 1}{\epsilon_X}}\right]^{\frac{\epsilon_X}{\epsilon_X - 1}}, \tag{7}$$

with $L_X = \int_0^N l_{Xj} dj = N l_X$ and $E = \int_0^N e_j dj = Ne$, aggregate labor and energy demand in manufacturing of intermediates. An equilibrium will occur when L_X and E stay constant. It follows that in such a case X will also be constant so that from equation (6) Q will grow with $N^{\frac{1-\beta}{\beta}}$.

We now proceed to the R&D sector and the assumptions on the innovation possibilities frontier. Let $\hat{N} \equiv \dot{N}/N$ be the growth rate of N. There are two prevailing approaches when it comes to the emergence of additional capital varieties. In each case we need to ensure that an equilibrium with constant $\hat{N}$ exists by assuming appropriate knowledge spillovers. First, in the "lab equipment model" we assume that new intermediate goods are created following $\dot{N} = \eta N^{-1/\beta} I$, with I being direct investment in R&D and $\eta > 0$ a scaling parameter. In this case, since I is part of the final output Q, it also grows with $N^{\frac{1-\beta}{\beta}}$. The spillovers term $N^{-1/\beta}$ ensures constant $\hat{N}$ in equilibrium. Moreover, it reflects the fact that the more advanced the economy becomes, the harder is for innovation to occur. An alternative would be to have just scientific labor L_J used in the lab. In this case it is common in the literature of endogenous growth to assume that $\dot{N} = \eta N L_J$. With this alternative, linear knowledge spillovers from past R&D, make the labor input more productive over time and ensure constant $\hat{N}$ in equilibrium.[7] In this paper we combine both approaches such that the R&D process uses both direct investment and scientific labor. With the reasoning above we assume the following innovation possibilities frontier where new intermediate varieties occur as follows:

$$\dot{N} = \eta N J, \tag{8}$$

with

$$J = \left[\alpha_J L_J^{\frac{\epsilon_J - 1}{\epsilon_J}} + (1-\alpha_J)(N^{-\frac{1-\beta}{\beta}} I)^{\frac{\epsilon_J - 1}{\epsilon_J}}\right]^{\frac{\epsilon_J}{\epsilon_J - 1}}. \tag{9}$$

Parameter ϵ_J represents the elasticity of substitution between labor and direct investments in research and $\alpha_J \in [0,1]$. Finally, the government collects labor taxes and taxes on polluting energy and redistributes the proceedings back to the representative household in a lump-sum way.

2.2. *Equilibrium*

The characterization of the equilibrium allocation is standard and can be followed in Acemoglu (2008), chapter 13. In the firm side, final good producers, operating in competition, demand symmetric intermediate

[7] See Acemoglu (2008), chapter 13 for an exposition to both approaches.

goods $x_j = x$ per variety, facing symmetric prices p_X for their use. With $X = Nx$, aggregate demand for intermediates, this leads to the following goods market equilibrium,

$$p_Q Q = p_X X. \tag{10}$$

The aggregate production of intermediates follows (7). Labor and energy are paid their marginal cost w and p_E, respectively; in addition a carbon tax t_E is paid to the government.[8] Due to imperfect substitutability in (3), the suppliers of intermediates are monopolistic and charge a monopoly price as a markup over their unit cost of production c_X, i.e. $p_X = c_X/\beta$. Assuming an interior solution, the first order condition that give the demand for energy and labor in manufacturing, are:

$$\beta p_X \frac{\partial X}{\partial E} = (1 + t_E) p_E, \tag{11}$$

$$\beta p_X \frac{\partial X}{\partial L_X} = w. \tag{12}$$

Profits of intermediate good producers cover the upfront costs of obtaining a patent. Profit per variety reads $\pi = p_X x - c_X x$, or with $x = X/N$, $c_X = \beta p_X$, and (10)

$$\pi = (1 - \beta) \frac{p_Q Q}{N}. \tag{13}$$

This profit, paid as dividend to equity holders, is only part of the return to the owner of a firm producing x. Equity holders would also expect a change in the equity value of the company, V. In equilibrium investors would be indifferent between investing into new capital varieties or into a riskless bond at the market interest rate r. This no-arbitrage condition reads

$$\pi + \dot{V} = rV. \tag{14}$$

Firms may enter freely into R&D. According to the innovation possibilities frontier in (8) and (9), the j^{th} entrepreneur who devotes l_{Jj} units of labor and spends i_j part of the final good to R&D for an infinitesimal time interval of length dt gets the knowledge spillovers as given and produces $\eta N J_j dt$ units of new varieties, with $J_j = \left[\alpha_J l_{Jj}^{\frac{\epsilon_J - 1}{\epsilon_J}} + (1 - \alpha_J)(N^{-\frac{1-\beta}{\beta}} i_j)^{\frac{\epsilon_J - 1}{\epsilon_J}} \right]^{\frac{\epsilon_J}{\epsilon_J - 1}}$. The total cost of this endeavour is $(w l_{Jj} + p_Q i_j) dt$. This effort should then create at least a value of $\eta V N J_j dt$, since V is the market value of each variety. Value maximization by an active entrepreneur implies the optimal employment of l_{Jj} and i_j. These are given by the following first order conditions, where the marginal benefit from employing each input equals its marginal cost:[9]

$$\eta N V \frac{\partial J_j}{\partial l_{Jj}} = w \qquad \text{and} \qquad \eta N V \frac{\partial J_j}{\partial i_j} = p_Q.$$

[8] We normalize the carbon intensity of the energy input to unity so that the energy input corresponds to polluting energy.

[9] We assume an interior solution with positive demand for both inputs. An equilibrium without labor or investment in an R&D firm could exist if $\epsilon_J > 1$, so that inputs in R&D were substitutes. Since $\epsilon_J \leq 1$ is more realistic we rule out such an outcome by focusing on an interior solution with positive demand for both inputs.

The technology for each firm performing R&D is the same and exhibits constant returns to scale. Based on that the R&D sector can be represented by one firm with $J = NJ_j$, $L_J = Nl_{Jj}$, and $I = Ni_j$. The optimal employment of total labor and direct investment in the research sector is given by:

$$\eta NV \frac{\partial J}{\partial L_J} = w, \tag{15}$$

$$\eta NV \frac{\partial J}{\partial I} = p_Q. \tag{16}$$

Turning to the household side, the representative household holds the assets of this economy, i.e. total equity value $A = NV$. It then chooses its levels of consumption and leisure in order to maximize (1) subject to its dynamic budget contraint, $\dot{A} = rA + (1 - t_L)w(1 - L_U) - p_Q C + T$, with t_L the labor tax rate set by the government, and T lump-sum transfers. This optimization involves the usual Keynes-Ramsey rule, and a condition for leisure that equates the marginal rate of substitution between consumption and leisure, to the marginal rate of transformation of the two inputs, i.e. their relative price (again the hat notation represents the growth rate of a variable):

$$\widehat{p_Q C} = r - \rho, \tag{17}$$

$$\theta \frac{C}{L_U} = \frac{w(1 - t_L)}{p_Q}. \tag{18}$$

Finally, the government chooses its fiscal instruments in order to balance its budget according to $t_L w(1 - L_U) + t_E p_E E = T$, and the optimizing decisions by firms and households.

2.3. Conditions for a Balanced Growth Path (BGP)

We define the equilibrium growth rate of varieties as $\hat{N} \equiv g$. For ease of exposition, we follow Grossman and Helpman (1991) and choose aggregate expenditure as the numeraire, i.e. $p_Q Q = 1$, so that $\hat{p}_Q = -\hat{Q}$ and from (10), $p_X X = 1$, $\hat{p}_X = -\hat{X}$. Moreover, in equilibrium $\hat{C} = \hat{I} = \hat{Q}$, such that from (4), $\widehat{p_Q C} = \widehat{p_Q I} = \widehat{p_E E} = 0$. The Euler equation (17) then sets $r = \rho$. On the BGP, the wage rate (w) grows with total expenditure, i.e. is constant after the normalization. Ad-valorem tax rates (t_L, t_E), and labor in its different uses (L_X, L_J, L_U), are also constant. By virtue of (7), so is energy demand in manufacturing (E) so that $\hat{X} = 0$, and from (6) $\hat{Q} = \frac{1-\beta}{\beta} g$. Following our previous discussion regarding knowledge spillovers in R&D, we get $\hat{J} = 0$. The budget constraints of the government and households point to a constant asset value $\hat{A} = 0$ and tax transfers $\hat{T} = 0$. Finally with $\hat{\pi} = -g$ from (13), the no-arbitrage condition (14) gives $\hat{V} = -g$. To summarize, we make the following definition:

Definition 1. *A BGP is an equilibrium path with $\hat{N} = g$, constant, on which aggregate variables $\{Q, C, I\}$ grow at $\frac{1-\beta}{\beta} g$, p_Q at $-\frac{1-\beta}{\beta} g$, and $\{V, \pi\}$ at $-g$. All other variables stay constant on the BGP (but not during a policy shock).*

To facilitate the analysis we define $\gamma_X \equiv \frac{\partial X}{\partial L_X} \frac{L_X}{X}$ and $\gamma_J \equiv \frac{\partial J}{\partial L_J} \frac{L_J}{J}$ the production elasticities of labor in manufacturing and reseach, respectively, constant in equilibrium. Constant returns to scale in the production of X and J implies that their complements, $1 - \gamma_X$ and $1 - \gamma_J$, are the production elasticities of the energy input in manufacturing and investment in research. In order to identify the conditions that allow for a growth dividend in our economy, we proceed as follows: first, we log-linearize equations (6) to (18) around the steady state; then relative changes in the growing variables are presented relative to the relative change in the stock of intellectual capital that corresponds to them. We use the *tilde* notation to indicate the relative change of a variable after the policy shock. For example, Q grows with $N^{1-\beta/\beta}$ so that $\tilde{q} = \tilde{Q} - \frac{1-\beta}{\beta}\tilde{N}$; L_X does not grow so that $\tilde{l}_X = \tilde{L}_X$. The model in relative terms is provided in the Appendix.

