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Author(s):
Karydas, Christos; Zhang, Lin

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Green tax reform, endogenous innovation and the growth dividend

Christos Karydas[a,*], Lin Zhang[b,]

[a]*CER-ETH Center of Economic Research at ETH Zurich, Zuerichbergstrasse 18, 8032 Zurich, Switzerland*
[b]*School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong*

Abstract

We study theoretically and numerically the effects of an environmental tax reform using endogenous growth theory. In the theoretical part, 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. Lump-sum redistribution performs best in terms of efficiency measured by aggregate welfare, while in terms of equity among social segments its progressive character 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 chapter 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). Existing empirical evidence supports the growth dividend hypothesis of an ETR and indicates that increases in the price of energy inputs have positive effects on innovation: Newell et al. (1999) show that following 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 car manufacturers tend to innovate more in clean technologies when they face higher tax-inclusive fuel prices.

*Corresponding author
Email addresses: `karydasc@ethz.ch` (Christos Karydas), `l.zhang@cityu.edu.hk` (Lin Zhang)

[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.

The theoretical literature initially failed to confirm positive results associated with an ETR 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.[2] 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.

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 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

[2]Even though a lump-sum redistribution does not improve the efficiency of the fiscal system, it increases the disposable income of households, which might also be welfare promoting. This applies especially to poorer households, because such a redistribution makes a big part of their income.

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 innovation – 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, staying closer to reality, 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 Bretschger et al. (2011) in the following ways. First, we consider a detailed representation of the Swiss fiscal system. Second, we include several heterogeneous households. Third, in the more complex computational model labor is mobile not only within manufacturing and R&D, but also between these sectors. 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 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 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.

In the numerical segment 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 tax revenue in a lump-sum way: shifting the tax burden from an ever increasing tax base (labor or capital) to a shrinking one (polluting energy) is inefficient. The results on equity are not straightforward: low emissions reduction targets follow the consensus in the literature and

[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.

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 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 growth dividend.

2.1. Aggregate economy

Consider a representative household that derives instantaneous utility $U(C, L_U)$ from consumption C, and leisure L_U. We normalize total labor supply to 1 and no population growth is considered. The aggregate economy features two sectors: manufacturing and R&D. The final good composite Q is ensembled from a continuum of intermediate goods x_j produced in the manufacturing sector in a Dixit-Stiglitz fashion:

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

where $\beta \in (0, 1)$ and N is the number of intermediate varieties. 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, the capital of the economy. Each patent is the costly outcome of research activity in the R&D sector. In a symmetric equilibrium where each intermediate firm produces the same quantity, $x_j = x$ per variety, the final good reads

$$Q = N^{\frac{1-\beta}{\beta}} X, \tag{2}$$

with $X \equiv Nx$ the aggregate output from manufacturing and the exponent $(1 - \beta)/\beta$ reflecting gains from diversification. Gross output can be used to meet the demand for consumption by households, investments by R&D firms, and energy imports by firms in the manufacturing sector, i.e.

$$p_Q Q = p_Q C + p_Q I + p_E E, \tag{3}$$

with p_Q the price of the final good and p_E the – exogenous – world's price of energy. Agents allocate their unit time budget between manufacturing L_X, research L_J, and leisure L_U. Labor market clears:

$$L_X + L_J + L_U = 1. \tag{4}$$

2.2. Manufacturing

In equilibrium final good producers maximize profits facing symmetric prices p_X for the use of intermediates x. This leads to the following goods market equilibrium,

$$p_Q Q = p_X X. \tag{5}$$

Each firm in the manufacturing sector has to buy a patent that allows it to produce according to the same technology. The aggregate production of intermediate machines follows a constant returns to scale function described by $X = f(L_X, E)$, with L_X and E aggregate labor and energy demand. We thus specify:

$$X = \left[\alpha_X L_X^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1 - \alpha_X) E^{\frac{\epsilon_X - 1}{\epsilon_X}} \right]^{\frac{\epsilon_X}{\epsilon_X - 1}}, \tag{6}$$

with $\alpha_X \in [0, 1]$ and ϵ_X the elasticity of substitution between labor and energy in manufacturing. Labor is paid its marginal cost w; a carbon tax t_E is also paid to the government. Due to imperfect substitutability in (1), the suppliers of intermediate machines 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 conditions, giving the demand for energy and labor, are:

