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THE COST OF REDUCING CO<sub>2</sub> EMISSIONS:  
INTEGRATING ABATEMENT TECHNOLOGIES  
INTO ECONOMIC MODELING

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## **The cost of reducing CO<sub>2</sub> emissions: Integrating abatement technologies into economic modeling**

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### **Abstract**

We explore two methods of incorporating bottom-up abatement cost estimates into top-down modeling: economy-wide and sector-specific. Carbon emissions depend basically on technology and scale. Given the technology options, abatement is possible without a substantial reduction in scale. Otherwise the change must come purely through a reduction in demand. Our analysis shows that the cost of environmental policy is considerably overestimated by top-down models if a bottom-up abatement cost curve is not included. Using the data for the Swiss economy, we demonstrate two techniques of representing abatement function explicitly in a computable general equilibrium model: a traditional and a hybrid (discrete technology modeling) approaches. The results suggest that the current climate policy in Switzerland will not be able to move the economy towards the required 10% CO<sub>2</sub> reduction. Both approaches provide virtually the same results when calibration process is precisely executed, which contradicts the results in previous studies.

### **Keywords:**

cost curve, elasticity of substitution, computable general equilibrium model, hybrid modeling, carbon tax

### **JEL:**

C68, D24, H21, Q52

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# 1 Introduction

The economic costs of environmental policies are determined by both the direct and the indirect costs of pollution reduction. The direct economic effects are given by the expert-based marginal abatement cost (MAC) curves and can be captured by bottom-up models, while indirect effects can be captured by some top-down models, because engineering models adopt a partial equilibrium framework. The general equilibrium framework is specifically designed to represent price-dependent market interactions as well as the origination and spending of income for different agents. On the other hand, the characteristics of the underlying abatement technologies<sup>1</sup> are important for bottom-up models, but not for top-down models. It is important to represent abatement opportunities explicitly within the top-down structure.

This paper focuses on the question of how to integrate bottom-up assessments of pollution abatement options into top-down analyses of economic cost. We consider computable general equilibrium (CGE) models. The majority of these models assume that the abatement technologies are either not available or prohibitively costly compared to fuel switching and therefore can be neglected in the model. If abatement activities are not endogenously modeled, then the only way to reduce emissions is to reduce output, when no substitution is possible. This is not a desirable solution for economies troubled with unemployment. Nestor and Pasurka (1995) show that imposing common simplifying assumptions in modelling the impacts of environmental compliance costs may seriously hamper the ability of CGE models to accurately characterize economic effects. We show that the economy-wide cost of environmental policy is considerably lower when abatement technologies are taken into account.

In order to properly assess the economic costs of environmental policy, top-down models should explicitly include the basic pollution abatement options: (1) inputs substitution, (2) output-demand reduction, and (3) installation of abatement equipment. The efficiency with which a policy instrument makes use of these three options, determines the intrinsic abatement cost (Bovenberg et al., 2008). The general idea is illustrated in Figure 1. A variety of assumptions representing different possible behaviour and scenarios could give a very large range of possibilities for the social marginal cost of emissions (Stern, 2010). When top-down models include only the first two options, the MAC is overestimated because we ignore the possibility to reduce emission through abatement equipment and energy efficient technologies are not precisely described. The substitution between capital and fuels is possible with CGE models, but not between materials (intermediate demand). If, for example, it is feasible to reduce emission by using fuel-efficient vehicles, a

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<sup>1</sup>By abatement technology (equipment) we mean any technology that reduces pollutants emitted or that allow to emit less pollution.

substitution between vehicle cost and fuels should be possible. However, top-down models does not allow for such substitution when demand for vehicle is considered as an intermediate demand. Such calculations can therefore give only a weak guide to policy.

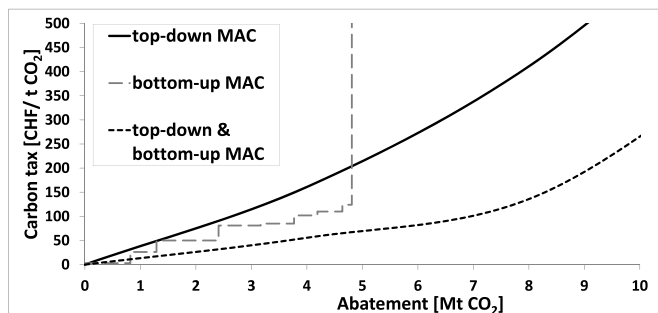
On the other hand, bottom-up models consider the options of reducing emissions through a number of discrete technologies but ignore the interactions between markets, indirect costs, and social welfare. Such models include behavioral assumptions that allow for new technologies to penetrate the market more easy, than top-down models. Integrating bottom-up estimations with top-down modeling allows us to generate a MAC curve that covers all three options of emission reduction. This curve lies below those that consider only some of these options (Figure 1). It follows that the cost of environmental policy is overestimated by top-down models if a bottom-up abatement cost curve is not included.

In the early CGE literature, whenever abatement possibility was taken into account, the abatement cost was modelled only implicitly. Contributions to the field include Bergman (1991), Robinson et al. (1994), Schmutzler and Goulder (1997), Xie and Saltzman (2000), Conrad (2002), Kiuila and Sleszynski (2003). In these models abatement cost was determined by the average pollution cleanup rate. The disadvantage of such approach is an inability to account for the effects of changes in prices brought about by policy reforms

Another commonly used approach is to implement the abatement expenditures through an emission tax or permits in order to generate MAC curves: Parry et al. (1999), Viguier et al. (2003), He and Roland-Holst (2005), Pizer et al. (2006), Boehringer et al. (2006), Loisel (2009). The curves are derived by setting progressively tighter abatement levels and recording the resulting shadow price of pollutant or by introducing progressively higher emission taxes and recording the quantity of reduced emissions. Such model-based MACs do not fully represent the opportunities that may serve future mitigation, because some technological possibilities to abate are ignored. This means that emission intensities of output in such models are not fully responsive to market circumstances.

There naturally emerges the question how to integration abatement possibilities and their direct and indirect costs. Welfare analysis is not possible with bottom-up modeling and therefore technological possibilities should be an input into top-down model. Such integration will make it possible to derive MAC schedules that accurately characterize the economic costs associated with all of the economy's substitutions, all of the market adjustments and technological changes that follow from the implementation of a particular mitigation strategy.

We propose an integration of bottom-up abatement costs with top-down models using either a smooth curve (traditional approach) or a step curve (hybrid approach). CGE models provide an environment for both approaches. The first approach is a highly stylized, based on, for example, constant elasticity of substitution (CES) function and



Source: CGE model described in section 4 of the paper

Figure 1: MAC curves obtained with different methodologies (top-down curve: no substitution possibilities between vehicles and fuels; bottom-up curve: the technological possibilities for transportation)

requires a precise to evaluation of parameters of the abatement function in order to replicate the bottom-up cost curve. We apply a non-linear optimization process with an ordinary least square (OLS) technique to calibrate the parameters of the function. This requires a formulation of separate from top-down model an optimization problem, that will “translate” a step curve into a smooth curve. Next, the results are implemented into the top-down model as parameters. This procedure, though mechanically different, is done in the spirit of Dellink (2005). An alternative techniques are proposed by Hyman et al. (2002) and Jorgenson et al. (2008).

The second approach does not require a definition of any additional optimization problems, because the results from bottom-up model are directly integrated into the top-down model using an activity analysis framework. The traditional approach is based on the concept of elasticities, but hybrid approach is not. It specifies technologies as fixed coefficient activities and therefore reduces the aggregate input substitutability of supply. A flip-flop feature allows us to deactivate technologies which would run at an economic loss at given prices. There are a few examples of this approach for electric power: Laroui and van Leeuwen, eds (1995), Koopmans and Velde (2001), Frei et al. (2003), McFarland et al. (2004), Jacoby et al. (2006), Laitner and Hanson (2006), Boehringer and Rutherford (2008), but none for the abatement process. We are filling this gap.