2.4. Implications for growth and welfare

To keep the results tractable we take the world price of energy as given implying that any environmental policy leaves it unaltered, i.e. $\tilde{p}_E = 0$. Moreover, we assume that the tax reform is revenue-neutral and that any additional tax revenue due to higher energy taxes are redistributed back to the representative household by reducing labor taxation, i.e. $\tilde{T} = 0$.

An increase in the energy tax has two first order counteracting effects on growth through equation (9): first it makes the final good more expensive and investment in innovation less attractive which suppresses growth; second, it reduces the real wage making labor employment in the lab cheaper, and thus more attractive, which promotes growth. However, such a reform entails also the standard static effect on labor supply: If the reduction of the real wage acts negatively on labor supply by increasing the demand for leisure and thus by reducing the available human resources to R&D, the latter positive effect on growth might fail. By combining equations (A.23)-(A.31) of the Appendix we get the relative change in the growth rate followed by a relative increase in energy taxation $\tilde{g}(\tilde{t}_e)$, as

$$\tilde{g}(\tilde{t}_e) = -\frac{1-\gamma_X}{\Delta}\left[s_J(1-\gamma_J)\epsilon_J + s_X(\epsilon_X - \gamma_J)\right]\tilde{t}_e - \frac{\gamma_X(1-\gamma_J)+\gamma_J}{\Delta}s_U\tilde{l}_U(\tilde{t}_e), \tag{19}$$

with $\tilde{l}_U(\tilde{t}_e)$ the relative change in leisure following the policy shock, $\Delta \equiv s_X\frac{g}{\rho+g}[\gamma_X + \epsilon_X(1-\gamma_X)] + s_J\left[\gamma_X + (1-\gamma_X)\left(\gamma_J + \frac{g}{\rho+g}\epsilon_J(1-\gamma_J)\right)\right] > 0$, and $s_J = wL_J$, $s_X = wL_X$, $s_U = wL_U$, the expenditure shares for labor in R&D, manufacturing, and leisure (remember $p_Q Q = 1$), constant in equilibrium.

Assume first that the demand for leisure is unaffected by policy, i.e. $\tilde{l}_U = 0$ (or that there is no leisure in the model, i.e. $s_U = 0$). In this case, according to (19), growth is promoted, supressed or unaffected by the tax policy if the first term of equation (19) is, respectively, positive, negative or zero. If our modeling assumptions consider labor as the main driver of research, as done in Grossman and Helpman (1991) and Bretschger and Ramer (2012), then $\gamma_J \to 1$. In this case, with limited substitutability between labor and energy in manufacturing, $0 \leq \epsilon_X < 1$, growth is promoted, i.e. $\tilde{g}(\tilde{t}_e) > 0$. In the "lab equipment" version, with research expenditure being part of the final product of the economy, $\gamma_J \to 0$ and $\tilde{g}(\tilde{t}_e) < 0$, i.e. growth is unambiguously suppressed. In the general and more realistic case where research combines scientists with financial investment in R&D, the effect of an environmental tax reform on growth is ambiguous.

According to (19), ambiguous are also the results if another option for labor exists, here proxied by the labor-leisure choice assumption. As explained in Parry (1998) and Bovenberg and Goulder (2002) in an economy with preexisting tax distortions, a carbon policy that increases the consumer price of energy might reduce labor supply, i.e. $\tilde{l}_U(\tilde{t}_e) > 0$, because the environmental tax drives up firm production costs which is passed onto the consumers through higher product prices, acting as an implicit labor tax. This negative *tax interaction effect* of higher energy taxes that reduces the disposable income of households, usually outweighs the positive *revenue recycling effect* of redistributing additional tax revenues back to the society, which increases it. Hence, we have proved the following:

Proposition 1. *In our model of endogenous growth with energy input in manufacturing subject to environmental policy, an increase in the energy tax has the following effects on growth:*

- *if leisure is disregarded (inelastic labor supply), labor is the only input in research activity, and labor and energy in manufacturing are complements, an increase in energy taxation promotes growth; the opposite occurs if research activity is the sole outcome of investment being part of the final output;*
- *in the realistic case of a labor - investment combination as inputs in R&D, or if leisure is considered (elastic labor supply), the results on growth are ambiguous.*

Proof: See equation (19) and the paragraph following it. ■

Even though usually neglected by models of an environmental tax reform due to their static nature, a positive growth dividend is important for higher welfare: following Bovenberg and De Mooij (1997), the welfare effects of an increase in energy taxation can by measured by the marginal excess burden, defined as $\tilde{\lambda} = d\lambda/C$. This amounts to the additional consumption that should be provided to the representative household after the policy shock in order for it to keep welfare at its initial level. It is straightforward to show that in our theoretical model

$$\tilde{\lambda} = -\tilde{C} - \theta \tilde{L}_U - \frac{1-\beta}{\beta}\frac{g}{\rho}\tilde{g}, \tag{20}$$

with $\frac{1-\beta}{\beta}g$ the consumption growth rate. A policy that increases current and future consumption, e.g. its growth rate, is welfare promoting. Hence, negative level effects of an environmental tax reform on consumption or labor supply can be compensated in terms of welfare by positive growth effects and vice versa.

2.5. Lessons from theory

The theory in this section exhibited the core mechanism behind the computational model used for our simulations and showed that a growth dividend is theoretically possible due to the input reallocation towards innovation. Moreover, we stressed through equation (20) the importance of the growth effects of an environmental policy on the welfare of households. This endogenous adjustment of economic growth and its effect on welfare is neglected by static models or models of exogenous growth. There are several effects on growth and welfare to consider. First, a positive *growth effect* due to higher labor employment in R&D: with limited substitutability between labor and energy in manufacturing, an increase of the energy tax can drive more labor out of manufacturing and into research which acts positively on growth. However, higher energy taxes that increase the price of the final good, suppress output and subsequently investment, which acts negatively on growth; a negative *level effect*. This is essentially the same effect that suppresses labor supply, and reduces current consumption, the *tax interaction effect*, as identified in Bovenberg and De Mooij (1994). The latter can be counteracted by the positive *revenue recycling effect* of redistributing additional tax revenues back to the society that increases the disposable income of the representative household which is beneficial both for welfare and growth. The presence of leisure in the model might additionally dampen the positive growth effect. In general, the results are ambiguous.

The model used in the theory part is highly stylized and can only capture part of the processes that occur in reality. In a real growing economy with more inputs and manufacturing sectors, the production functions of manufacturing and R&D need to be enhanced to match the data: inputs from different sectors are needed for any production process, and supplied labor is mobile also across and within manufacturing sectors leaving even less available labor to R&D. Moreover, changes in relative prices between sectors due to higher energy taxes lead to input reallocation, which may favor direct investment in capital accumulation.[10] Finally, the analytical model considers a representative household for analytical convenience. Such a framework cannot capture heterogeneous welfare effects, although such effects become important when studying a real world economy. Hence, in the numerical segment we include several heterogeneous consumer groups in order to study the effects of our policies on heterogenous agents. Using our numerical model in the subsequent sections we study the effects of an environmental tax reform on production, growth and welfare of different households in a real growing economy, for various emissions reduction targets and tax revenue redistribution options. For our computational part we will conveniently focus on the case of Switzerland, which has recently agreed upon implementing an environmental tax reform from 2020 on.

3. Estimating the dividends of an ETR in the Swiss economy

3.1. Background

The Swiss Federal Council (SFC) announced in September 2013 a set of proposed fiscal measures as a means of reaching its energy and environment related strategic targets up to 2050 (Energy Strategy 2050). In the context of the announced proposal the existing promotional measures, including energy and CO2 emission related contributions and taxes, used to finance subsidies to renewables and building renovations, will be replaced after 2020 by a "steering" system. In this system, fiscal measures will lead to the agreed upon energy and environmental targets, by setting appropriate price signals through the market. Moreover, the revenues of these fiscal measures could be redistributed back to the public in various ways. Redistribution schemes considered include lump-sum redistribution, reduction of income taxation, reduction of the VAT tax, reduction of social contributions, or a mix of these measures.

Following this, a tax revenue redistribution by skipping the VAT was rejected by referendum in March 2015. To avoid any political tension, the SFC decided in October 2015 through a Federal Message that tax revenues from higher environment-related taxes are only to be recycled in a lump-sum way.[11] The strand of applied economic literature used in this consultation consists of static CGE models replicating the Swiss economy without considering any growth effects. As we already explained, this approach neglects innovation and sectoral change, which are very important aspects of the environmental tax reform. Furthermore, estimating the growth effect of tax reform with static models becomes a moot point.

The proposed fiscal measures by the SFC are mainly based on Ecoplan (2012), Ecoplan (2013). Using a static but detailed model of the Swiss economy based on the Swiss Input-Output Table (IOT) with different household categories, these studies present the social consequences of an environmental tax reform for different redistribution schemes. They find that only a small second dividend can be achieved and then only under a certain scenario of redistribution through lower direct federal taxes. Equity issues are being addressed by redistributing part of the revenues in a lump-sum fashion. A version with the most relevant results from the first two previous papers can be found in Boehringer and Müller (2014). Mostly negative welfare results from an ETR in Switzerland has been also found in Imhof (2012).

[10] It was stated in the introduction that an empirically relevant point is that as the consumer price of energy increases due to higher carbon taxes, it becomes more attractive to develop technologies that can produce clean energy or improve the efficiency of polluting energy. As in the case of leisure, this could crowd-out scientific labor and investment from intermediate varieties, which could act negatively on overall growth. This mechanism is assumed away in this part, although it is in fact included in the numerical segment of section 3.