$$\beta p_X \frac{\partial X}{\partial E} = (1 + t_E) p_E, \tag{7}$$

$$\beta p_X \frac{\partial X}{\partial L_X} = w. \tag{8}$$

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 $x = X/N$ and $c_X = \beta p_X$,

$$\pi = (1 - \beta) \frac{p_X X}{N}. \tag{9}$$

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 market value of the company. In equilibrium investors would be indifferent between investing into new capital varieties or into a riskless bond at the market interest rate r. With V representing the equity value of a firm, this no-arbitrage condition follows:

$$\pi + \dot{V} = rV. \tag{10}$$

2.3. Research and Development

Additional capital varieties emerge in the research lab following

$$\dot{N}/N \equiv g = \eta J, \tag{11}$$

$$J = \left[\alpha_J L_J^{\frac{\epsilon_J - 1}{\epsilon_J}} + (1 - \alpha_J)(zI)^{\frac{\epsilon_J - 1}{\epsilon_J}} \right]^{\frac{\epsilon_J}{\epsilon_J - 1}}, \tag{12}$$

with $\alpha_J \in [0, 1]$, ϵ_J the elasticity of substitution between labor and direct investments in research, and $\eta > 0$ a scaling parameter. According to (2) and (6), the growth rate of output Q, and thus of investment I, is $\frac{1-\beta}{\beta} g$, with g from (11). Through variable z, with $\dot{z}/z = -\frac{1-\beta}{\beta} g$, we impose negative spillovers from higher capital accumulation for two reasons: conceptually, it reflects the fact that the more advanced the state of the art becomes, the harder it is for innovation to occur; technically, it ensures that the growth rate of the economy is constant on a balanced growth path.

The representative R&D firm that devotes L_J units of labor and I part of the final good to R&D for an infinitesimal time interval of length dt builds upon existing knowledge and produces $\eta JNdt$ new varieties. The total cost of this endeavour is $(wL_J + p_Q I)dt$. This effort should then create at least a value of $VN\eta Jdt$, since V is the market value of each variety. We assume an interior solution with positive demand for both inputs.[4] The optimal employment of L_J and I for an active R&D sector is given by the following first order conditions, where the marginal benefit from employing each input equals its marginal cost:

$$\eta NV \frac{\partial J}{\partial L_J} = w, \tag{13}$$

$$\eta NV \frac{\partial J}{\partial I} = p_Q, \tag{14}$$

while in a competitive equilbrium $\eta NVJ = wL_J + p_Q I$.

2.4. Households and the Government

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 its intertemporal utility, $U = \int_0^\infty (\log C_t + \theta \log L_{Ut}) e^{-\rho t} dt$, subject to its dynamic budget contraint, $\dot{A} = rA + (1-t_L)w(1-L_U) - p_Q C + T$, with ρ the time discount rate, t_L the labor tax rate set by the government, and $\theta \geq 0$.[5] 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 (the hat notation represents the growth rate of a variable, i.e. $\hat{M} \equiv \dot{M}/M$.):

$$\widehat{p_Q C} = r - \rho, \tag{15}$$

$$\theta \frac{C}{L_U} = \frac{w(1 - t_L)}{p_Q}. \tag{16}$$

The government levies a tax t_L on labor income, a carbon tax t_E on energy expenditures, and redistributes the proceedings back to households in a lump-sum fashion.[6] It then chooses its fiscal instruments in order to optimize household utility subject to the budget constraint, $t_L w(1 - L_U) + t_E p_E E = T$, and the optimizing decisions by firms and households.

2.5. Conditions for a Balanced Growth Path

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 (5), $p_X X = 1$, $\hat{p}_X = -\hat{X}$. Moreover, in equilibrium $\hat{C} = \hat{I} = \hat{Q}$, such that from (3), $\widehat{p_Q C} = \widehat{p_Q I} = \widehat{p_E E} = 0$. The Euler equation (15) then sets $r = \rho$. On the

[4] An equilibrium without labor or investment in R&D 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.