For each approach we demonstrate two techniques that endogenize the abatement within a static CGE model: economy-wide and sector-specific. The first method, with an economy-wide perspective, considers a fixed abatement capacity and the MAC is applied for the whole economy rather than for a specific sector. The second method allows for a sector specific abatement process and the abatement is proportional to the size of the sector. Instead of the marginal cost, it calibrates the total cost of abatement and it requires that the original social accounting matrix (SAM) is rebalanced. Endogenizing expert-based (bottom-up) abatement cost via either method allows for a consistent

Table 1: GHG abatement technologies for light duty vehicles in Switzerland

#	Technology	Abatement [Mt CO <sub>2</sub> e/year]	Marginal cost [2005 CHF/t CO <sub>2</sub> e]
1	LDV Gasoline Bundle 1	0.82	-127
2	LDV Diesel Bundle 1	0.47	-104
3	LDV Gasoline Bundle 2	1.12	-81
4	LDV Diesel Bundle 2	0.60	-50
5	LDV Gasoline Bundle 3	0.76	-45
6	LDV Diesel Bundle 3	0.42	-28
7	LDV Gasoline Bundle 4	0.45	-20
8	LDV Diesel Bundle 4	0.17	-6

\*The exchange rate was 1.55 CHF/EUR in 2005.

Source: McKinsey study 2009, p.11

assessment of an environmental policy.

We compare both approaches and both methods through a simulation of climate policy in Switzerland. The transportation sector is one of the two largest sources for greenhouse gas (GHG) emission in the country. We illustrate our methodology for this sector only. Specifically, only the abatement technologies for light duty vehicles (LDV) are considered. Our work is based on the top-down static model developed by Imhof and Rutherford (2010) and the bottom-up cost curve was developed in the McKinsey report (2009)<sup>2</sup>.

The authors of the engineering study claim that vehicle improvements, based on known technologies and rendering no change in vehicle characteristics, could reduce Swiss annual GHG emissions from 13.5 to 8.7 Mt. Their base scenario shows 8 possibilities to reach this goal (Table 1) with negative cost. We are not going to analyse the credibility of the study, but just to show the application of our methodology with commonly available expert-based MAC curve. However, this no regrets structure (negative cost) is inconsistent with CGE modeling and a reconciliation is required. We have applied an additive adjustment, where the original marginal cost  $C_i$  per technology  $i$  is proportionally increased by a constant  $a = \max(0, \min_i C_i)$ . This allows us to fit a neoclassical CES function with the McKinsey technology options.

Our main finding is that the traditional and the hybrid CGE modelling have virtually the same results of simulation, unless different assumptions are applied. It contradicts the findings of Boehringer (1998) and Wing (2006), where the Authors conclude that the traditional approach underestimates the welfare costs compared to the hybrid approach. The disadvantage of the hybrid approach is a possibly bounded solution in the case of a

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<sup>2</sup>Our choice of the McKinsey curve is only explained by increasing attention given to it by audience.

limited number of available technologies. On the other hand, the traditional approach with smooth abatement function calibration is time consuming, especially for a sector-specific method.

The remainder of this paper is divided into four sections. Section 2 describes two methods of calibrating abatement function using the traditional approach. The detailed explanation for the piecewise-smooth representation of a step curve can be found in Kiuila and Rutherford (2011). The sector-specific method is in the spirit of Dellink (2005), but we implement it in a different way. Section 3 explains the hybrid approach to implementing abatement costs with the same two methods. Section 4 outlines the core of the top-down model and defines scenarios. Using Swiss data, we discuss the results of climate policy simulation. Section 5 provides a summary and concluding remarks.

## 2 Traditional approach

The inclusion of bottom-up information on abatement options into a top-down model in the traditional way involves (i) a piecewise-smooth approximation that best describes the bottom-up cost curve, (ii) an integration of the results of the approximation into the top-down model. We discuss and compare the two alternative methods to represent the abatement function explicitly into CGE models. Both methods use an OLS technique to approximate the CES function with a decreasing returns to scale (DRTS) technology, but differ in substitution possibilities, benchmark abatement level, and aggregation. The purpose of calibration is to determine the parameters of the abatement function in a way that would replicate the shape of bottom-up MAC curve.

### 2.1 Method 1: Economy-Wide

The first approach considers abatement possibility as an economy-wide opportunity. This means that we are not able to link the abatement possibilities to specific sectors, but we apply it to the whole economy or region. In this case we model the pollution abatement service  $Q$  using the technical potential  $X$  and the technology-specific capital  $K$ . In the case of transportation sector, the capital is represented by vehicle costs. The potential to reduce pollution through technical abatement activities provides an upper bound on abatement. Additional pollution abatement can be achieved through a decrease in economic activity.

The Figure 2 shows a schematic tree of the economy-wide approach in a CGE model. There is no direct connection between the left and the right tree. The left figure is related to the whole emission in the region, not just in the transportation sector. This means that

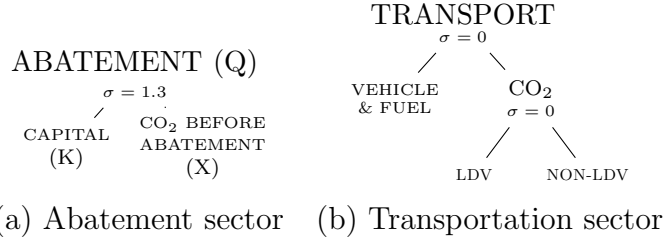


Figure 2: Economy-wide approach for abatement sector in a CGE model

the cost of abatement will be underestimated with this approach if the abatement data  $Q$  cover only a specific sector while a CGE model applies it to the whole economy. On the other hand, if we are not able to distinguish abatement technologies by sector, the economy-wide method allows us to spread it out to the whole economy.

In our experiment, all abatement technologies are related to LDVs only. Thus we consciously create a pessimistic scenario in order to compare the results with the second approach. The transportation sector is defined by a simple Leontief function as shown in Figure 2b. The emission level is proportional to aggregate demand on transport goods. We distinguish between the sources of emission in order to be able to apply different fuel standards. Either a carbon tax or a fuel standard would have to be proportional to the emissions level.

The abatement sector (Figure 2a) is defined as a CES function based on the following calibration procedure, where the abatement process is characterised by DRTS technologies. When abatement capacity is in fixed supply  $X = \bar{X}$ , we may represent DRTS technology with a production function<sup>3</sup> of constant returns to scale (CRTS):

$$Q = \bar{Q} \left( \theta \left( \frac{K}{\bar{K}} \right)^{(\sigma-1)/\sigma} + (1 - \theta) \right)^{\sigma/(\sigma-1)} \quad (1)$$

where  $\bar{Q}$ ,  $\bar{K}$  and  $\bar{X}$  are the reference levels of variables,  $\sigma$  shows the substitution possibility between the abatement capacity and the required expenditures on a vehicle,  $\theta$  is a value share of vehicle cost in the total cost at the reference point  $(\bar{X}, \bar{K})$ . The DRTS technology implies that the abatement level increases less than proportionally with the variable input (Figure 3). In order to calibrate the abatement function (1), we need to determine the marginal abatement cost  $C$  as a function of output  $Q$ . This will allow us to represent the bottom-up marginal cost curve. A detailed algorithm is discussed in Kiiula and Rutherford (2011). The scale of output at a given price (equal to marginal cost) is consistent with the