[11] In German: Botschaft zum Verfassungsartikel über ein Klima- und Energielenkungssystem, 28.10.2015.

3.2. Numerical model

For the numerical segment we construct a multi-sectoral numerical general equilibrium model of endogenous growth that keeps the core components of the theoretical framework in section 2 and builds on Bretschger et al. (2011). In this model intentional investments in R&D endogenously determine the growth rate of each sector and the economy as a whole.[12] It gives a detailed representation of the input/output linkages of the Swiss economic sectors, imports-exports and has a detailed technological representation of the energy outlook of Switzerland. The model of Bretschger et al. (2011) can capture directed technical change in the sense that it allows for the reallocation of R&D inputs depending on the relative prices among sectors and it has been used to study environmental policies in Switzerland. It has been also used in Bretschger and Zhang (2016) for evaluating the economic cost of a nuclear phase-out policy.

Here, we extend its structure in several directions. First, we consider a detailed representation of the Swiss fiscal system. In the previous versions of the model preexisting taxation was not considered, which is however essential when studying an environmental tax reform. Second, we keep the multi-sectoral representation of the Swiss economy, but we include several household categories with heterogeneous economic behavior as found in the benchmark data. Third, we include leisure in the model and the possibility that labor is mobile not only within manufacturing and R&D, but also between these sectors, which, based on our theoretical framework, opens up a new channel for input reallocation towards innovation. Fourth, we examine different redistribution schemes for the carbon tax implemented and show the results in terms of growth and welfare, in aggregate, but also for each household group. Figure 1 sketches the model.

Technology and production

As illustrated in Figures 1 and 2, sectoral output Y_i, is produced through a three-stage production process. At the highest level, final good producers, operating in a competitive market, use both sector-specific inputs along with commodities from all other non-energy sectors. The second nesting corresponds to the sector-specific Dixit-Stiglitz production function of section 2, i.e.

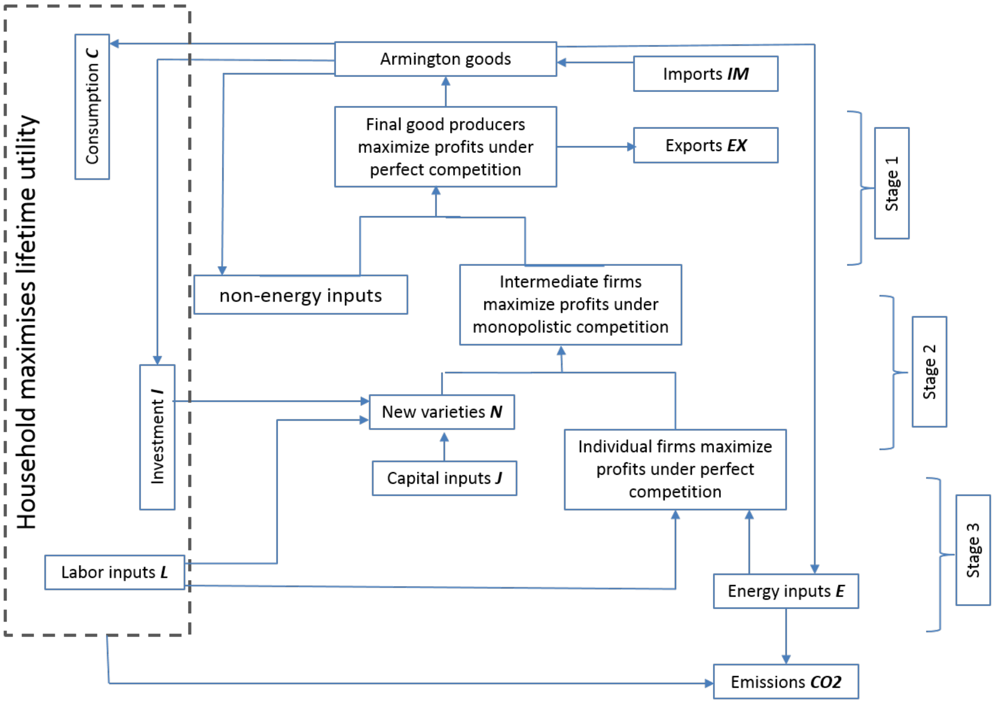
$$Q_i = \left(\int_{j_i=0}^{N_i} x_{j_i}^{\beta} d j_i \right)^{1/\beta}. \tag{21}$$

Intermediates use labor in manufacturing and energy directly as factors of production, while capital used in Q accumulates using labor and direct investments. In the numerical model simulating the real world economy, physical capital is combined with knowledge capital and forms the composite capital to represent the firm value. Specifically, we assume that knowledge capital and physical capital are perfect substitutes as in Suzuki (1976). Therefore, each new intermediate firm owns a new composite capital good which consists of physical and knowledge capital. This ensures that our analysis rests on a broad concept of capital and reflects the real world production process.[13] Labor is freely mobile between every economic activity and

[12] The assumption of a significant R&D sector for such a small country as Switzerland might seem dubious. However Switzerland is in fact the leader of innovation in Europe. It spends more than twice as much on R&D than the EU27 average (as a percentage of GDP in 2013: Switzerland 3.1%; Germany 2.83%; EU27 2.03%; Japan 3.47%; US 2.73%. In $/capita: Switzerland 1'835; Germany 1'290; EU27 690; Japan 1'310; US 1'470 (World Bank indicators - own calculations)). In 2007 it obtained the highest number of patents per million inhabitants among industrialized countries (118), three times higher than the OECD average (42) (Raiser and Gill, 2012).

[13] The motivation for this assumption is mainly driven by the fact that there is no explicit data available to adequately measure the knowledge capital in a multi-sector economy. A future research could be conducted to differentiate between different types of capital goods based on sound empirical estimations.

Figure 1: Sketch of the model (one good)



leisure while we are using a time step of ten years so that the economy has enough time to educate and train its labor force to take up positions in the research sector; see footnote 4.

Each firm in the same sector produces symmetric products with limited substitutability; see equation (21). This fact supports a degree of market power so firms in the intermediate sector operate in a setting of monopolistic competition. As in (6), to raise the output of sectoral specific intermediates, one can increase the production of individual firms, or expand the number of firms in the sector. Since new firms need blueprints embedded in the capital for production, this effectively indicates a growing process of capital build-up. In the capital formation sector, firms enter freely into investment activity producing the sector-specific capital with research labor and direct investments. The law of motion of capital in the model reads:

$$N_{i,t+1} = \left[\alpha_{Ni} I_{Pi,t}^{\frac{\tau-1}{\tau}} + (1-\alpha_{Ni}) I_{Ni,t}^{\frac{\tau-1}{\tau}}\right]^{\frac{\tau}{\tau-1}} + (1-\delta_t) N_{i,t}, \tag{22}$$

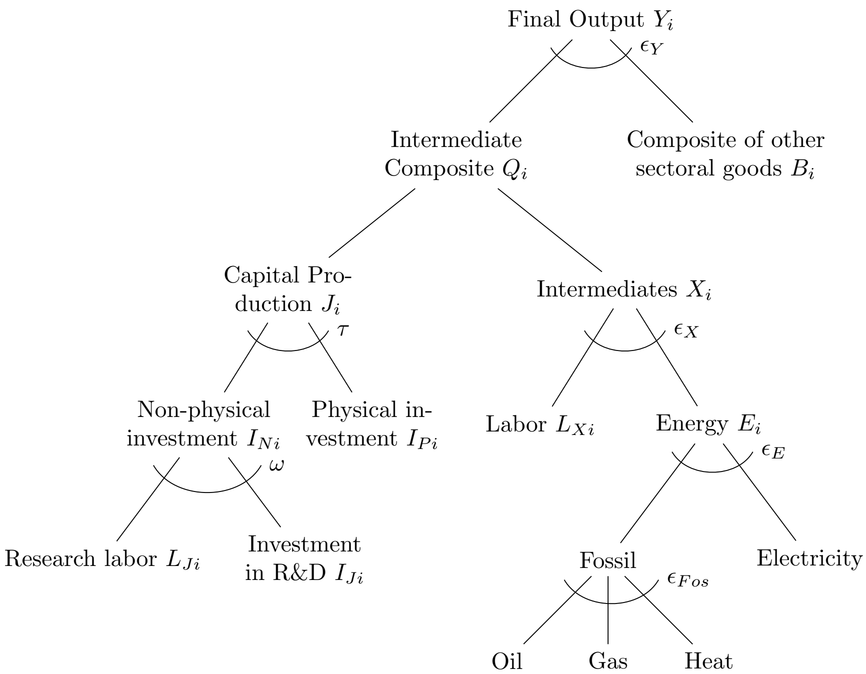
with investments in physical capital denoted by $I_{Pi,t}$, and in non-physical capital by $I_{Ni,t}$. Parameter τ represents the elasticity of substitution between the two investment types, α_{Ni} is the value share of physical investment, and δ_t is the depreciation rate. New investments can be directed to any sector according to its expected profitability. Similar to (9), non-physical investments I_{Ni}, are determined by scientific labor L_{Ji}, and non-labor inputs in research I_{Ji}.

