# Supplement to "OeNB climate risk stress test – modeling a carbon price shock for the Austrian banking sector"

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*This supplement contains the formal write-up of the sectoral carbon price model as described in detail, albeit in natural language in section 3.1 of the paper "OeNB climate risk stress test – modeling a carbon price shock for the Austrian banking sector" in the OeNB's Financial Stability Report 42. The sectoral carbon price model is implemented as a multiregional input-output analysis for 21 NACE sectors in the 27 countries of the European Union.*

*We start with a short introduction to input-analysis and carbon prices, section 2 is then structured along the five calculation steps of our input-output model: 1) carbon price shocks, 2) price model with incomplete cost pass-through, 3) final demand model, 4) quantity model and 5) second-round effects.*

## 1. Introduction

The purpose of the sectoral carbon price model is to calculate the effects of a carbon price shock on industries' cost and turnover curves. These two results, sectors' cost and turnover changes, are the inputs for the corporate insolvency model as described section 3.2. in the paper "OeNB climate stress test – modeling a carbon price shock for the Austrian banking sector".

The sectoral carbon price model is implemented as a multiregional input-output (IO) analysis as described in Miller and Blair (2009). The data basis for our model is the latest available multiregional input-output table from the FIGARO data base published by Eurostat in 2021.[2] We use the nowcast table for 2019 including all 27 countries of the European Union with 21 NACE Rev.2 sectors each. The emission data used are from Eurostat from 2019 and matched to the input-output table.

Input-output models are well established in the literature for analyzing the impact of carbon prices and other environmental policies (Owen, 2017). Sectors differ substantially in their carbon intensity and are therefore affected very differently by an increase in the cost of emitting

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[2] FIGARO stands for "full international and global accounts for research in input-output analysis."

greenhouse gases. Input-output models can describe these differences as well as demand interlinkages between economic sectors on a granular level. They can capture the transmission of the cost shock caused by a carbon tax to all industries as well as final demand components (private and government consumption, investment, exports). However, input-output models are static in that they assume fixed production functions. This means there is no technological change or substitution of inputs. Firms are assumed to continue producing with the same mix of input materials, they only react to carbon price-driven changes in demand by producing more or less of the same goods (Miller and Blair, 2009). Integrated assessment models or generalized equilibrium models, which are widely used for the analysis of carbon prices, do not have those caveats but require a much a higher degree of modeling power (Timilsinas, 2018).

We expand the classic input-output framework with three aspects. First, we do not assume that firms are able to fully pass on cost increases to demand right away. Instead, we assume that a sector's ability to pass on costs depends on its emission and trade intensity (for details, see section 2.2.1). Second, we incorporate exogenous own-price elasticities to model demand changes after a price change. Third, we simulate second-round effects of wage reductions by a reduction of private consumption demand using a Keynesian multiplier.

## 2. An enhanced input-output model for pricing $CO_2$ emissions

### 2.1 Calculating carbon price shocks per sector

We take direct emission data from Eurostat and calculate the cost shock $tax$ using

$$tax = (ed_i + ei_i) * t, \tag{1}$$

where a tax $t$ is applied to a sector's direct emissions $ed_i$ and to its imported emissions $ei_i$.The tax thus includes a direct carbon tax as well as a Carbon Border Adjustment Mechanism (CBAM) on imported goods as explained in section 2 of Guth et al. (2021). In contrast to the current CBAM proposal by the European Commission, the border tax is not applied to specific products such as fossil fuels and cement but to all sectors. In accordance with the Commission proposal, we follow the approach to price imported goods as if they would have been produced in the EU

(European Commission, 2021). Hence, we calculate the border tax for imports from outside the EU based on the average emissions intensity of the respective European economic sectors.