<sup>3</sup>We use the calibrated share form representation of functions, rather than the classical form. The classical form representation for the function (1) is  $Q = \phi \left( \alpha K^{(\sigma-1)/\sigma} + (1 - \alpha) \bar{X}^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)}$



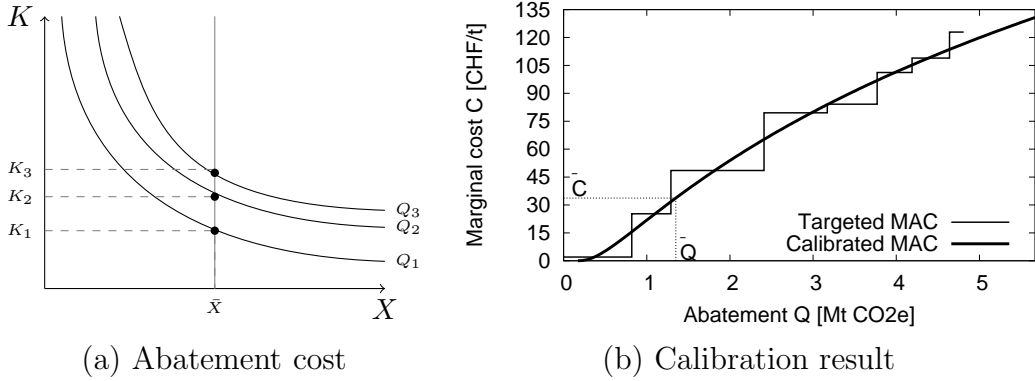


Figure 3: CES calibration using the economy-wide approach

profit maximization problem. The corresponding inverse supply CES function becomes:

$$C = \bar{C} \left( \frac{1 - (1 - \theta)(Q/\bar{Q})^{(1-\sigma)/\sigma}}{\theta} \right)^{1/(\sigma-1)} \quad (2)$$

Once we have defined the marginal cost function, we are able to approximate the bottom-up curve. For a given set of technologies  $i$ , the MAC curve represents the relation between potential abatement level and its cost. It has the shape of a step function, increasing each time the next cheapest technology is introduced, as shown in Figure 3a. The emission abated by technology  $i$  is simply  $(Q_i - Q_{i-1})$ , while the aggregate abatement level  $Q_i$  is an emission reduction cumulative to the upper point of step  $i$ . Let us match the abatement schedule close to the middle point of step  $i$ . The objective is to minimize the sum of a squared distances between the bottom-up step curve and the CES curve:

$$\min_{\sigma, \theta, \hat{C}_i, \hat{C}, \hat{Q}} \sum_i (Q_i - Q_{i-1}) \left( C_i - \hat{C}_i \right)^2 \quad \text{s.t.} \quad \hat{C}_i = f(\hat{C}, \hat{Q}, Q_i, \theta, \sigma) \quad \forall i \quad (3)$$

where the constraint is the inverse supply function (2).  $C_i$  and  $\hat{C}_i$  represent the observed and the evaluated marginal cost of abatement associated with technology  $i$ , while  $\hat{C}$  is the calibrated reference marginal cost. The observed levels  $(Q_i, C_i)$  corresponds to the bottom-up curve, the evaluated level  $(\hat{Q}, \hat{C})$  corresponds to the calibrated point at the smooth curve.

The result of the calibration using the additively adjusted bottom-up cost from Table 1 is presented in Figure 3b. The figure shows the difference between the bottom-up curve and the smooth calibrated curve. The calibration point determines the part of the curve where elasticity of substitution and value share parameter are evaluated. It is (1.3 Mt CO<sub>2</sub>e, 34

CHF/t) with  $\theta = 40\%$  and  $\sigma = 1.3$  in our example. We can see that the reference abatement level  $\hat{Q}$  is positive. However, it is not necessary to assume that the abatement level was greater than zero at the benchmark equilibrium. The advantage of the economy-wide approach is that in a top-down model we don't have to assign any abatement in a benchmark equilibrium ( $Q = 0$  while  $\hat{Q} = 1.3$  Mt CO<sub>2</sub>e) and we can simulate the abatement possibilities in counterfactual equilibria.

The rest of the parameters in the production function (1) depend on the above values:  $\bar{K} = \theta\hat{C}\hat{Q}$  and  $\bar{X} = (1 - \theta)\hat{C}\hat{Q}$ . There is no demand for inputs ( $K = 0$  and  $X = 0$ ) at the benchmark, if there is no abatement. The abatement capacity constraint implies that exogenous supply  $\bar{X}$  should not be less than the compensated demand  $X(Q) = \bar{X}(C\bar{P}_X/P_X)^\sigma Q/\bar{Q}$ :

$$1 \geq \left(\frac{C\bar{P}_X}{P_X}\right)^\sigma \frac{Q}{\bar{Q}} \quad \perp P_X$$

The price of both inputs can be normalized to one. The benchmark marginal cost of abatement will be zero, if there is no benchmark emissions tax or permits ( $C = 0$  while  $\bar{C} = 34$  CHF/t). The supply of variable input  $K$  is endogenous. A standard zero profit condition can be applied.

Thus, we precisely calibrate the abatement function to portray the bottom-up cost curve within a top-down model.

## 2.2 Method 2: Sector-specific

The second approach considers abatement possibilities as a sectorial opportunity. It is based on total cost instead of marginal cost as in the first approach. The basic idea is to split the sectorial emissions  $Y$  into an abatable part  $A$  and an unabatable part  $U$  (Figure 4). In our example sectorial total abatement cost (TAC) curve shows the relationship between the LDV-transportation emissions level and the abatement cost. The goal is to evaluate abatable emission level, but not the abatement level directly as in the previous approach.

Sectorial output of the abatement process  $Q$  is the difference between abatable gross emissions (before abatement)  $A$  and net emission  $S$ . The key assumption is that we observe (from the social accounting matrix) the sectorial net emissions level  $X = S + U$  and using bottom-up data we proceed to estimate the gross emissions  $Y = A + U$ . It is opposite to the economy-wide approach, where we assumed that the social accounting matrix represents gross emissions. The Figure 4 shows a schematic tree of the sector-specific approach in a top-down model. For simplicity we assume no fuels substitution in transportation. The abatement process is integrated within the specific sector and it is proportional (zero

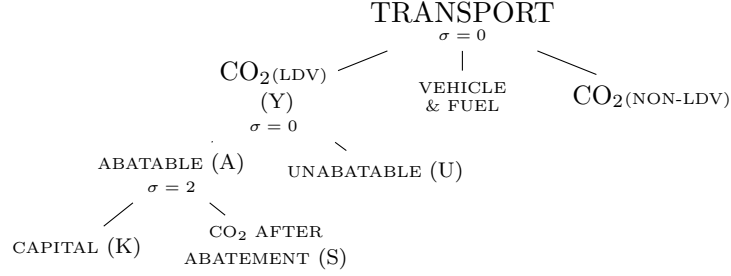


Figure 4: Sector-specific approach for abatement sector in a CGE model

elasticity of substitution) to the activity level of this sector. The emissions level is also determined only by the activity level of the specific sector, i.e.  $Y = \bar{Y}$ .