Finally, the production of the energy sector differs slightly in that it assumes an additional level at the top of the nested production function, where sectoral output is being produced with fossil energy and electricity.[14] They are assumed to be imperfect substitutes with elasticity of substitution ϵ_E. Non-fossil

[14]Electricity in Switzerland is almost CO2-free, so electricity and fossil fuels are differentiated in the model.

energy is produced in the same way as regular goods, while fossil energy consists of refined oil, gas and district heating, with different carbon intensities (amount of carbon emitted per unit).[15][16]

Figure 2: Production structure of each regular good



Preference and household consumption

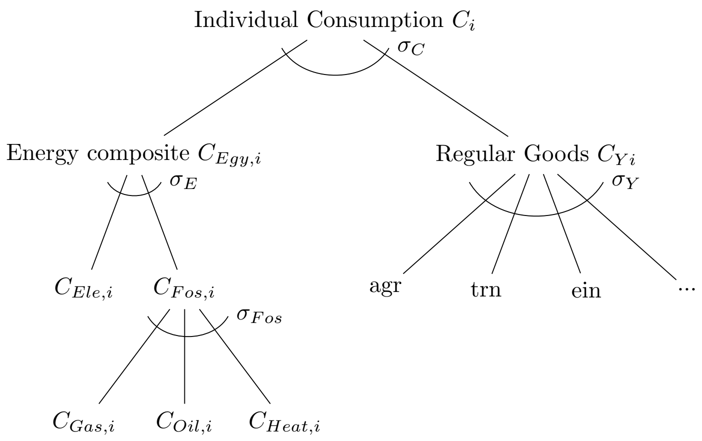
We distinguish different household categories based on their working status (active - retired) and on their income level. Each household, holding ownership of intermediate firms in all sectors, the capital of the economy, supply this along with labor in manufacturing and research. Households maximize intertemporal utility by allocating their time endowment between work and leisure, and their income between consumption and saving for investment under perfect foresight. Their total income consists of net factor income and transfers by the government and other households, while their expenditure of gross consumption expenses, tax payments, social security contributions, direct transfers to other households and investments.

[15] District heating uses heat from large thermal power plants or waste incineration facilities and delivers hot water to consumers via pipelines. We therefore consider it as fossil fuel technology. Carbon intensities in the model are 1.35 for oil, 1.01 for gas and 1 for district heating.

[16] In this part of the paper each energy good is itself an economic sector with its own R&D. Research efforts respond to climate policies through the various layers of substitution and scarce inputs flow to the sectors with the highest returns. The input substitution between fossil energy (dirty) and electricity (clean) is affected by the relative price of fossils (affected by carbon taxes) over electricity price. As the production of electricity is almost carbon free in Switzerland, a higher carbon tax will strongly affect the choice of using fossils and electricity. In the bundle of fossil energy, the substitution between different types of fossil energies exists. Energy sources with lower carbon content will be chosen compared to ones with higher carbon content. To produce energy, both energy and non-energy inputs are required. As energy input becomes relatively expensive, the non-energy inputs are favored in the production process. We also open up labor mobility, which means that labor can be reallocated between energy and non-energy sectors, as well as between research and non-research (manufacturing) activities. Furthermore, the efficiency improvement is introduced through the increases-in-varieties effect. With increasing capital accumulation, the use of other inputs, like energy, becomes more efficient because their productivity increases with more capital being available.

Instantaneous utility is composed of commodity consumption where each household group presents its own preference for different consumer goods, and leisure. Commodity consumption includes the consumption of energy goods and non-energy goods. Within the aggregate energy demand, electricity trades-off with fossil energy which comprises of gas, oil, and district heat. Substitution possibilities within each nesting are given by CES preferences. Figure 3 shows the consumption structure of an individual.

Figure 3: Consumption structure of individual households



Government and international trade

The government collects taxes in order to finance transfers and to provide public services, which are produced with commodities purchased at market prices. In the model, we keep the level of public service provision fixed and balance the public budget through lump-sum transfers proportional to the benchmark share of persons in each household class. This is the equal-yield instrument we choose for our policy comparison.

The economy is small but open to international trade in goods. Goods produced in domestic firms can be used for the domestic market or the export market with a trade-off ruled by a constant-elasticity-of-transformation function. We assume imports are Armington substitutes for domestic goods due to product heterogeneity; the demand for good i can be covered by domestic output Y_i and imports M_i according to

$$A_i = \left[\alpha_A Y_i^{\frac{\xi-1}{\xi}} + (1-\alpha_A) M_i^{\frac{\xi-1}{\xi}}\right]^{\frac{\xi}{\xi-1}}, \tag{23}$$

with α_A the value share of output Y_i, and ξ the elasticity of substitution between Y_i and M_i. Trade is balanced in every period. As in section 2, due to the small country assumption foreign prices are exogenous. Trade in assets is also not considered. Finally, even though our model is based on endogenous innovation and the sectoral spillovers it creates (see for example equation (8)), we do not include international knowledge spillovers. The effects of international knowledge diffusion on growth and on the costs of climate policy for different aggregated regions have been studied in Bretschger et al. (2017).

Data and parameterization

This study makes use of a Swiss social accounting matrix (SAM) for 2008 which comprises of different sources: the manufacturing sectors come from the Swiss Input-Output table for 2008. The household sector is disaggregated using household budget surveys from 2007 to 2009, both by the Swiss Federal Office of Statistics. Data on tax payments and transfers are taken from the Swiss National Accounts for the year 2008. Our sources were used in the following ways:

IOT data was used to calibrate the production of the Swiss economy. Sectors are aggregated into 10 non-energy sectors, which are agriculture (agr), chemical industry (chm), machinery (mch), costruction (con), transport (trn), banking and financial services (bnk), insurances (ins), health services (hea), other services (oth), and other industries (oin).[17] Energy disaggregation follows Bretschger et al. (2011). We identify three fossil energy sources (gas, oil, district heat (dhe)), and electricity (eles), which is almost CO_2 free in Switzerland, as found in the input-output table.

To infer the tax payments across sectors, households, and the government we use the Swiss National Accounts . The model features a detailed representation of the Swiss tax system: it includes value-added taxes, income taxes on both the federal and the cantonal level, social security contributions, output taxes and import tariffs for firms, but also Swiss specific environmental taxes such as the Mineral-oil tax and the Climate-cent tax.[18] Other minor taxes and subsidies were also included as taxes on sectoral inputs by firms and consumption for households.

Furthermore, we use the household budget surveys from 2007 to 2009 to calibrate the households consumption, investment, and transfers. We have divided the Swiss population in five groups according to their professional status (active-retired) and income. Each household group features also its own labor-leisure choice with data taken from the Swiss Federal Office of Statistics.[19] Figure 4 presents the demographics of the representative households. The active low income group accounts for around 47% of the total population in Switzerland with an average income of approximately 4200 CHF per month, where 80% of the total income is from labor earnings. The average income of the active high income group is more than four times larger than the active low income group. Both capital and labor earnings contribute equally to the total income of the active high group households. Similarly, for retired households, the high income group receives most of its income from capital earnings. In terms of expenditure, high income groups (both active and retired) are the major sources of investment while low income groups spend most of their income on consumption.

The elasticities of substitution between polluting fossil fuels and CO2-free electricity in production (ϵ_E), and consumption (σ_E), are obviously very important for our results as poor substitutability leaves less room for the economy to respond to a carbon policy and substitute away from polluting energy technologies; this might dampen the whole production process and impair economic growth and household welfare. The estimated values in the literature range from 0.5 (Boehringer and Rutherford, 2008; Goulder and Schneider, 1999) to 1.5 (Gerlagh and van der Zwaan, 2003). We will use a low value of 0.7 for our main simulations while in the sensitivity analysis we present the results in terms of growth and welfare for a high elasticity of substitution. Table A.6 in the Appendix presents the chosen values for the elasticities used along with their sources.[20]

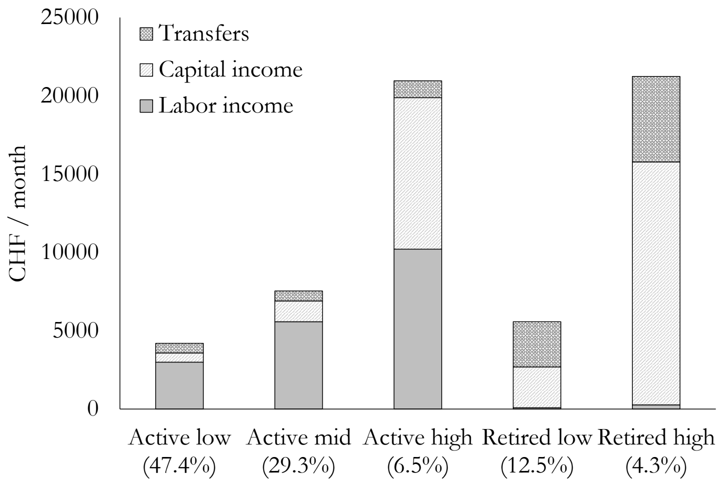
[17]We have limited the number of regular sectors to 10 due to the computational complexity of the dynamic model. However, all the important sectors for the Swiss economy are presented in the model. Moreover, we have a detailed representation of the Swiss fiscal system and several household categories.

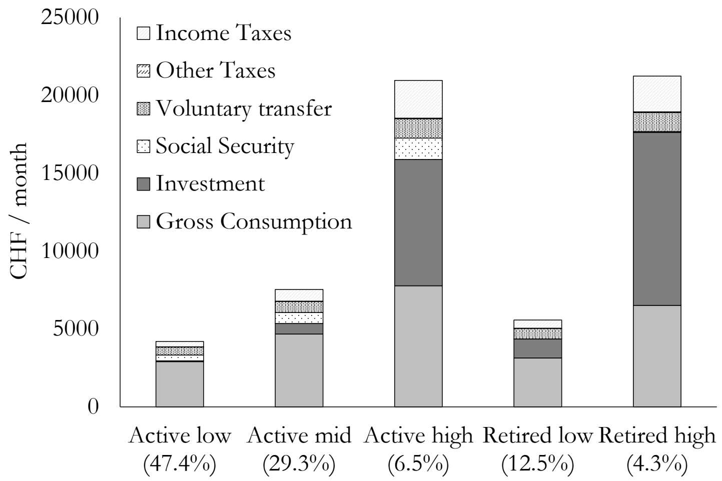
[18]These two taxes on fuels made together about 5.5 billion CHF in 2008, or about 3% of total tax revenue. Even though their contribution is small, we include them for the sake of completeness.