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

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 (6), so is energy demand in manufacturing (E) so that $\hat{X} = 0$, and from (2) $\hat{Q} = \frac{1-\beta}{\beta} g$. Following our previous discussion with $\hat{z} = -\frac{1-\beta}{\beta} g$ 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 (9), the no-arbitrage condition (10) gives $\hat{V} = -g$. To summarize, we make the following definition:

Definition 1. *A balanced growth path (BGP) is an equilibrium path with $\hat{N} = g$, constant, on which aggregate variables $\{Q, C, I\}$ grow at $\frac{1-\beta}{\beta} g$, $\{p_Q, z\}$ 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 (2) to (16) 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. 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.

2.6. 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 (12): 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

$$\tilde{g}(\tilde{t}_e) = -\frac{1-\gamma_X}{\Delta}\left[s_J(1-\gamma_J)\epsilon_J + s_X(\epsilon_X - \gamma_J)\right]\tilde{t}_e - \frac{\gamma_X(1-\gamma_J)+\gamma_J}{\Delta} s_U \tilde{l}_U(\tilde{t}_e), \tag{17}$$

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 (17), growth is promoted, supressed or unaffected by the tax policy if the first term of equation (17) 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 (17), 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 (17) 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

$$\tilde{\lambda} = -\tilde{c} - \theta\tilde{l}_U - \frac{1-\beta}{\beta}\frac{g}{\rho}\tilde{g}, \tag{18}$$

with $\frac{1-\beta}{\beta}g$ the consumption growth rate and $r = \rho$ the interest rate along the BGP. 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.

2.7. 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. Moreover, we stressed through equation (18) 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. 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. Finally, the analytical model considers a representative household, whereas in the numerical segment we include several heterogeneous consumer groups. 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 2021.

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.[7] 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

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

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).

3.2. Numerical model

This model extends the theoretical framework presented in section 2 to a multi-sectoral numerical general equilibrium model of endogenous growth, where intentional investments in R&D endogenously determine the growth rate of each sector and the economy as a whole. The model 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. It can capture directed technical change in the sense that it allows for the reallocation of R&D activities depending on the relative prices among sectors. While the model is a fully-fledged multi-sector dynamic general equilibrium model, we restrict the model description in this section to a non-technical summary of the main characteristics. A more detailed description of the model's basic structure can be found in Bretschger et al. (2011) where it has been employed to study the growth effects of environmental policies in Switzerland. This model has been also used in Bretschger and Zhang (2016) for evaluating the economic cost of a nuclear phase-out policy.

Here, we extend the structure of Bretschger et al. (2011) 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. 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

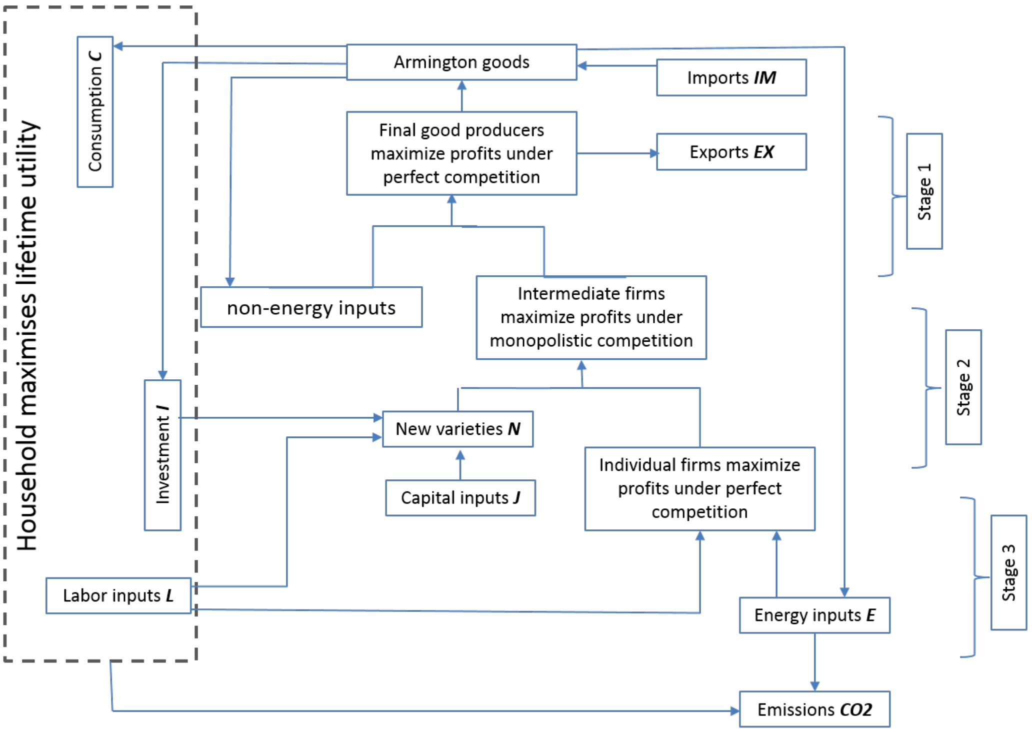
As illustrated in Figures 1 and 2, sectoral output Y_i, is produced through a three-stage production process. At the highest level, final good producers, operating in a competitive market, use both sector-specific inputs along with commodities from all other non-energy sectors. The second nesting corresponds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