Calibration of the abatement function is not straightforward under this approach. Instead of  $A = f(K, S)$  we rather simulate  $Y = f(K, X)$  to define the abatement cost function (Figure 5a). When output is constant and  $X = \bar{X} - Q$ , the production function<sup>4</sup> exhibits DRTS:

$$1 = \left( \theta \left( \frac{K}{\bar{K}} \right)^{(\sigma-1)/\sigma} + (1 - \theta) \left( \frac{\bar{X} - Q}{\bar{X}} \right)^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)} \quad (4)$$

where the technology-specific capital  $K$  is represented by the vehicle purchase price,  $\bar{K}$  and  $\bar{X}$  are reference levels of the variables,  $\sigma$  shows substitution possibility between emission and abatement cost,  $\theta = \bar{K}/(\bar{P}_K \bar{K} + \bar{P}_X \bar{X})$  is a value share of the abatement cost in total expenditures at the reference point. The isoquant to be calibrated can be defined from (4):

$$K = \bar{K} \left( \frac{1 - (1 - \theta)(1 - Q/\bar{X})^{(\sigma-1)/\sigma}}{\theta} \right)^{\sigma/(\sigma-1)} \quad (5)$$

Before we start the calibration process, we should identify activities in the convex hull in order to illustrate precisely which technology “packages” are employed in each activity. Assume that the abatement technologies are applied sequentially: before the second technology is installed, the first one must already be installed. The bottom-up cost curve, that is represented by 8 technologies in Figure 3b, corresponds to 24 technology packages in Figure 5b. The convex hull is our targeted isoquant because it describes the minimal convex set containing all relevant technologies, i.e. those which could be operated at positive intensity for some set of reference prices.

It is necessary to calibrate both the isoquant and the isocost because the benchmark price

<sup>4</sup>The classical form representation for the function (4) is  $\bar{Y} = \phi(\alpha K^{(\sigma-1)/\sigma} + (1 - \alpha)(\bar{X} - Q)^{(\sigma-1)/\sigma})^{\sigma/(\sigma-1)}$

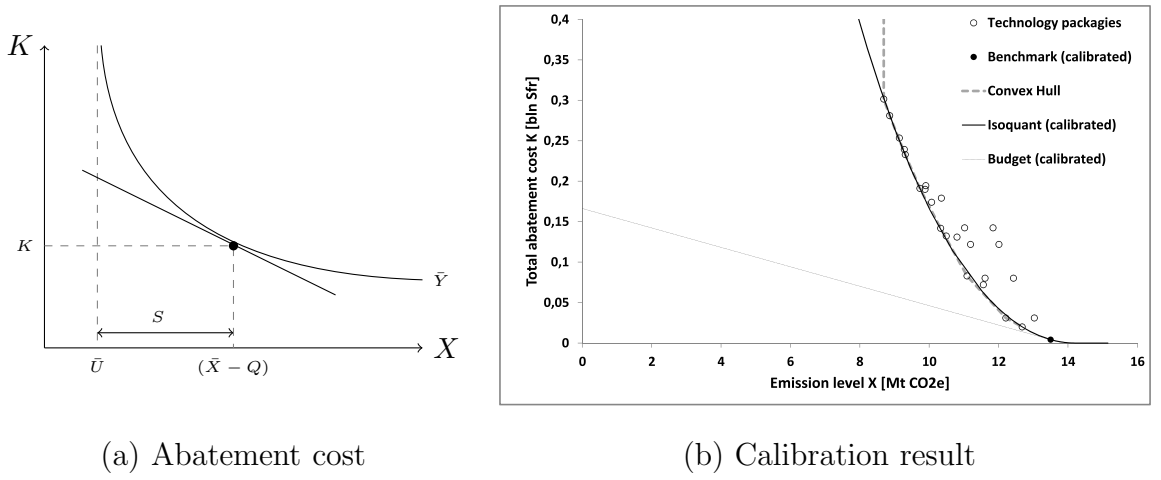


Figure 5: CES Calibration using the sector-specific approach

of emission (abatement) and the benchmark abatement level should be greater than zero under this approach. The reference isocost line ( $\bar{P}_X \bar{X} + \bar{P}_K \bar{K}$ ) is defined with the reference cost of abatement  $\bar{K}$ , while the calibrated isocost - with the calibrated reference cost  $\hat{K} \leq \bar{K}$ . If no carbon tax or permits were applied in the benchmark period, then the reference cost of abatement should be low in order to ensure a relatively small benchmark price of emissions in the top-down model. Assuming  $\bar{K} = 0.02$  bln CHF and the price of emission at the level of the first carbon tax in Switzerland ( $\bar{P}_X = 12$  CHF/t CO<sub>2</sub>e), this requires a rebalancing of the social accounting matrix in order to take into account the existence of the abatement process in the benchmark equilibrium. If we normalize the price of capital  $\bar{P}_K = 1$ , the calibrated reference cost becomes:

$$\hat{K} = \theta(\bar{P}_X \bar{X} + \hat{K}) \quad (6)$$

The objective is to minimize the sum of squared distances between the targeted and the approximated isoquants. Each activity coefficient should be connected to the closest point on the targeted isoquant, represented by the convex hull:

$$\min_{\sigma, \theta, \hat{K}, \hat{K}_i, \hat{X}_i} \sum_i \left( \hat{X}_i - X_i \right)^2 + \left( \hat{K}_i - K_i \right)^2 \quad (7)$$

$$\text{s.t. } \hat{K}_i = f(\hat{K}, \bar{X}, X_i, \theta, \sigma) \quad \wedge \quad \hat{K} = \theta \bar{P}_X \bar{X} / (1 - \theta) \quad \forall i$$

where the first constraint is the isoquant (5) and the second constraint is the reference cost (6).  $X_i$  and  $K_i$  represent the observed net emissions and the cost of abatement associated with technology  $i$ , while  $\hat{X}_i$  and  $\hat{K}_i$  represent the calibrated variables. The results of the calibration are presented in Figure 5b.

The graph shows the difference between the convex hull and the smooth calibrated curve. The reference point  $(\bar{X}, \hat{K})$  determines the part of the curve where the elasticity of substitution and the value share parameter are evaluated. It is (13.5 Mt CO<sub>2</sub>e, 0.004 bln CHF) with  $\theta = 3\%$  and  $\sigma = 2$  in our example. Note that the reference emission level  $\bar{X}$  is not calibrated, but given exogenously. The components of the net emissions also do not need to be calibrated:  $\bar{S} = \sum_i Q_i$  shows the cumulative emissions level within both the isoquant and the isocost domain, while  $\bar{U} = \bar{X} - \sum_i Q_i$  shows the emission level out of the isoquant domain but within the isocost. The abatement level  $Q_i$  comes from the bottom-up data and it determines the components of net emissions.

The calibrated abatement cost allows us to define the abatable gross emissions  $\hat{A} = (\bar{P}_K \hat{K} + \bar{P}_S \bar{S}) / \bar{P}_A$ , where  $0 < \bar{P}_A \leq \bar{P}_S = \bar{P}_U = \bar{P}_X$  are the reference prices of emission and they cannot be normalized to unity. It is not possible to calibrate a top-down model with zero abatement level within this approach, so we have to normalize the benchmark prices of emissions  $P_S$  and  $P_U$  and  $P_A$  to the reference level  $\bar{P}_X = 12$  CHF/t CO<sub>2</sub>e, that is below the marginal cost of the first technology (Figure 3). The price of emissions before abatement process should not be greater than the price of emissions after abatement. The calibrated abatement level  $\hat{Q}_i = \hat{A} - S_i$  is not directly implemented into top-down model (Figure 4).

The advantage of the sector-specific approach is that we consider the abatement possibilities separately in each sector (not uniformly across the economy).

### 3 Hybrid approach

The technical possibilities to change a production function in a CGE models are usually represented with a smooth cost curve. It is possible to use a step curve too within top-down modeling. Rather than describing an abatement possibility by the means of a CES cost function, we may use activity analysis, i.e. capture abatement possibilities by Leontief technologies that are active or inactive in equilibrium, depending on their probability. It yields an analyses of production as an efficient combination of activities.