[19]We use the complement of the labor participation rate as a proxy for leisure. The Swiss Federal Office of Statistics publishes data on income and on the labor force participation rate for several age groups. We therefore do a mapping for the time endowment of the households between age groups and income groups according to our household categories: Active low (0.15), Active mid (0.1), Active high (0.25), Retired low (0.9), Retired high (0.9).

[20]In our analysis, the elasticity of substitution between fossil fuels and electricity is set to be 0.7 in the reference scenario. The

Figure 4: Income and expenditure structure of household groups. In parentheses the population share.





Calibration for the balanced growth path

In the model, a general equilibrium is a set of prices and quantities which clears goods and factor markets and satisfies the first order conditions for firms and households. On the balanced growth path (BGP) all variables grow at a constant rate. Let g_Q and g be, respectively, the growth index (in the discrete

compensated own-price elasticity of a CES function is approximately $\epsilon = -\sigma(1-\phi)$, where σ is the elasticity of substitution and ϕ the share of fossils fuel in total energy consumption. The value of ϕ is about 40% from Swiss statistics, the compensated own-price elasticity is therefore about -0.4. Labor supply elasticities (or Frisch elasticity) is highly dependent on the level of labor supply relative to the amount of leisure for each household group. For active households with leisure ratio between 0.1 and 0.25, the labor supply elasticity ranges between 0.1 and 0.3, which is consistent with most microeconomic estimates ranging from 0 and 0.5.

time framework of the numerical model this is one plus the growth rate) for final output and the number of varieties. According to (6) and (21) on the BGP final output grows at $g_Q = g^{1/\beta}$. To ensure that a BGP exists, following Bretschger et al. (2011) and Bretschger and Zhang (2016), we calibrate the model so that each sector's capital expenditure is a share $1 - \beta$ of the value of intermediate composite Q with $\beta = 0.25$. Accordingly, on the BGP all sectors grow at the same rate. We calibrate the model to a steady-state baseline extrapolated from the Swiss SAM for 2008 using exogenous assumptions on the growth rate of output, the interest rate, the intertemporal elasticity of substitution, and capital depreciation rate in time. The choice of the annual interest rate is important for the results of a long-term analysis like the present one. We use a value of $\bar{r}$=0.01 for the, net-of-tax, return on capital.[21] To waive the gains from specialization effect in (22), which ensures a growing investment over time, the depreciation rate δ_t rises moderately every year, with δ_0 set to 0.07. This is equivalent with using the negative spillovers for direct investments in (9). The benchmark growth rate of the economy is set to 1.33 percent reflecting roughly an annual average of Switzerland in the last two decades. The discounting rate ρ is thus endogenously determined by the model along a balanced growth following the usual Keynes-Ramsey rule of consumption growth (Euler equation).[22]

Computational strategies

To approximate the infinite horizon by a finite-dimensional computational model, we use the state-variable targeting approach proposed by Lau et al. (2002). Importantly, this allows us to target the terminal capital stock of each sector individually. After policy is implemented, this leads to an endogenous growth rate for the overall economy on a new balanced growth path, by using a series of complementarity constraints on the growth rates of sectoral investments. 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 solve the numerical mixed-complementarity problem. The baseline model includes the current fiscal status of the Swiss economy.

3.3. *Design of computational policy experiments*

Switzerland has one of the lowest CO2 emission levels among the OECD countries with about 5 tons per capita in 2010. Part of its ambitious plan of sustainable development is to reduce this number by about 60-65% in 2050. The "business as usual scenario" (BAU) includes all the existing energy related contributions and taxes that are in place in the Swiss economy as reflected in the base year data. To comply with the aforementioned CO2 reduction target we impose carbon allowances where the level of CO2 tax is determined by the shadow prices of quotas in equilibrium. We will present results on growth and welfare for 20%, 40%, and 60% emissions reduction in 2050 compared to 2010.

The revenue from the additional carbon emissions taxation is collected by the Swiss government and enters the government budget. Regarding the revenue-neutral tax swap we keep the level of public good provision constant, while the government recycles the excess income through lowering preexisting taxation or through a lump-sum redistribution. We consider three alternative revenue recycling schemes: i) lump-sum per-capita transfers to households; ii) proportional cuts of federal labor income taxes; iii) proportional reduction of capital income taxes. Due to the fact that the VAT in Switzerland is already very low (8% for normal goods, 3.8% for lodging, and 2.5% for basic goods) and that a redistribution of tax revenues by skipping the existing VAT tax was rejected by referendum in 2015, this scenario will not be examined.

[21] According to the Swiss Federal Office of Statistics, the interest rate in Switzerland averaged 1% from 2000 until 2016, reaching an all-time high of 3.5% in June 2000 and a record low of -0.75% in January of 2015. Therefore, we decided to use the value of 1% for our simulations.

[22] For a detailed explanation of how to calibrate a growth model to a BGP see Rutherford (1999).

Scenario i) follows from the recent decision by the Swiss government to redistribute the additional tax revenue from a green tax reform in a lump-sum way. However, such an option is not alleviating any inefficiencies in the fiscal system since the positive revenue recycling effect mentioned in the introduction is absent which might lead to wasting valueble government revenues. Accordingly, this option should in general cause a worsening of overall economic efficiency even if it increases the disposable income of households which can be welfare promoting at the household level. This applies especially to poorer households because such a transfer makes a larger part of their income. Consistent with the above, our results on aggregate welfare show that redistributing additional carbon tax revenue by lowering capital and labor income taxes outperforms lump-sum redistribution.

Our model does not explicitly simulate external effects such as environmental benefits from emission mitigation activities, i.e. we do not consider the first dividend of the environmental policy in our calculations. An ex-post monetization of the reduction of externalities associated with pollution can be introduced by using exogenous estimates. For example in Boehringer and Müller (2014), external environmental effects from an environmental tax reform amount to an increase in welfare by 0.2 – 0.5%, depending on the stringency of the emission reduction target. Finally, we also do not assume any exogenous energy efficiency improvements or escalating costs for non-renewable resources. We do that in order to focus on the dynamic response of the benchmark economy to the carbon policy, and on the quantification, in terms of economic growth and welfare, of the maximum cost that the Swiss society has to incur.

4. Simulation results

4.1. The carbon tax

Table 1 shows the CO2 tax needed for Switzerland to reach 60% reduction in CO2 emissions in 2050 in comparison to 2010. We choose a linear increase in the CO2 reduction target until 2050 relative to 2010. The tax profile is very similar for all the tax recycling schemes: the standard deviation from the mean is 2.2 \$/tonCO2 in 2030, increasing to 9 \$/tonCO2 in 2050. The level of the tax is in-line with other studies made for Switzerland: for example in Ecoplan (2015) for a 63% emissions reduction a uniform carbon tax on all emitting sources of 336 \$/tonCO2 in 2030 is calculated. These tax rates raise tax revenue equal to about 1.5% of Swiss GDP in 2020 up to almost 10% of GDP in 2050. Below we present the effects of this increasing tax on economic growth and welfare of the Swiss society.[23]

Table 1: Carbon tax in \$/tonCO2 and carbon tax revenue as a percentage of GDP for 60% emissions reduction in 2050 and different redistribution options

Year	Capital tax	Fed. Income tax	Lump-sum	Carbon Tax Revenue (% GDP)
2020	107	107	106	1.5
2030	314	311	310	3.5
2040	722	717	716	6.1
2050	1’717	1’705	1’706	9.9

4.2. Effects of carbon policy on production

In the theoretical part we showed that, following a green tax reform, the positive growth effect of induced innovation can counteract the negative level effect of increasing production costs and can lead to higher

[23]The initial calculation was made in Swiss Francs (CHF). We used the conversion 1 CHF/\$ for our calculations.

growth rate of output, while the results are in general ambiguous. In this section we exhibit and discuss the results of our carbon policy on investment, sectoral growth and aggregate production.

Table 2 presents the growth rate of total output in 2050 for the different emissions reduction targets and different tax revenue redistribution scenarios. There are three points to raise here: first, out of all the redistribution scenarios the one that performs best in terms of economic growth is redistribution through lowering capital taxation. This result is intuitive since a lower price of capital leaves room for more investment into capital formation. The impact of the green tax reform on economic growth is independent of the redistribution scheme for the other two scenarios. In general, the effects are small. Second, Switzerland can reach a long term environmental target of 60% CO2 emissions reduction with a small reduction in economic growth up to 0.5% in 2050 compared to the BAU. Third and most important, a moderate carbon reduction target of up to 40% in 2050 can still lead to enhanced investment activity even in the case of limited substitution possibilities away from polluting energy sources. For high emission taxes, however, one is to expect slightly negative results on investment and growth as the stringent carbon policy imposes restrictions on the economy which cannot be overcome by stronger innovation or substitution between energy and other factor inputs. This can be best seen in Figure 5 where we plot the growth paths (normalized to the BAU trajectory) of aggregate output, R&D labor expenditure, and total investment in the lab for 20% and 60% emissions reduction in 2050 and two redistribution scenarios, reduction in capital taxation and lump-sum redistribution.[24]

Table 2: Long-run aggregate output growth (% p.a.) for different CO2 emissions reduction targets in 2050 and different redistribution options

Target	BAU	Capital tax	Fed. Income tax	Lump-sum
20%	1.33	1.35	1.31	1.31
40%	1.33	1.34	1.30	1.30
60%	1.33	1.31	1.28	1.28

Our discussion in sections 2.4 and 2.5 is relevant for explaining the results of such a carbon policy on investment and growth in our endogenous growth framework. On the one hand, as explained in part 3.2 and in particular using the top two nestings of figure 2, to raise sector-specific output one can increase the input of other sectoral goods, of intermediates, or the number of intermediate firms, each entitled to a blueprint of production, i.e. the capital stock of the economy. Accordingly, higher growth through induced innovation in the research lab can translate to higher levels of production and investment in subsequent periods.