$$Q_i = \left(\int_{j_i=0}^{N_i} x_{j_i}^{\beta} dj_i \right)^{1/\beta}. \tag{19}$$

Intermediates use labor in manufacturing and energy directly as factors of production, while capital used in Q accumulates using labor and direct investments. Labor is mobile between every economic activity (manufacturing and research), leisure, and sector of production.

Each firm in the same sector produces symmetric products with limited substitutability (equation (19)). This fact supports a degree of market power so firms in the intermediate sector operate in a setting of monopolistic competition. As in (2), 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

Figure 1: Sketch of the model (one good)



build-up. In the capital formation sector (R&D) 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:

$$N_{i,t+1} = \left[\alpha_{Ni} I_{Pi,t}^{\frac{\tau-1}{\tau}} + (1-\alpha_{Ni}) I_{Ni,t}^{\frac{\tau-1}{\tau}}\right]^{\frac{\tau}{\tau-1}} + (1-\delta_t) N_{i,t}, \tag{20}$$

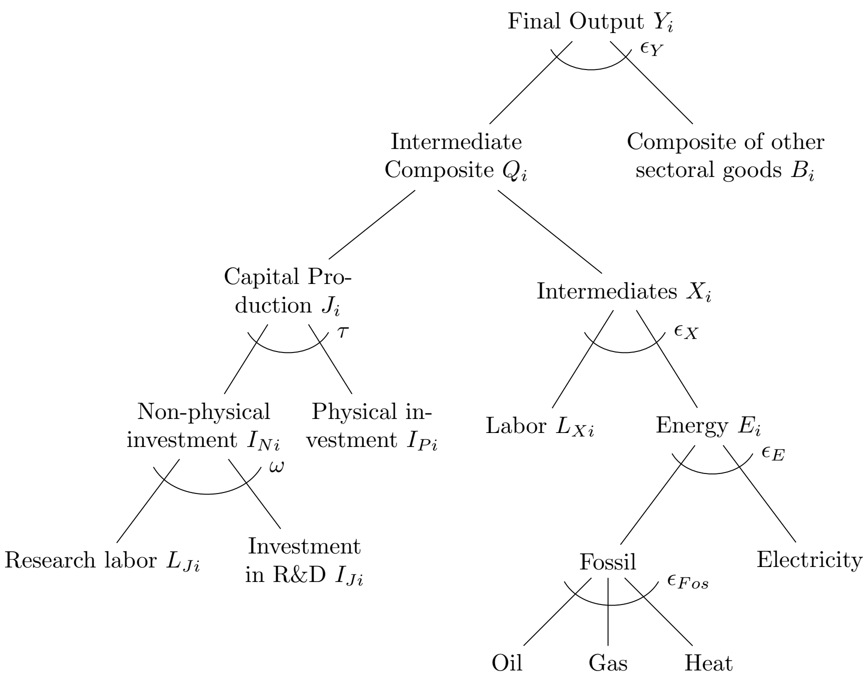
with investments in physical capital denoted by $I_{Pi,t}$, and in non-physical capital by $I_{Ni,t}$. Parameter τ represents the elasticity of substitution between the two investment types, α_{Ni} is the value share of physical investment, and δ_t is the depreciation rate. New investments can be directed to any sector according to its expected profitability. Similar to (12), 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.[8] They are assumed to be imperfect substitutes with elasticity of substitution ϵ_E. Non-fossil 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).[9]

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

[9]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.