Besides this direct combination of bottom-up and top-down via activity analysis, it is also possible either to link both models (soft-linked or hard-linked models) or to focus on one model type and use a reduced form of the other (as models MERGE or TIMES). In this paper, we focus on activity analysis only. The advantage of this method is that it encompasses in a single mathematical format, both the technological details of a bottom-up model and the economic richness of top-down model. It requires a definition of economic equilibrium conditions as a mixed complementarity problem, where the

substitution possibilities are described by the characteristics of available technologies (including those which are inactive in the benchmark).

Method 1 (economy-wide) can be formulated as a complementary pair of abatement cost and capacity:

$$Q = \sum_i Q_i \quad \text{where} \quad Q_i = \bar{Q}_i \min \left( \frac{K_i}{\bar{K}_i}, \frac{X_i}{\bar{X}_i} \right)$$

The reference levels are described by the bottom-up data:  $\bar{K}_i = C_i Q_i$ ,  $\bar{X}_i = \bar{Q}_i = Q_i$ . The first abatement technology is associated with a positive abatement level (Figure 2b), however all technologies are inactive in the benchmark ( $Q = 0$ ). Dimensionality imposes a limitation on the lower bound of decision variables, since they must be associated with explicit price variables in order to account for income effects. Thus a condition on the reference quantity is required when the scarcity rent  $P_{X_i}$  is defined. The reference rent level is zero, but the endogenous rent is determined by the market clearing condition  $\bar{X}_i \geq X_i(Q_i)$ :

$$\bar{Q}_i \geq Q_i \quad \perp P_{X_i} \quad \text{s.t.} \quad \bar{X}_i > 0$$

The price of another input is normalized to unity and it does not require the additional condition on reference quantity of capital. On the other hand, the reference price of abatement  $\bar{P}_Q$  is zero, but no additional constraint on reference level is required since the benchmark level of abatement is zero. The market clearing condition determines the endogenous price: the emissions limit together with  $\sum_i Q_i$  should not be less than total emissions. A zero-profit condition determines the active technologies via complementarity slackness:  $P_K C_i + P_{X_i} \geq P_Q \perp Q_i$ , where  $C_i = K_i/Q_i$  is the marginal cost in a unit-profit function for abatement.

Method 2 (sector-specific) can be formulated as a complementary pair of abatement cost and unabatable part of emissions after the abatement took place in a given sector:

$$A = \bar{A} \sum_i \min \left( \frac{K_i}{\bar{K}_i}, \frac{S_i}{\bar{S}_i} \right)$$

The reference levels are described by the convex hull data:  $\bar{K}_i = C_i Q_i$ ,  $\bar{S}_i = (\sum_j Q_j) - Q_i$ ,  $\bar{A} = \sum_i Q_i$ . Thus we do not consider all 24 technology packages shown in Figure 5b, but only those which could be operated at positive intensity for some set of reference prices. The reference prices of emission ( $\bar{P}_A, \bar{P}_U, \bar{P}_S$ ) are zero, but  $\bar{P}_K = 1$ . The level of unabatable emission  $\bar{U}$  is defined in the same way as in the traditional approach.

It is not necessary to assume a positive benchmark level of abatement, as in the traditional approach. Thus the benchmark abatement cost is zero ( $K = 0$ ) and the benchmark emissions level  $S = A = \sum_i Q_i$  implies that there is no abatement initially. In this case,

unlike with the economy-wide method, there is no dimensionality problem because only one technology is active in the benchmark. This active technology describes a positive level of input  $S$  and zero level of input  $K$ , so, in fact, no abatement takes place since no capital is applied. In the case of the economy-wide method, no technology can be active in the benchmark because both inputs ( $X$  and  $K$ ) equal zero.

The advantage of the hybrid approach for both methods is that the marginal abatement cost curves are based on actual technologies rather than on aggregate flows. In the engineering view, abatement output is generated from a number of distinct technologies, each with its own distinct characteristics. Integrating the bottom-up and top-down modelling via a hybrid approach allows us to consider both the technical information and the indirect effects at the same time within one model. Due to the price change, inactive technologies might turn active and formerly active technologies may turn inactive.

This approach allows the inclusion of several environmental themes at the same time, similar to the traditional approach. It contradicts Dellink et al. (2004) where the authors claims that the large number of technological options available for pollution reduction complicates the broad use of hybrid approach. Kiuila (2011) applies three environmental themes in a CGE model and shows that neither the large number of available technologies nor the number of environmental themes creates a problem for the discrete technology modelling (hybrid approach). It is rather a small number of available technologies that may create a problem as we show in the next section.

## 4 Numerical example

There are two purposes of numerical experiment. The first one is to show the importance of considering technological possibilities to reduce pollution emission within a CGE models. The other one is to compare the results of the hybrid and the traditional approach. This numerical experiment requires a simulation of 6 underlying models, all calibrated to the same input data:

- td* - a CGE model with no technological possibility to abate CO<sub>2</sub>,
- td\_wide* - the *td* model with an economy-wide abatement process under the traditional approach,
- td\_sect* - the *td* model with a sector-specific abatement process under the traditional approach,
- bu\_wide* - the *td* model with an economy-wide abatement process under the hybrid approach,
- bu\_sect0* - the *td* model with a sector-specific abatement process under the hybrid approach,

*bu\_sect* - the *bu\_sect0* model with the assumption of non-zero abatement level at the benchmark.

We parametrize our models with 2005 economic data for Switzerland and the abatement data described in the previous sections. The first model is the core model and serves as the base for the other five models. Two models with abatement technologies are based on a CES approximation and three others are based on activity analysis formulations. The additional model for sector-specific method is a result of the different assumptions between the traditional and the hybrid approaches. The sector-specific method requires an assumption of non-zero abatement level at the benchmark when the traditional approach is applied (*td\_sect*), but there is no such requirement with hybrid approach (*bu\_sect0*). In order to properly compare the two modeling methods we examine two cases for the hybrid approach: with and without the benchmark abatement level. It is a part of the sensitivity analysis for the assumptions applied in method 2 (see Section 2.2).

## 4.1 Core model

The Swiss CGE model (*td*) is a static framework designed by Imhof and Rutherford (2010) in a complementarity format with a detailed representation of transportation service. We have added the possibility to reduce carbon emissions via abatement equipment for LDV, as discussed in the previous two sections. The structure of the transportation sector is presented in Figure 2b. By applying different abatement approaches described in the previous sections, we have adjusted the nested structure of this sector accordingly while all other components are the same for all six models. We assume no abatement activities took place in 2005 (since no data are available), except for two models (*td\_sect* and *bu\_sect*) which require non-zero abatement level at the benchmark. The carbon tax is zero at the benchmark, because the first carbon tax in Switzerland was implemented in 2008.

The supply side of the economy is divided into 54 industries (excluding the abatement sector) each of which is modeled as representative firm that produces a single commodity. The commodities are of two types: transportation (LDV and non-LDV) and non-transportation. Nested CES technologies account for the substitution possibilities between six production factors: capital, labor, oil, gas, coal, and electricity. The labor and capital supplies are fixed. Labor is homogenous and perfectly mobile between sectors, but other factors are not. A perfectly competitive factor markets are assumed.

Households are collectively modeled as a representative agent who is endowed with factors of production: labor, capital (but not the capital for abatement because that is represented by vehicle cost in the case of transportation sector), and abatement capacity (for the economy-wide method). The government is modeled as a passive entity which demands public goods, but not public transportation (non-LDV). Both transportation services



(public and private) are consumed by the representative agent. His preferences are modeled according to a CES utility function.

The numeraire is the price index of a composite of households' consumption of commodities. As Switzerland being small open economy, world prices are not affected by the Swiss markets. Imports are determined using Armington assumption and the trade balance is fixed. The benchmark equilibrium describes prices and quantities at a reference point. Properly calibrated, this point is the same in both the traditional and the hybrid approaches.