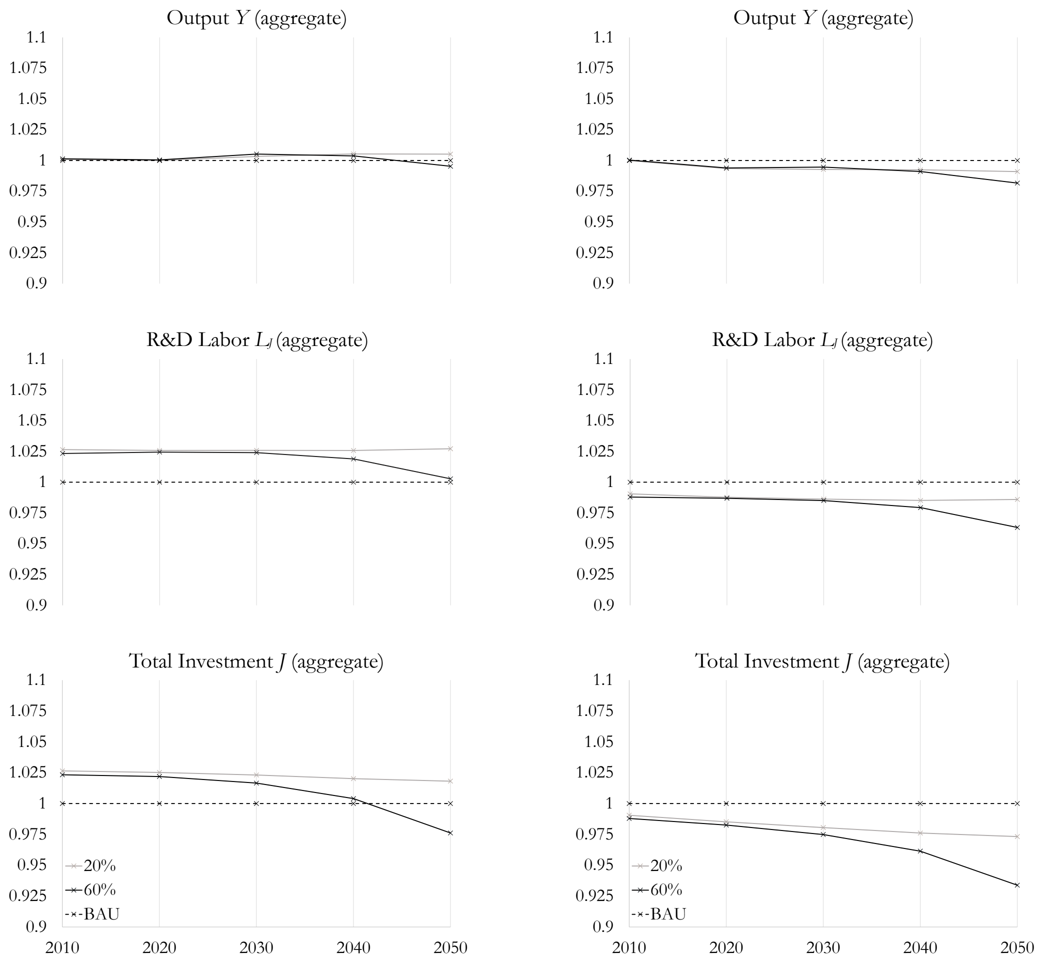
An increase in the consumer price of energy exerts a downward pressure on the real wage rate making labor in the lab cheaper which can promote growth. This of course can be counteracted by a reduction in aggregate labor supply, as explained in the theoretical part. Counter to the positive growth effect runs a level effect that reduces the demand for the final good and leaves less available resources to investment; a carbon policy that suppresses the demand for energy intensive goods might dampen the whole production process. Our results show that redistributing additional tax revenue by lowering capital taxation is beneficial for investment, resulting also in aggregate production being relatively unaffected. However, the increasing carbon tax that continuously dampens production, turns the results negative in the long-run when we aim at a high emission reduction target. A lump-sum redistribution is the least favorable option for entrepreneurial

[24]As in (9), total investment uses labor in R&D and final output from the different sectors in the form of direct investments in the lab.

activity. In this case the path of investment is always lower than in the BAU and the growth dividend of an environmental tax reform fails instantly; the level of aggregate production is also subsequently lower since the loss in demand caused by the high energy price in not compensated by higher investment in innovation and growth.

Our numerical model of endogenous growth shows that, in a real economy with a detailed representation of its sectoral linkages and preexisting tax distortions, an environmental tax reform is not detrimental either in terms of production levels or output growth; see Figure 5 and Table 2. On the contrary, even in the relatively pessimistic case of limited substitutability between clean and dirty energy inputs, higher growth through induced innovation is a plausible outcome for not very stringent carbon taxation.

Figure 5: Production, R&D labor expenditure, and total investment (normalized to BAU) for 20% and 60% CO2 emissions reduction in 2050 - aggregates.



(a) Capital tax redistribution

(b) Lump-sum redistribution

4.3. Effect of carbon policy on consumers

A central feature of the green tax reform reform is that the efficiency of the economic system should be promoted while existing inequalities between social segments should be minimized. Our indicator for the efficiency of the economic adjustment is welfare, including both the discounted stream of consumption and leisure for each individual household group. Aggregate welfare is measured by introducing population-based weights of each household group shown in Figure 4. This metric quantifies the aggregate efficiency impact of our policy experiments in comparison to the BAU scenario, according to which Switzerland follows its current environmental and energy policy.

As we already noted, we do not consider the first dividend of the environmental policy in our calculations. An ex-post monetization of the reduction of externalities associated with pollution can be introduced by using exogenous estimates as in Boehringer and Müller (2014). In this contribution external environmental effects from an environmental tax reform amount to an increase in welfare by $0.2-0.5\%$, depending on the stringency of the emission reduction target. This increase is potentially larger if we take into account the economic cost of continuously increasing future climate degradation. Accordingly, our welfare indicator includes the second and the third, but not the first dividend of the policy.

Aggregate welfare

The aggregate efficiency of the green tax reform crucially depends on the stringency of the environmental targets, on the redistribution option, and on the tax base considered. A high CO2 emissions tax, on a rather narrow tax base, creates distortions in the economy that cannot be overcome by any redistribution scenario. Labor and capital income tax rates in Switzerland, both applying on a wide tax base, are not that big compared to energy taxes.[25] Hence, labor and capital are "undertaxed" in comparison to polluting energy sources, and so, using additional carbon tax revenues to further reduce labor or capital taxation is inefficient and leads to welfare losses. As we already indicated, a lump-sum redistribution is bound to perform even worse in terms of economic efficiency since it does not correct any distortions in the fiscal system.

The positive effects of reduced tax distortions from the various redistribution schemes along with the potentially induced growth effects are not able to exactly offset the negative tax interaction effects of higher carbon taxes. In addition, the inefficiency increases over time as demand for polluting energy is decreasing and the carbon tax base is effectively shrinking; apart from missing any growth considerations, static models tend to underestimate the effects of such a tax reform on welfare. Our results indicate that an environmental tax reform does not allow for higher welfare when the first dividend is absent. On the premise, however, that a green tax reform will promote a cleaner environment, one should search for the least distortive option. Table 3 suggests that the welfare loss under capital tax redistribution is the smallest. Building on equation (20) and our discussion in the previous section, this option is preferable for capital accumulation which then promotes the growth effects of the policy on the aggregate level.[26]

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[25] On net basis, labor income tax rate varies between 9-20%, capital income tax rate between 8-11%, while energy taxes associated with the environment between 30-45%.

[26] As indicated in Saez et al. (2012), the taxable income elasticity captures all the behavioral responses to taxation and can, thereby, be used as a measure of the relative efficiency gains between policies. Using their definition we find that in the reference scenario and for the most stringent CO2 emissions reduction target, the value of this elasticity is 0.18 for capital tax redistribution and 0.09 for the labor income tax redistribution. This effectively indicates that redistributing additional carbon tax revenue by lowering capital taxes is most efficient by this metric as well.

Table 3: Welfare change (in % from BAU) for different CO2 emissions reduction targets – excludes the first dividend

Target	Capital tax	Fed. Income tax	Lump-sum
20%	-1.19%	-1.24%	-1.33%
40%	-2.09%	-2.13%	-2.25%
60%	-3.79%	-3.83%	-4.00%

Distributional considerations

Figure 6 presents the effects of a environmental tax reform in Switzerland on the welfare of the different social groups for each redistribution scheme for a low and a high emission reduction target. In a static setting, household consumption expenditure is affected by the positive revenue recycling effect that increases their disposable income and the negative tax interaction effect of higher energy taxes that reduces it (Bovenberg and De Mooij, 1994). As already discussed, our model includes additionally distorting effects of an ever shrinking tax base – the polluting energy goods – and the potential positive growth effects of induced innovation. The first dividend is not quantified.

Table 4 shows the energy expenditure share of total disposable income for different household categories: the least well-off spend a larger part of their disposable income on polluting energy. Accordingly, higher emission taxes are more likely to harm poor segments of the population, i.e. carbon taxation is inherently regressive. Apart from that, one needs to consider the main income sources of the different social groups.

Redistributing tax revenues from additional environmental taxes by lowering capital or labor taxation produces in general regressive results because capital and labor income is relatively low for poor households in comparison to the middle or rich segment. If the emission reduction target is low, the welfare of the upper social segments is least distorted when the government uses additional carbon tax revenue to cut income taxation. Moreover, an increase in welfare results for the upper social group of the active population and the retirees if, respectively, cuts in labor and capital income taxation are considered, because in this case existing market distortions are reduced. However, stringent emissions reduction targets coupled with high carbon taxation, tend to reduce available income more than they reduce distortions in the active population and individual welfare is worsened. This does not apply to the rich retirees since they spend only 1.2% of their disposable income on polluting energy; a welfare increase is possible in their case.