Figure 2: Production structure of each regular good



Preference and household consumption

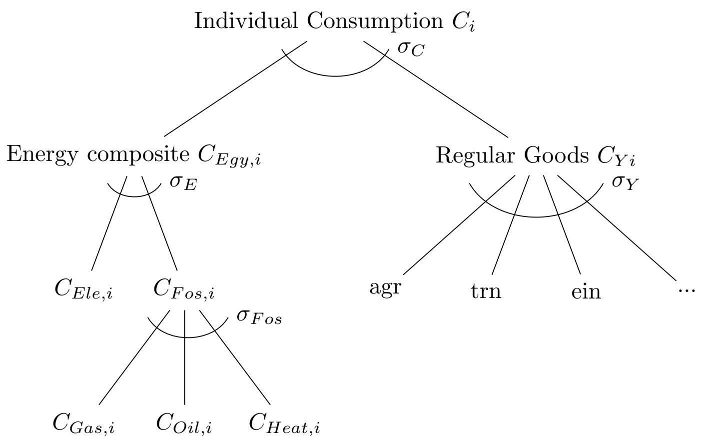
We distinguish different household categories based on their working status (active - retired) and on their income level. Each household, holding ownership of intermediate firms in all sectors, the capital of the economy, supply this along with labor in manufacturing and research. Households maximize 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. 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.

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

Figure 3: Consumption structure of individual households



heterogeneity; the demand for good i can be covered by domestic output Y_i and imports M_i according to

$$A_i = \left[\alpha_A Y_i^{\frac{\xi-1}{\xi}} + (1-\alpha_A) M_i^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}, \tag{21}$$

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 (11)), 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. (2015).

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).[10] 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

[10]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.

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.[11] Other minor taxes and subsidies were also included as taxes on sectoral inputs by firms and consumption for households.

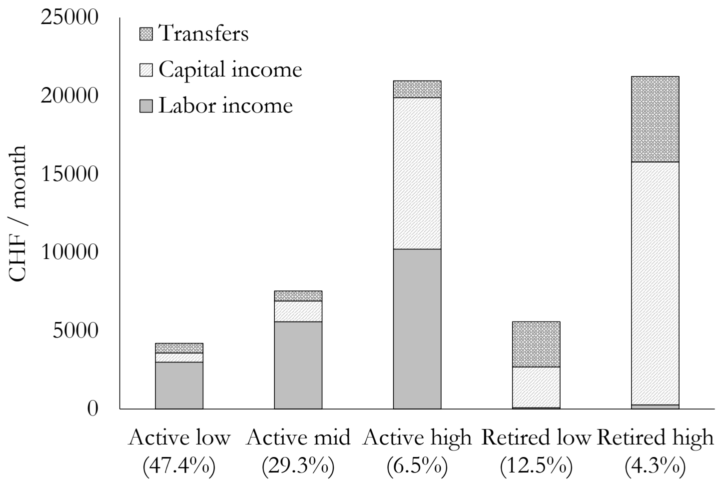
Furthermore, we use the household budget surveys from 2007 to 2009 to calibrate the households consumption, investment, and transfers. We have divided the Swiss population in five groups according to their professional status (active-retired) and income. Each household group features also its own labor-leisure choice with data taken from the Swiss Federal Office of Statistics.[12] 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.