## 4.2 Scenarios

Switzerland has relatively low CO<sub>2</sub> emissions per capita due to its access to hydro and nuclear power for electricity production. Heating production and gasoline consumption are responsible for most of the emission. Swiss law requires a 10% reduction of carbon emission by 2012 from the 1990 level of 40.9 Mt CO<sub>2</sub> (BAFU, 2007). The 1990 level was similar to the benchmark 2005. Using static model, we are only able to see what would have happened in the economy if this emission target was implemented in 2005.

The key issue in climate policy design is the choice of instruments. In stark terms, there is a choice between uniform taxation, this is first best in the undistorted competitive economy, and efficiency standards, which can be used to correct for systematic errors in the vehicle choice. The Swiss parliament implemented the tax 12 CHF per ton of CO<sub>2</sub> since 2008, but it is applied only to fuels used by stationary sources. For transportation fuels there is a charge that corresponds to 6 CHF per ton of carbon. Carbon tax revenue is recycled to households as a lumpsum and to companies as a reduced labour tax, but transportation fuel charges are in practice not recycled. The current tax rate for stationary sources is 36 CHF/t CO<sub>2</sub>.

With our six models, we quantify the effect of the 10% emission reduction using the following alternative instruments:

- *ltax* - Uniform carbon tax with labor tax recycling
- *lump* - Uniform carbon tax with lumpsum revenue recycling
- *mandate* - Uniform carbon tax with lumpsum revenue recycling and mandate improvement in LDV energy efficiency by 15%
- *rentseeking* - Auctioned emission permits with 50% cost associated with lobbying

Considering an emissions tax or emissions permits<sup>5</sup>, firms can choose the fraction of the emissions they wish to abate. It is not necessary that firms reduce emissions directly through installation of abatement equipment, they can buy the abatement service from a specialized company. In CGE models it is only important that firms have a possibility to reduce their emission through the use of abatement equipment, but it is not important which method they choose (such distinction is important in bottom-up models).

The deadweight loss created by carbon taxation can be reduced via tax revenue recycling to consumers (*lump*). A carbon tax with the rate at the marginal abatement cost level will be equivalent to auctioned emission permits if there are no transaction costs. However, creating a market for emission permits requires some transaction cost. We can take it into account through a rent-seeking agent that represents additional lawyers hired by firms once the market for emission permits is established (*rentseeking*). The welfare loss of emission reduction through technological standards will be higher than pure carbon taxation, if the marginal abatement costs differ significantly among firms but the standards do not. In our simulation we assume that the technological standards (*mandate*) will be implemented only for LDV. On the other hand, the deadweight-loss of carbon taxation can be reduced if other tax rates are reduced, for example the labour tax (*ltax*).

### 4.3 Results

For the purpose of our simulation, we use three possible levels of emissions reduction that relate to the current Swiss and EU climate policies: 10%, 20%, and 30%. The endogenous carbon tax is applied uniformly with no exemptions (including households), but the abatement function is applied only for LDV. Carbon emission caused by LDV represents 33% of benchmark total emissions. Other sectors may reduce emissions only through demand reduction or input substitution.

We start analysing the results by comparing the methods of integrating the abatement technologies with in the CGE model. For this purpose we select one out of four policy instruments - *lump* - to show the sensitivity of results in terms of abatement possibilities. Next, we compare the results for the traditional and the hybrid approaches. Lumpsum recycling is used again as an example. Finally we show the role of selected policy instruments in the simulated experiment. For this purpose we concentrate on current the climate policy only, i.e. to move the Swiss economy to the 10% reduction of carbon emission from the 1990 level.

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<sup>5</sup>For other price mechanisms to reduce negative externalities see Sandholm (2005).

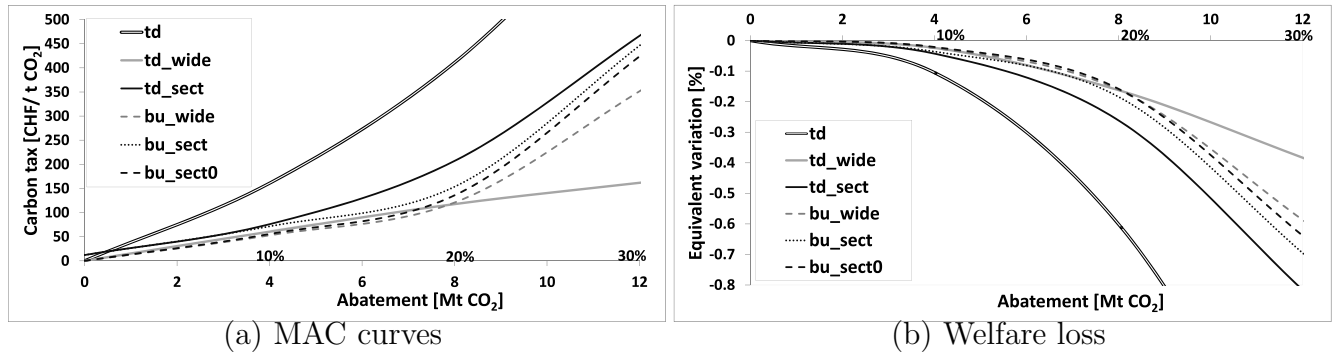


Figure 6: Simulating carbon emissions reduction with lumpsum recycling

### 4.3.1 Role of abatement technologies

Figure 6a presents the marginal abatement cost curves without (*td*) and with the possibility to reduce emissions via abatement technologies. In addition, the curves includes two other possibilities to abate: input substitution and output reduction. The curves *td\_sect* and *bu\_sect* start from non-zero marginal cost as was explained in the previous section. Beside this difference, the five curves with abatement technologies show similar result for the 10% emission reduction, but different results for additional carbon reduction. The shape of the MAC curve for *td\_wide* also differs from other curves. Let us analyse these differences.

In each case, there is a great role of abatement technologies in the proper estimation of the carbon tax rate. Once they are taken into account within a CGE model, the carbon tax rate is considerably reduced. For example, the 10% emissions reduction requires at most 77 CHF per ton CO<sub>2</sub> when LDV abatement technologies are considered instead of 163 CHF when there are no technological possibilities to abate. Carbon emissions related to LDV use represent only 33% of total emissions. If we include in the analysis the whole bottom-up abatement cost curve instead of covering just a part of this curve (only the technologies related to LDV), the estimated carbon tax rate will be even lower. The range depends of course on the shape of the original bottom-up cost curve (it is the McKinsey report (2009) in our case).

For the same reason the economy-wide method (*td\_wide* and *bu\_wide*) may underestimate results. Under this method the LDV abatement technologies are addressed to the whole economy, not just to a specific sector. It gives wrong opportunity to economy to reach the emission reduction (when the target is over 10%) compared to the sector-specific method (*bu\_sect0*). This problem can be solved by including the whole bottom-up abatement cost curve into the CGE model. It will require a relatively low modelling effort for the economy-wide method, but not for the sector-specific one.