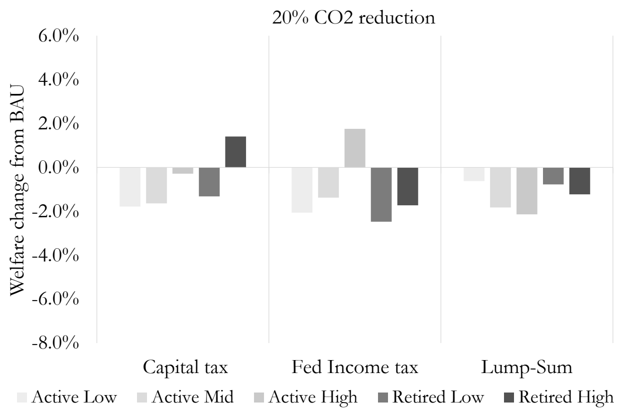
When it comes to pure equity considerations in Switzerland the consensus in the literature speaks in favor of a lump-sum redistribution; see for example Imhof (2012) and Boehringer and Müller (2014). This redistribution scenario that increases the available income of households without reducing any distortions in the fiscal system is more beneficial to the poor. If the emission reduction target is not too high, redistributing tax revenues in a lump-sum fashion mitigates the reduction in disposable income, from higher energy prices, and consumption of the poor segments due to higher energy taxes. In this case we also get that a lump-sum redistribution produces progressive results. Nevertheless, the progressive character of the lump-sum tax redistribution fails when we consider a very high emission reduction target.

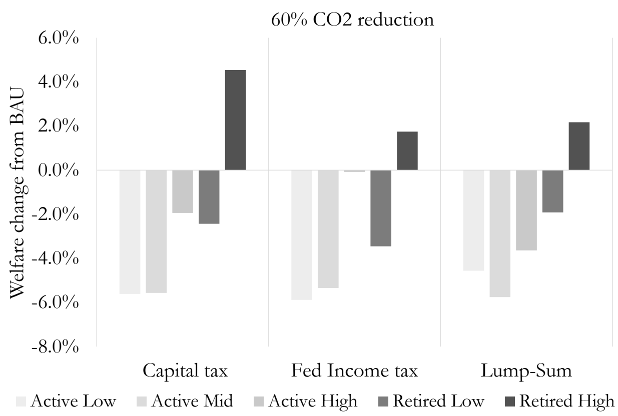
In the case of the lump-sum per-capita redistribution and the stringent CO2 emission reduction target, the difference between the first two groups of the active population, which are mostly dependent on polluting energy, can be understood as follows: for a low emission reduction target the additional lump-sum income allocated to the poor almost compensates the income reduction from the higher energy tax because lump-sum transfers consider a big part of the household income for the least well-off. Since, however, such a scenario does not correct distortions in the labor market, the middle segment is genuinely worse-off. The same comparison applies between the poor and the rich social group. However in this case the CO2-intensive energy expenditure share of the total disposable income for the rich group is almost the half compared to the poorer, i.e. higher energy taxes do not affect their disposable income that much.

Table 4: CO2-intensive energy expenditure share of total disposable income for different household categories

Active Low	Active Mid	Active High	Retired Low	Retired High
3.9%	3.7%	2.3%	2.3%	1.2%

Figure 6: Welfare change (in % from BAU) for 20% and 60% CO2 emissions reduction in 2050 – excludes the first dividend





4.4. Policy implications

The Swiss Federal Council decided to go forward with an environmental tax reform from 2020 on as a means of reaching its energy and environmental targets up to 2050. To comply with the stringent CO2 reduction targets we impose a carbon tax on polluting energy sources according to their carbon intensity. The redistribution of the tax revenues should take into account its effect on economic growth, aggregate welfare and equity among social segments.

Production side considerations would speak in favor of lowering capital taxation. This result is intuitive since by reducing distortions in the capital market, investment is promoted. Increasing capital varieties make the use of other inputs like energy more efficient. This can counteract the negative level effects of increasing energy taxes compensating for the additional tax burden, and resulting to higher economic growth if a low CO2 emission reduction target is followed. Higher growth translates to higher output in subsequent periods; the level of output is subsequently only minimally impaired even for a very stringent environmental policy. In general the results on economic growth are not detrimental even in the case of limited substitutability away from polluting energy sources.

Concerning welfare, in aggregate, relatively low capital and labor taxation, along with a narrow, and ever-shrinking, tax base of the energy input end up exacerbating rather than alleviating preexisting tax distortions. Lump-sum redistribution produces the least efficient option since the positive revenue recycling effect of the green tax reform is absent. If CO2 reduction target is not too ambitious redistributing tax revenues by lowering capital taxation allows for a welfare increase to the upper segment of the retired population; lowering labor income taxes benefits the upper segments of the active. A more stringent environmental policy mostly benefits the richer social segments due to their low expenditure share on CO2-intensive energy. When it comes to lump-sum redistribution, our results are also aligned with those of the Swiss economic literature but only for a low emission reduction target: a 20% emissions reduction in 2050 compared to 2010 produces progressive results; considering, however, the more stringent target of 60% reduction, produces regressive results. Accordingly, using lump-sum tax redistribution from a stringent environmental fiscal policy to address equity considerations might not be the best option for Switzerland.

Even though there is still a long way to go to fight climate change, there has been a great improvement in terms of international cooperation. As an example, the Paris climate change agreement has been a worldwide diplomatic success. Yet, although many countries have signed the agreement, the collective efforts from all those countries are still far away from saving our planet. This study suggests to policy makers in individual countries that the effects of carbon policy on the economys performance could be limited through the positive growth effects of induced innovation, and that a stringent climate policy does not necessary hurt the country's economy. To that respect, at the global level, Bretschger et al. (2017) show that knowledge diffusion can lower the costs of climate policy for all countries, in particular for developing countries like China. Hence, if carbon tax revenue is used for the capital investment for research and new technology development, the spillover effects of knowledge will spread across the border and finally reduce the costs of climate policy for the world at large.

4.5. Robustness

The elasticities of substitution between polluting and clean energy (electricity) in production and consumption are crucial for the results, while their values vary greatly within the literature. Low elasticities reduce the substitution possibilities away from polluting sources which dampens the economic performance of the market at stringent emissions reduction targets. So far we have assumed limited substitutability in order to be on the safe side and reduce the risk of understating the economic costs of a green tax reform. Here we are presenting also the results for a high value of 1.5 for both ϵ_E and σ_E.[27] Table 5 shows the results in 2050 for a 60% emissions reduction, in terms of carbon tax, economic growth and aggregate welfare.

As expected, a high value for the elasticities of substitution between polluting and non-polluting energy in production and consumption, $\epsilon_E/\sigma_E = 1.5$, is beneficial for the performance of the economy considered. That is exactly because the economy is able to substitute away from polluting energy sources and because in this way input reallocation between economic sectors is easy. In this case the effects of the environmental policy are not detrimental. This adds on top of the growth effect we identified of reallocating resources to the R&D sector and growth is raised further. The latter is a proof about the growth dividend of the green tax reform. Accordingly, economic growth is higher in the long-run, the carbon tax needed for Switzerland to reach the ambitious target of emissions reduction is lower than in the main simulation, and the impact of the carbon policy on aggregate welfare is smaller. Between the redistribution options nothing has changed: redistributing additional tax revenues through lower capital taxes performs best in terms of economic growth and aggregate welfare.

Table 5: Robustness check for the elasticities ϵ_E/σ_E. Results in 2050 for 60% emissions reduction

$\epsilon_E/\sigma_E = 1.5$	Capital tax	Fed. Income tax	Lump-sum
Carbon tax ($/tonCO2)	1209	1200	1200
Output growth (% p.a.)	1.36	1.33	1.33
Aggr. welfare (% from BAU)	-2.65	-3.12	-3.19

5. Conclusions

In this paper we examined theoretically and computationally, using endogenous growth theory, the effect of a green tax reform on a growing economy. We first identified in a framework of endogenous growth the modeling conditions that lead to higher economic growth due to higher energy taxes.

The theoretical model showed that in a setting where R&D activity is the growth mechanism of the economy, an environmental tax reform can result in a positive growth dividend through input reallocation if two conditions are met: first, labor input should be mobile between manufacturing and R&D; second, the elasticity of substitution in manufacturing between the scarce factors and energy should be lower than unity. In such a case, increasing taxation of the polluting factor of production pushes more labor into innovative activities and promotes growth; a positive *growth effect*. The growth dividend fails to realize if investment in innovation is the sole result of foregone consumption. In such a case increasing the consumer price of the polluting factor makes output and direct investment more expensive, which suppresses growth; a negative *level effect*. Adding elastic labor supply reduces the scope for growth. In general the results of a green tax reform on economic growth are ambiguous.

For the numerical part we used the case of Switzerland, which has recently agreed upon implementing an environmental tax reform from 2020. To test our theoretical results we expanded our core theory model to a fully-fledged dynamic computational general equilibrium model of endogenous growth with multiple

[27] Ramer (2011) has run sensitivity analysis on a similar numerical model without taxes and with only one representative household that supplies labor inelastically for most of the parameters used here. The results for most of the parameters are qualitatively comparable; repeating this analysis here would, therefore, not add any insight. Same applies for a sensitivity analysis on the time endowment of households, as well as on the elasticity of substitution between consumption and leisure, as shown in Imhof (2012).

sectors and consumer categories. In this model investment in innovation arises endogenously, and so does economic growth. We consider three redistribution scenarios for the additional revenues of the tax reform and five social groups according to their employment status (active - retired), and income level.