## 2.2 The input-output price model with imperfect pass-through

We consider an economy with $N$ industries. The Leontief price model describes how a cost shock is transmitted to output prices (Miller and Blair, 2009). We start by defining total output per industry $x_i$ as the sum of intermediate inputs plus value added.

$$x_i = \sum_{i=1}^{N} x_{ij} + v_j, \tag{2}$$

whereas $x_{ij}$ denotes intermediate demand from industry $i$ for output of industry $j$ and $v_i$ denotes value added for industry $j$. Assuming a fixed production technology, we can define the output coefficients as

$$b_{ij} = \frac{z_{ij}}{x_j}. \tag{3}$$

Inserting (3) into (2) gives us the following expression for total output

$$x_j = \sum_{i=1}^{N} b_{ij} x_j + v_j. \tag{4}$$

We now split nominal output $x_j$ into its quantities $\widehat{x_j}$and prices $p_j$ and divide by $\widehat{x_j}$

$$p_j = \sum_{i=1}^{N} b_{ij} p_j + \frac{v_j}{\widehat{x_j}}. \tag{5}$$

In matrix notation, (5) becomes

$$\mathrm{p} = \mathrm{Bp} + \bar{\mathrm{v}}\ , \tag{6}$$

where B is the output coefficient matrix and $\bar{v} = \left(\frac{v_1}{x_1}, \frac{v_2}{x_2}, \ldots, \frac{v_N}{x_N}\right)'$ is a vector of value added per unit of output[3].

Solving (6) for $x$ gives us the familiar solution of the IO price model

$$\mathrm{p} = G^{p\prime}\bar{\mathrm{v}}, \tag{7}$$

[3] Note that input-output tables are in nominal terms. Therefore, we can define $p_j = 1$. In this case, $x_j = \widehat{x_j}$.

where $G^p = (I - B)^{-1}$ denotes the output inverse of the price model.

Equation (7) contains the explicit assumption of a full pass-through of a shock to value added (i.e. a cost shock) to output prices. Under the assumption of an incomplete pass-through, we modify (5) to

$$p_j = \left(\sum_{i=1}^{N} b_{ij} p_j + \frac{v_j}{\widehat{x_j}}\right) \theta_j. \tag{8}$$

Rewriting in matrix formulation and solving for p, (8) becomes

$$\text{p} = G^{pic\prime} \bar{\text{v}}, \tag{9}$$

where $G^{pic} = (\Theta - B)^{-1}$ denotes the output inverse of the price model with incomplete pass-through. $\Theta$ is a diagonal matrix with pass-through rates $\theta_j$ as diagonal elements. A cost shock such as a $CO_2$ tax is passed on to output prices $p_j$ only partially.[4] The share of the cost shock $c_{it}$ not transmitted $(1 - \theta_j)$ reduces the profit in industry $j$. The change of $x_{i0} + c_{it}$ is the first input into the insolvency model:

$$dc_{it} = (x_{i0} + c_{it})/x_{i0}, \tag{10}$$

As the tax calculated with (1) is effectively a tax on a sector's value added, plugging (1) into (9) yields

$$\text{dp} = G^{pic\prime} tax \quad , \tag{11}$$

to calculate sectoral price changes dp due to a cost shock resulting from incomplete pass-through rates.

### 2.2.1 Pass-through rates

The methodology to classify sectors into groups with different pass-through rates is derived from the EU Emissions Trading System (ETS) used to determine the number of free emission allowances. The distribution of free ETS allowances is "based on an assessment of the inability of

[4] Our scenario is defined as baseline deviation in percent. Hence, the incomplete pass-through applies to the shock only.

industries to pass on the cost of required allowances in product prices without significant loss of market share to installations outside the Community (…)" (European Commission, 2018).