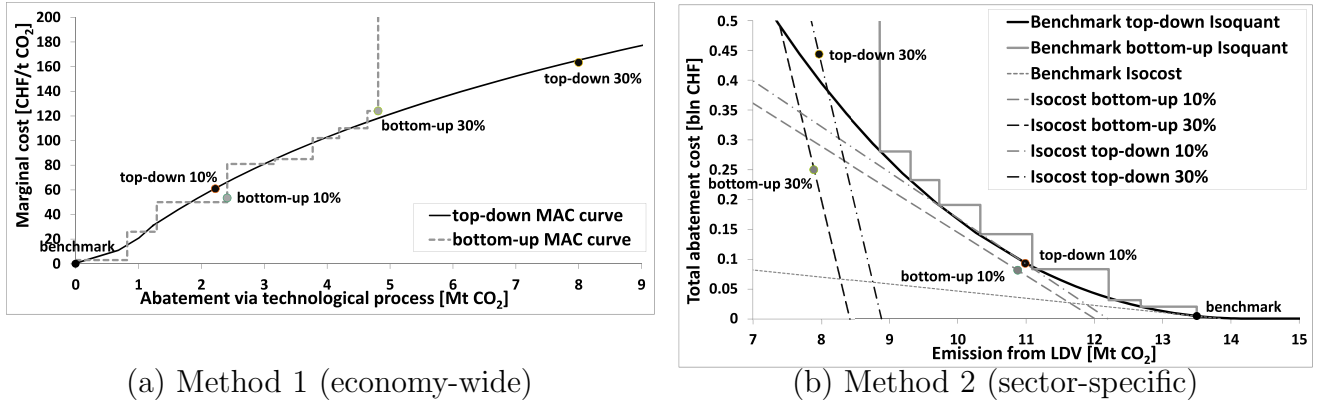


Figure 7: Decomposing the results of simulation with lumpsum recycling

There is a small difference between the results of the two methods for the lower emission reduction (under 10%). The carbon tax rate is 53 CHF per ton for *bu\_wide* and it is 56 for *bu\_sect0*. The welfare loss is 0.02% in both cases (Figure 6a). Other results are also very similar because both methods show that the same technology bundles should be involved to reach the 10% reduction (they are the first three technologies in the Table 1). The 20% reduction requires to employ all available technologies and there is still space for more abatement. The 30% reduction requires further abatement, but there is no more abatement technology available. This means that we reach a boundary solution with the hybrid approach.

It is not the case for the traditional approach as smooth cost curves are used. We discuss it in the next section. The comparison of the smooth versions (*td\_wide* and *td\_sect*) is irrelevant because the sector-specific method assumes non-zero benchmark carbon tax rate (12 CHF per ton), while there is no carbon tax in the benchmark with the economy-wide method. This means that the simulation with the sector-specific method using the traditional approach gives greater numbers than with the economy-wide method. For example, the carbon tax rate is 77 CHF per ton for *td\_sect*, but only 61 for *td\_wide* when a 10% reduction is the target.

The difference increases as emissions reduction increases, because the MAC curve for the economy-wide method is relatively flat. It is the results of the assumption that LDV abatement technologies are applied to the whole economy, but not to a specific sector. When there are no abatement technologies available, the MAC curve is the steepest (*td*). When the technologies are available and it is possible to precisely match technologies with sectors, then the curve is flatter (*td\_sect*). But if we apply the same abatement technologies not to specific sectors but to the whole economy (and these abatement technologies not cover all technological possibilities to abate), the curve will be the flattest.

### 4.3.2 Traditional versus hybrid approaches

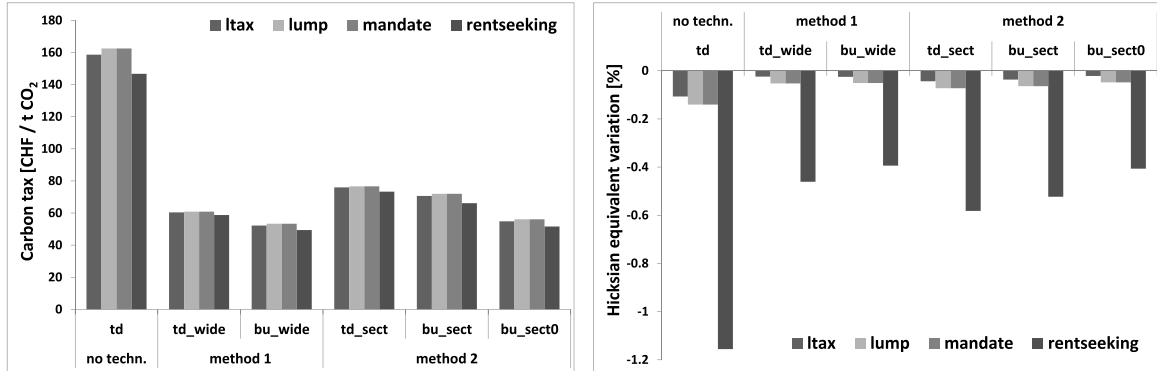
The benchmark equilibrium describes prices and quantities at a reference point. Properly calibrated, this point is the same in both the traditional and the hybrid approaches. However the simulated results differ (Figure 6). To clarify the results, we decompose the MAC curves and analyze how abatement technologies contribute to its shape (Figure 7).

Figure 7a shows the benchmark and the counterfactual allocations for the economy-wide method. The benchmark level is the same for both approaches. The 10% emission reduction corresponds to 4.03 Mt less of CO<sub>2</sub>, of which 2.41 Mt will be reduced by abatement technologies and the rest - by input substitution and demand reduction, according to the *bu\_wide* model. It would be 2.22 Mt according to the *td\_wide*. The 5% difference in the estimation is a result of approximating the smooth abatement cost curve by matching the abatement schedule close to the middle point of each step on the step curve. In the hybrid approach, the point on the right ridge of each step is used. The longer the steps of the curve, the greater the difference between both approaches.

For the higher target of emissions reduction, the difference between the two approaches increase considerably. For example, the 30% reduction corresponds to a removal of 12.1 Mt of CO<sub>2</sub> of which 4.81 Mt will be removed by abatement technologies according to the *bu\_wide* model, and 8 Mt according to the *td\_wide*. The reason lies in the available abatement technologies: when the hybrid model reaches the last available technology, further emission reduction is more expensive than with the traditional approach because the smooth cost curve approaches infinity more slowly. This means that the smooth approximation of the bottom-up curve is not precise when a policy simulation moves outside the domain of available abatement options.

Figure 7b illustrates an alternative situation for the sector-specific method using isoquants and isocosts. We illustrate the benchmark and the counterfactual isocost lines, but not the counterfactual isoquants, in order to keep the figure readable. The abatement technologies are related to LDV only and therefore the emissions on the figure cover only this source. The benchmark level was 13.85 Mt of CO<sub>2</sub> and the 10% target implies a shift to the 10.99 and 10.88 levels for the *bu\_sect* and *td\_sect* models respectively. As a result, the abatement level will be 2.71 Mt and 2.59 Mt respectively. This is more than what the economy-wide approach predicts, because the benchmark abatement level was positive for the sector-specific method (0.35 Mt), but zero for the economy-wide method.

Let us now examine why the results differ between the hybrid and the traditional approach. The benchmark smooth isoquant covers precisely the benchmark convex hull. But it is not enough to exactly match the simulated results. The characteristics of abatement technologies are important. The best fit CES elasticity (traditional approach) is



(a) Carbon tax

(b) Welfare loss

Figure 8: Instruments choice for 10% emission reduction

that which minimizes the weighted deviation from the bottom-up curve (hybrid approach) among nearby netput vectors. When the distance between netput vectors is relatively big (e.g. bundle # 3 in Table 1), the traditional approach may pick the optimal level between the netput vectors for the counterfactual equilibrium, while the hybrid approach cannot. As a result, the new allocation will differ slightly under the two approaches.

For the higher target of emission reduction, the difference between the two approaches are caused by the lack of available technologies in the hybrid approach (the same as for the economy-wide method). Thus higher weights on points (netput vectors) close to the benchmark produce a better local approximation, whereas higher weights on points far from the benchmark produce a better discrete approximation at those prices. If we assign the best fit elasticity (traditional approach) and there is a sufficient number of activities (hybrid approach), then the two approaches will match closely.