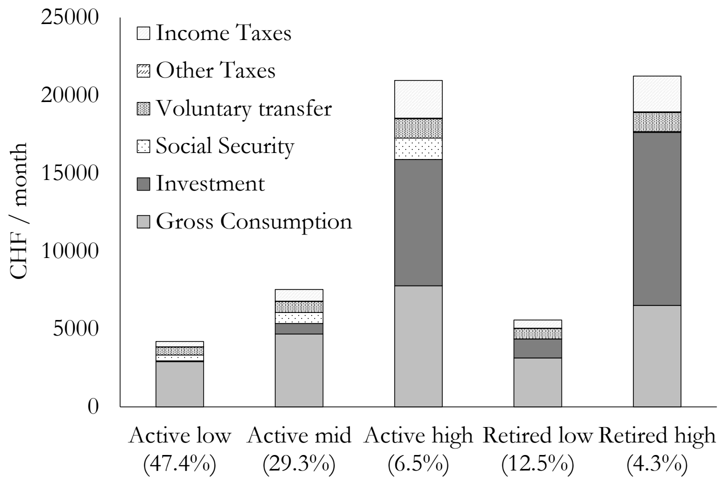
The elasticities of substitution between polluting fossil fuels and CO2-free electricity in production (ϵ_E), and consumption (σ_E), are obviously very important for our results as poor substitutability leaves less room for the economy to respond to a carbon policy and substitute away from polluting 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.

[11] 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.

[12] 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). In the Appendix we run a sensitivity analysis with a uniform time endowment of 0 and 1.

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 time framework of the numerical model this is one plus the growth rate) for final output and the number of varieties. According to (2) and (19) 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. To waive the gains from specialization effect in (20), which ensures a growing investment over time, the depreciation rate δ_t rises moderately every year, with δ_0 set to 0.07.[13] 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).[14]

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 CO2 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.[15]

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

[13]This is equivalent with introducing the z variable in (12).

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