When substituting away from polluting energies is not an option, the growth dividend fails in the long-run for very stringent emissions reduction targets, while it can succeed for low and medium stringency; induced innovation is effective when we redistribute additional tax revenues through lower capital taxation. Again for limited substitution possibilities away from polluting energy sources, as displayed in the simulation part, the negative level effect is, in general, dominating the positive growth effect when taxes are increasing over time. In total, an environmental tax reform in Switzerland is not detrimental for its economic performance, whichever the redistribution scenario followed, while the sensitivity analysis showed that high substitutability between clean and dirty energy in manufacturing can lead to enhanced growth through input reallocation even for very stringent environmental targets, thus giving indication of a positive growth dividend. Aggregate welfare would also speak in favor of a redistribution of additional carbon tax revenues through lower capital taxes. Equity issues are addressed by a lump-sum redistribution only for a low emissions-reduction target; the progressive character of such an option fails when we consider very high reduction targets, contradicting the consensus in the literature and showing the importance of using an endogenous growth framework over a static or an exogenous growth one when studying environmental policies.

Appendix A. Theoretical model

Appendix A.1. Definitions: relative change in the marginal products

The methodology follows Bovenberg and De Mooij (1997). Take a general production function $Y = f(m, n)$. Y exhibits constant returns to scale so that $\frac{Y}{m} = f(1, \frac{n}{m})$, or, $\psi = \psi(b)$, with $\psi = Y/m$ and $b = n/m$. Then:

$$\frac{\partial Y}{\partial n} = \psi', \qquad \frac{\partial Y}{\partial m} = \psi - b\psi'. \tag{A.1}$$

The elasticity of substitution between m and n is defined as

$$\frac{1}{\epsilon} = -\frac{\partial\left(\frac{\partial Y/\partial n}{\partial Y/\partial m}\right)}{\partial(n/m)}\frac{n/m}{\frac{\partial Y/\partial n}{\partial Y/\partial m}} = -\frac{b\psi''}{\psi'}\frac{\psi}{\psi - b\psi'}. \tag{A.2}$$

With the definitions (A.1) we can calculate,

$$\frac{\partial(\partial Y/\partial n)}{\partial n} = \frac{\partial \psi'}{\partial n} = \psi''\frac{b}{n}, \tag{A.3}$$

$$\frac{\partial(\partial Y/\partial n)}{\partial m} = ... = -\psi''\frac{b}{m}, \tag{A.4}$$

$$\frac{\partial(\partial Y/\partial m)}{\partial n} = \frac{\partial(\psi - b\psi')}{\partial n} = -\psi''\frac{b^2}{n}, \tag{A.5}$$

$$\frac{\partial(\partial Y/\partial m)}{\partial m} = ... = \psi''\frac{b^2}{m}. \tag{A.6}$$

The production elasticity of m is defined as $\gamma = \frac{\partial Y}{\partial m}\frac{m}{Y}$. The relative change in the marginal product of m and n reads

$$\frac{\Delta \partial Y/\partial m}{\partial Y/\partial m} = \frac{1}{\partial Y/\partial m}\left[\frac{\partial(\partial Y/\partial m)}{\partial n}dn + \frac{\partial(\partial Y/\partial m)}{\partial m}dm\right],$$

and

$$\frac{\Delta \partial Y/\partial n}{\partial Y/\partial n} = \frac{1}{\partial Y/\partial n}\left[\frac{\partial(\partial Y/\partial n)}{\partial n}dn + \frac{\partial(\partial Y/\partial n)}{\partial m}dm\right].$$

The last two equations with (A.3)-(A.6), (A.1), and (A.2) give

$$\frac{\Delta \partial Y/\partial m}{\partial Y/\partial m} = \epsilon^{-1}(1-\gamma)(\tilde{n}-\tilde{m}), \tag{A.7}$$

$$\frac{\Delta \partial Y/\partial n}{\partial Y/\partial n} = -\epsilon^{-1}\gamma(\tilde{n}-\tilde{m}). \tag{A.8}$$

With equations (A.7) and (A.8) we can calculate the relative change of the marginal products in equations (11), (12), (15), and (16).

Appendix A.2. Definitions: relative change in the tax rates and shares (with $p_Q Q = 1$)

$$\tilde{t}_l = \frac{dt_L}{1-t_L}, \qquad \tilde{t}_e = \frac{dt_e}{1+t_e}.$$

$$s_X = wL_X, \quad s_J = wL_J, \quad s_U = wL_U, \quad s_\Pi = \pi N, \quad s_A = A,$$

$$s_C = p_Q C, \quad s_I = p_Q I, \quad s_E = p_E E, \quad s_\tau = T.$$

Appendix A.3. Relations between the shares

Market clearing for goods (4)

$$s_C + s_I + s_E = 1 \tag{A.9}$$

Market clearing for labor (2)

$$s_X + s_J + s_U = w \tag{A.10}$$

No profit condition for X

$$s_X + s_E(1+t_E) + s_\Pi = 1 \tag{A.11}$$

First order conditions (11) and (12)

$$s_E(1+t_E) = \beta(1-\gamma_X) \tag{A.12}$$

$$s_X = \beta\gamma_X \tag{A.13}$$

Profit function (13)

$$s_\Pi = 1 - \beta \tag{A.14}$$

No arbitrage condition (14)

$$\frac{s_\Pi}{s_A} = g + \rho \tag{A.15}$$

R&D technology (8)

$$g s_A = s_J + s_I \tag{A.16}$$

First order conditions (15) and (16)

$$g s_A \gamma_J = s_J \tag{A.17}$$

$$g s_A (1 - \gamma_J) = s_I \tag{A.18}$$

Leisure - consumption tradeoff (18)

$$\theta s_c = (1 - t_L) s_U \tag{A.19}$$

Appendix A.4. The Model in relative changes

Final good composite (6)

$$\tilde{q} = \tilde{x} \tag{A.20}$$

Demand for intermediates (10) with $p_Q Q = 1$ and (A.20)

$$\tilde{p}_x = \tilde{p}_q = -\tilde{x} \tag{A.21}$$

Market clearing for goods (4) with $\tilde{p}_e = 0$ and (A.21)

$$-(s_C + s_I)\tilde{x} + s_C\tilde{c} + s_I\tilde{i} + s_E\tilde{e} = 0 \tag{A.22}$$

Market clearing for labor (2)

$$s_X\tilde{l}_X + s_J\tilde{l}_J + s_U\tilde{l}_U = 0 \tag{A.23}$$

Aggregate output in manufacturing (7)

$$\tilde{x} = \gamma_X\tilde{l}_X + (1 - \gamma_X)\tilde{e} \tag{A.24}$$

Labor demand in manufacturing (12) using (A.7) and (A.21)

$$\tilde{w} = -\tilde{x} + \epsilon_X^{-1}(1 - \gamma_X)(\tilde{e} - \tilde{l}_X) \tag{A.25}$$

Energy demand in manufacturing (11) using (A.8) and (A.21)

$$\tilde{t}_e = -\tilde{x} - \epsilon_X^{-1}\gamma_X(\tilde{e} - \tilde{l}_X) \tag{A.26}$$

No arbitrage condition (14) with (A.15)

$$g\tilde{g} = -(g + \rho)\tilde{a} \tag{A.27}$$

Innovation technology (9) with $\tilde{g} = \tilde{j}$

$$\tilde{g} = \gamma_J\tilde{l}_J + (1 - \gamma_J)\tilde{i} \tag{A.28}$$

Labor demand in the R&D sector (15) using (A.7) and (A.21)

$$\tilde{w} = \tilde{a} + \epsilon_J^{-1}(1 - \gamma_J)(\tilde{i} - \tilde{l}_J) \tag{A.29}$$

Investment demand in the R&D sector (16) using (A.8) and (A.21)

$$-\tilde{x} = \tilde{a} - \epsilon_J^{-1}\gamma_J(\tilde{i} - \tilde{l}_J) \tag{A.30}$$

Leisure - consumption tradeoff (18) with (A.21)

$$\tilde{c} - \tilde{l}_U = \tilde{w} - \tilde{t}_l + \tilde{x} \tag{A.31}$$

Appendix A.5. Used elasticities in the numerical part

Table A.6: Elasticities and their sources

Parameter	Description	Value
ϵ_Y	Elasticity of substitution between Q and inputs B	0.392 (AGR); 0.568 (OIN); 1.264 (CON); 0.848 (FOSS, CHM); 0.518 (MCH); 0.352 (TRN); 0.100 (ELES); 0.492 (rest)
ϵ_X	Elasticity of substitution between labor L_X and energy E	0.7 (AGR, MCH, ELES, FOSS); 0.52 (CON); 0.55 (CHM, TRN, OIN); 0.4 (rest)
ϵ_E/σ_E	Elasticity of substitution between fossil energy and electricity	0.5-1.5 (chosen 0.7)
$\epsilon_{Fos}/\sigma_{Fos}$	Elasticity of substitution between different fossil fuel sources	1
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor L_J	0.3
σ_C	Elasticity of substitution between energy and non-energy goods	0.5
σ_Y	Elasticity of substitution between different regular goods	0.5
$1/\zeta$	Inter-temporal elasticity of substitution in the welfare function	0.6
σ_L	Elasticity of substitution between consumption and leisure in the welfare function	0.65
ξ	Trade ("Armington ") elasticities	3.2 (AGR); 4.6 (MCH); 3.8 (ELES, OIN); 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

Sources: ϵ_Y Okagawa and Ban (2008); ϵ_X van der Werf (2007), Mohler and Mueller (2012); ϵ_E/σ_E Goulder and Schneider (1999), Gerlagh and van der Zwaan (2003); $\epsilon_{Fos}/\sigma_{Fos}$ Bretschger and Zhang (2016); $\tau/\omega/\chi$ Bretschger et al. (2011); σ_C/σ_Y Ecoplan (2007); $1/\zeta$ Hasanov (2007); σ_L Imhof (2012); ξ Donnelly et al. (2004); υ Paltsev et al. (2005)

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