This contradicts Boehringer (1998) and Wing (2006) who found that the traditional approach underestimates costs. The first Author found significant quantitative and qualitative differences in results for input demands between the traditional and the hybrid approach. The second Author shows that the hybrid specification produces less abatement at a higher welfare cost than the traditional specification. We show (Figure 6) that the opposite is possible. If CES elasticity is (exogenously) set lower than the optimal value, the cost of abatement in the traditional approach will be higher than in the hybrid approach (the case of Boehringer (1998) and Wing (2006)). If the CES elasticity is (endogenously) set at the optimal value, the abatement costs are more or less equivalent for both approaches (if there is no boundary solution).

### 4.3.3 Instruments choice

We compare different instruments to find the lowest cost way to reduce CO<sub>2</sub> emission in Switzerland. Figure 8a shows carbon tax rates (adjusted by the consumer price index) for the full range of policies described in Section 4.2, all of which target carbon emissions level reduction at 10%.

In a first best world under complete information and no uncertainty and no transaction cost, either the correct number of permits or the carbon tax rate at the marginal abatement cost should reach the same efficient abatement level. When market distortions are taken into account, the theoretical prescription of the most efficient instrument changes. Figure 8a shows that the marginal cost of carbon emission reduction is the lowest under emissions permits, even when transaction costs are taken into account (*rentseeking*). But transaction costs create a welfare loss (Figure 8b).

Other instruments show result close to zero in terms of welfare cost, but the best result is for the carbon tax with a labor recycling option (*ltax*). Our analysis does not take into account the labour-leisure choice. Once we consider it (Imhof and Rutherford, 2010), the tax rate decreases by 3%. Generally, the choice of tax revenue recycling scheme has little influence on carbon price and welfare cost.

Combining fuel standards with lumpsum recycling (*mandate*) gives the same effect as using lumpsum recycling alone (*lump*). In reality, fuel standards may imply that after we buy more an efficient car, we want to use it more frequently and the carbon emissions level may go up. Our simulation does not catch the rebound effect since ours is a static modeling. The dynamic version with no abatement technologies and no fuel standards (Imhof and Rutherford, 2010) generates a tax rate that is 9% lower compared with the static version.

The current carbon tax rate in Switzerland is 36 CHF/t and it allows exemptions for mobile sources. According to our simulation, this rate will not be enough to achieve the 10% targeted. Our calculations are based on the assumption that no exemption will be applied and there are available abatement technologies for light duty vehicles. These are one of the cheapest technologies according to the McKinsey study. A uniform carbon tax should be at least 50 CHF/t according to our results.

## 5 Conclusion

We explored the methods to incorporate bottom-up abatement cost estimates into top-down models. Abatement possibilities are usually taken into account implicitly in such

models. Such approach is different than in bottom-up models, since the characteristics of the technologies and how they are specified are essential here. The integration of abatement technologies with top-down modelling allows properly to assess the economic costs of environmental policies properly. Otherwise the marginal abatement cost is overestimated.

It suggests that the existing analysis of national climate policies shows the upper bound of costs if only some input substitution and output reductions are possible. When additional demand on capital is substituted with fuels, it is usually interpreted as an installation of abatement technologies. The decreasing marginal rate of substitution implies that this way of abatement is relatively expensive. The explicit representation of the abatement technologies with top-down models allows us to avoid this problem and decrease the estimated cost of pollutions abatement. The paper describes two techniques of dealing with this under a CGE model.

The first method - economy-wide - treats an abatement sector as a set of technologies in the same way as any other sector. This means that producers do not abate themselves but request services from the abatement sector. An abatement capacity is determined by the total national emissions, not by the sectorial emissions. It works well provided that it is not possible to match the bottom-up data with the sectors in the top-down model. Otherwise it is better to use the second method, where the abatement process is directly related to a specific sector, not to the whole economy.

The second method - sector-specific - considers abatement possibilities as a sectorial opportunity. The pollution emissions for a given sector is split into an abatable and an unabatable part. The abatement level is not evaluated directly, as with the first method, but through the distinction between abatable emissions before and after the abatement process. The calibration process is relatively complicated and it requires an assumption (for the traditional approach only) of a positive benchmark abatement level.

We demonstrated the traditional and the hybrid approaches with CGE modeling for both methods. The traditional approach is highly stylized and it is based on a smooth cost curve described by a CES function. The hybrid approach uses the activity analysis framework and it is based on a step cost curve described by Leontief functions. The calibration of abatement function using the traditional approach is a time consuming process, but it allows a precise replication at the bottom-up curve within its domain. On the other hand, the hybrid approach may creates a dimensionality problem.

The results for both methods are comparable (*bu\_wide* versus *bu\_sect0*) for the hybrid approach if the benchmark abatement levels are similar. The results are different when the traditional approach is applied (*td\_wide* versus *td\_sect*) because both methods differ in the definition of benchmark emissions level. The sector-specific method assumes a non-zero abatement level at the benchmark, while the economy-wide method does not. This means



that if the benchmark emission level is reached with a non-zero carbon tax ( $td_{sect}$ ), then the reduction of emissions will require a proportionally higher tax rate, than with the zero tax rate ( $td_{wide}$ ) in the benchmark.

Our simulation experiment includes six models calibrated to the same database, but differentiated by abatement possibilities. To set up and test the equivalence between the traditional and the hybrid approach, the parameters of a bottom-up curve should be specified endogenously. The usual practice in model building is to pick the substitution elasticities from literature. This implies different results for the two approaches. We show that a smooth curve precisely calibrated to a step curve should produce virtually the same results over the entire price domain for both approaches. The differences appears when technologies available are few or if the technologies differ extremely in effectiveness.

The precise calibration requires a definition of an additional optimization problem, where the set of technology options on the efficient frontier is described through a convex hull (interior technologies are ignored). We have constructed a convex hull for the sector-specific method only because the convex hull is only required when there is a trade off (in our example carbon trades off against other inputs). Constructing a convex hull is not necessary for the economy-wide method because this method does not provide any details about substitution possibilities. Instead, an additional optimization problem needs to be defined in each case in order to determine the parameters for the bottom-up curve endogenously.

From a bottom-up perspective, hybrid modelling is a simplistic characterization of the way in which abatement process is actually organized. Substitution possibilities between inputs (capital versus emission) are described by the characteristics of available technologies, including those which are inactive in the benchmark. Thus, we integrate top-down modelling directly with the bottom-up cost curve using zero elasticity of substitution. An advantage of this approach is the possibility to determine technologies that will be active in counterfactual equilibria. We cannot do this with the traditional approach, where elasticities of substitution describe technological options over the entire price domain.

At last, we compared four instruments of climate policy. Our simulation experiment shows that the theoretical prescription of the most efficient instrument changes when distortions in markets are taken into account. Emission permits are equivalent to carbon taxation when no transaction costs are considered. However, a creation of market for emission permits involves a transaction cost which results in a deadweight loss higher than carbon taxation.

Swiss government is pollution-averse, according to a definition by Baldursson and von der Fehr (2007), since emission taxes are in favour to emission quotas. The current carbon tax rate in Switzerland is 36 CHF/t of CO<sub>2</sub> and many exemptions apply. Our simulation shows

that this rate will not be enough to reach a 10% emission reduction. If abatement technologies are available for light duty vehicles and the tax is applied uniformly, the carbon tax rate should be at least 50 CHF/t. Thus, the current Swiss climate policy would not reach the emission target.

According to our knowledge, this is the first paper with hybrid modelling applied to abatement sector. We show methods to represent abatement technologies with top-down modeling. Finally, we prove that the hybrid and the traditional CGE modelling provide similar results if the calibration process is precisely executed (with endogenous elasticity of substitution).

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