[15]If anything the VAT tax in Switzerland is too low: evidence that a shift of direct income taxes to VAT can be welfare and growth promoting can be found in Albi and Martinez-Vazquez (2011) and Fuentes (2013).

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 CHF/tonCO2 in 2030, increasing to 9 CHF/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 CHF/ton CO2 in 2030 is calculated. Below we present the effects of this increasing tax on economic growth and welfare of the Swiss society.

Table 1: Carbon tax in CHF/tonCO2 for 60% emissions reduction in 2050 and different redistribution options

Year	Capital tax	Fed. Income tax	Lump-sum
2020	107	107	106
2030	314	311	310
2040	722	717	716
2050	1717	1705	1706

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 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. 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.[16]

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

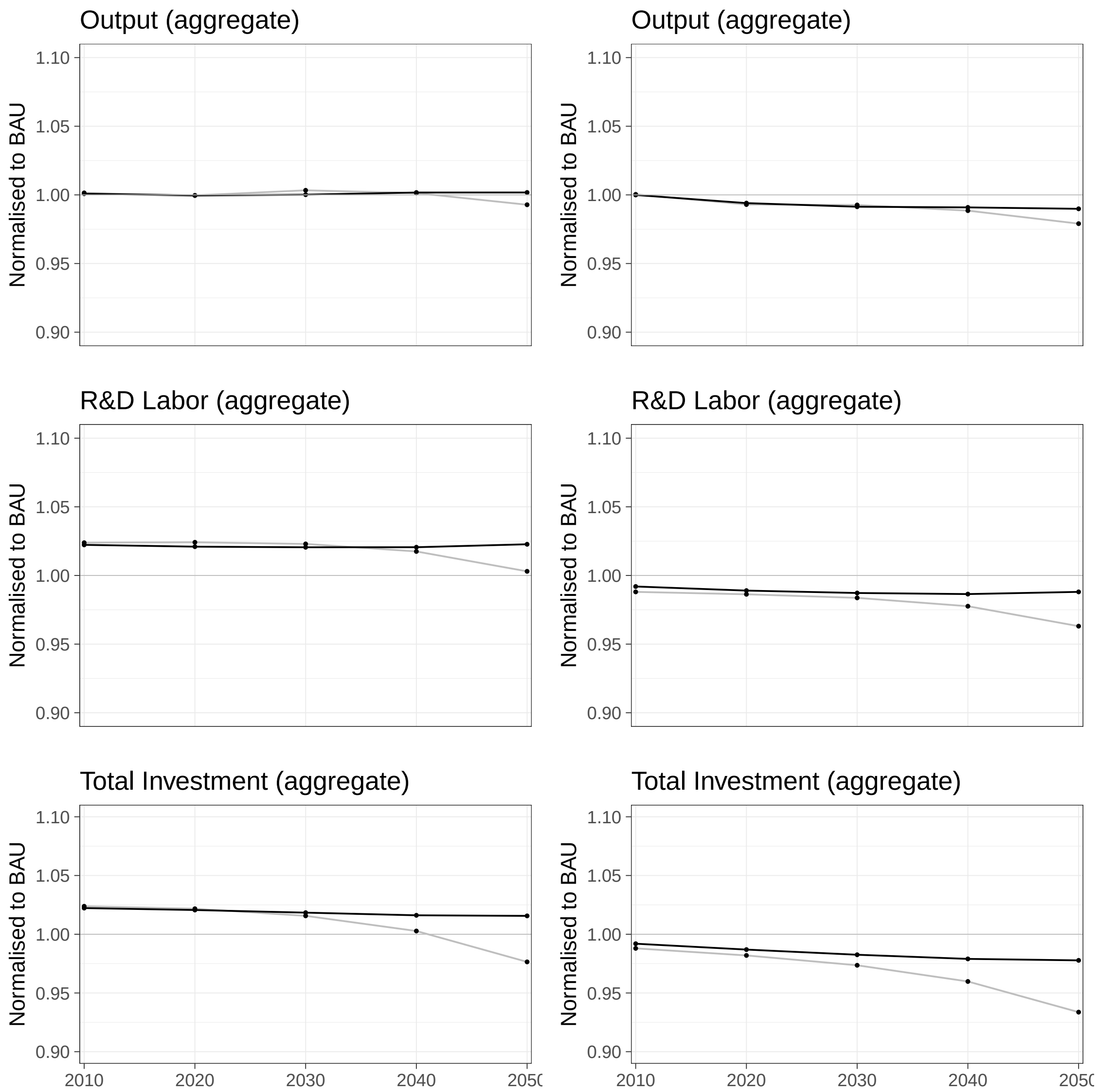
Our discussion in sections 2.6 and 2.7 is relevant for explaining the results of such a carbon policy on investment and growth in our endogenous growth framework. On the one hand, as explained in part 3.2 and in particular using the top two nestings of figure 2, to raise sector-specific output one can 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 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. In the Appendix we also present the effects of such a policy on the primary, secondary, and tertiary sector of the Swiss economy.

[16]As in (12), total investment uses labor in R&D and final output from the different sectors in the form of direct investments in the lab.

Figure 5: Production, R&D labor expenditure, and total investment (normalized to BAU) for 20% (black) and 60% (grey) 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 (see Chapter 3). 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. A high CO2 emissions tax, on a rather narrow tax base, creates distortions in the economy that cannot be overcome by any redistribution scenario: building on equation (18), the positive effects of reduced tax distortions from various redistribution schemes along with the potentially induced growth effects are not able to compensate for the negative effects imposed through carbon taxes.

Turning to the inefficiencies of the fiscal system, labor and capital tax rates in Switzerland, both applying on a wide tax base, are not that big compared to energy taxes.[17] 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. 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.

According to our results, 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 the lump-sum redistribution scheme is the lowest, as this type of scheme increases household income which could be used for higher consumption.

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%	-1.1%	-1.2%	-0.9%
40%	-2.4%	-2.7%	-2.1%
60%	-4.4%	-4.6%	-4.1%

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 growth effects of induced innovation. The first dividend is not quantified.

[17] 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%.

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.

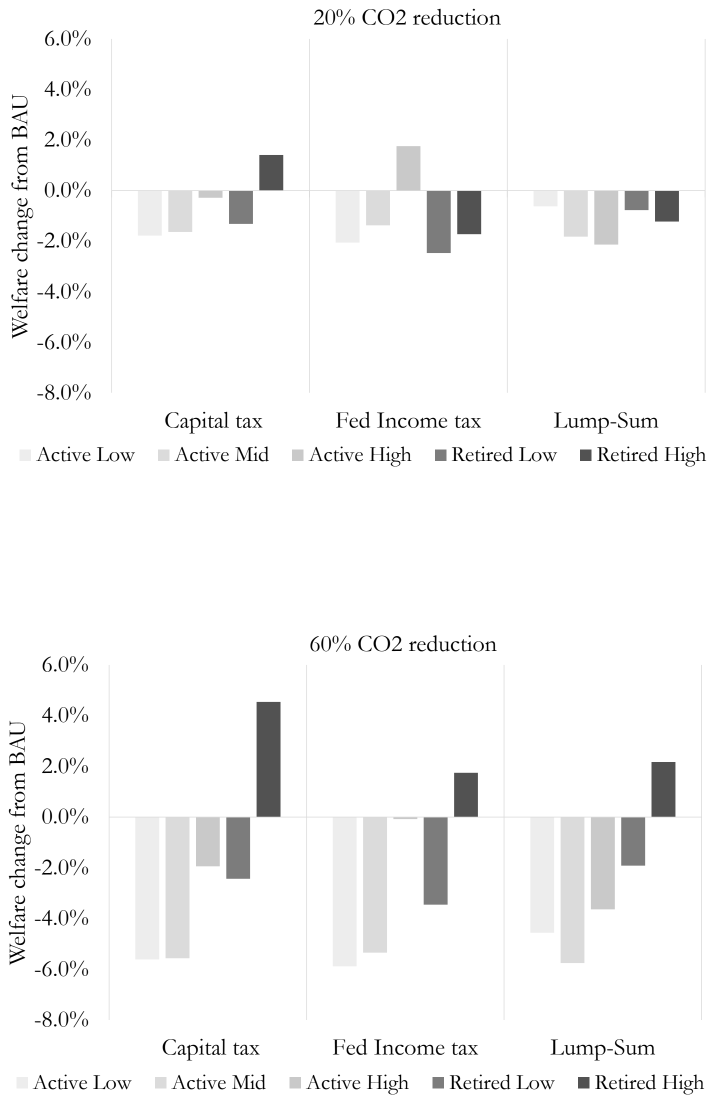
When it comes to pure equity considerations in Switzerland the consensus in the literature speaks in favor of a lump-sum redistribution; see for example Imhof (2012) and Boehringer and Müller (2014). This redistribution scenario that increases the available income of households without reducing any distortions 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 does 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 2021 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 usage 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. This can counteract the negative effect of increasing energy taxes on investment activity compensating for the additional tax burden, 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.

Concerning welfare, in aggregate, lump-sum redistribution produces the least distorting option. 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. 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.

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.[18] 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, while lump-sum redistribution is the preferred option for a smaller welfare loss in aggregate welfare.

[18] 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).

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

$\epsilon_E/\sigma_E = 1.5$	Capital tax	Fed. Income tax	Lump-sum
Carbon tax (CHF/tCO2)	1209	1200	1200
Output growth (% p.a.)	1.36	1.33	1.33
Aggr. welfare (% from BAU)	-3.5	-3.7	-3.3

5. Conclusions

In this chapter of the thesis 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 despite, or 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 if two conditions are met: first, the scarce factor of production should be mobile between manufacturing and R&D; second, the elasticity of substitution in manufacturing between the scarce factor 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 R&D investment more expensive, which suppresses growth; a negative *level effect* on investment. 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 2021. 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 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 a lower capital taxation. As displayed in the simulation part, the negative level effect is dominating the positive growth effect when taxes are increasing over time. In total, an environmental tax reform in Switzerland is not detrimental for growth, 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 speak in favor of a lump-sum redistribution, in line with the decision of the Swiss Federal Council, however, equity issues are addressed likewise only for a low emissions-reduction target; the progressive character of of lump-sum redistribution 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 (7), (8), (13), and (14).

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

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

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

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

Appendix A.3. Relations between the shares

Market clearing for goods (3)

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

Market clearing for labor (4)

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

No profit condition for X

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

First order conditions (7) and (8)

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

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

Profit function (**??**)

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

No arbitrage condition (10)

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

R&D technology (11)

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

First order conditions (13) and (14)

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

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

Leisure - consumption tradeoff (16)

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

Appendix A.4. The Model in relative changes

Final good composite (2)

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

Demand for intermediates (5) with $p_Q Q = 1$ and (A.20)

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

Market clearing for goods (3) 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 (4)

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

Aggregate output in manufacturing (6)

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

Labor demand in manufacturing (8) 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 (7) 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 (10) with (A.15)

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

Innovation technology (12) 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 (13) 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 (14) 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 (16) 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); η Donnelly et al. (2004); υ Paltsev et al. (2005)

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