Economic theory has identified multiple factors affecting the ability of firms to pass through carbon costs. The most important ones are: (1) emissions intensity of competing firms, (2) market structure and the nature of competition, (3) price and trade elasticities and (4) profit margin (Acworth et al., 2020). Additionally, empirical studies have found that the higher a cost shock is compared to production cost and the shorter the observation period is, the lower the pass-through rate (Dias et al., 2011). Empirical estimates of the pass-through of carbon costs remain scarce and have found rates ranging from 40% to 100%. At the same time, different studies have found that the classical assumption of full pass-through generally holds true (De Bruyn et al., 2015). This is the reason we have chosen relatively high pass-through rates ranging from 90% to 99% (see table 1). For regulatory purposes, two carbon leakage indicators, carbon costs and trade intensity, have been developed to approximate competitiveness effects (European Commission, 2019; De Bruyn et al., 2015). Although the empirical evidence on trade intensities as a proxy for carbon leakage is mixed (Acworth et al., 2020), we opted for the straightforward Phase III ETS approach (European Commission, 2003) to reduce model complexity.

Table 1

**ETS thresholds and pass-through rates**

| ETS (phase III) thresholds | Pass-through rate |
|---|---|
| Direct and indirect cost increase <5% and trade intensity <10%. | 99 % (high) |
| Direct and indirect cost increase >5% and trade intensity >10%. | 95 % (medium) |
| Direct and indirect cost increase >30% or non-EU trade intensity >30%; | 90 % (low) |

*Source: European Commission (2015), OeNB.*

## 2.3 Final demand model

After obtaining the vector of price changes with (11) we calculate the impact on final demand using own price elasticities for all 21 goods of our input-output framework[5] (see table 2). We do this separately for private consumption and for exports by scaling the price elasticities of final demand for exports by a factor of 1.5.

[5] Price elasticities for the 21 sectors have been obtained by a review of empirical estimates in academic literature.

Table 2

**Own price elasticities per NACE Rev.2 sector**

| Sector | Own price elasticity |
|---|---|
| A Agriculture, forestry and fishing | –0.9 |
| B Mining and quarrying | –0.3 |
| C Manufacturing | –0.6 |
| D Electricity, gas, steam and air conditioning supply | –0.1 |
| E Water supply; sewerage, waste management and remediation activities | –0.1 |
| F Construction | –1.3 |
| G Wholesale and retail trade; repair of motor vehicles and motorcycles | –0.3 |
| H Transportation and storage | –2 |
| I Accommodation and food service activities | –2 |
| J Information and communication | –1 |
| K Financial and insurance activities | –0.1 |
| L Real estate activities | –1 |
| M Professional, scientific and technical activities | –1 |
| N Administrative and support service activities | –1.25 |
| O Public administration and defence; compulsory social security | –0.4 |
| P Education | -0,5 |
| Q Human health and social work activities | -0,2 |
| R Arts, entertainment and recreation | -1.25 |
| S Other service activities | -0.5 |
| T Activities of households as employers; undifferentiated goods and services producing activities of households for own use | -0.5 |
| U Activities of households as employers; undifferentiated goods and services producing activities of households for own use | -0.5 |

Source: OeNB.

## 2.4 The basic input output quantity model and second-round effects

In contrast to the input output price model, the quantity model describes how a shock to final demand is mapped into output per industry. We start by looking at how total output per industry $x_i$ at current prices is distributed to other industries as intermediate input and to final demand.

$$x_i = \sum_{j=1}^{N} z_{ij} + y_i \tag{12}$$

$z_{ij}$ denotes intermediate demand from industry $j$ for output of industry $i$ and $y_i$ denotes final demand for good $i$. Since we assume a fixed production technology, we can define the input coefficients as

$$a_{ij} = \frac{z_{ij}}{x_i}. \tag{13}$$

Inserting (13) into (12) gives us the following expression for total output

$$x_i = \sum_{j=1}^{N} a_{ij} x_i + y_i. \tag{14}$$

In matrix notation, (14) becomes

$$\mathrm{x} = \mathrm{Ax} + \mathrm{y}. \tag{15}$$

Solving (15) for *x* gives us the familiar solution of the Leontief quantity model

$$\mathrm{x} = \mathrm{L}^q \mathrm{y}, \tag{16}$$

where $L^q = (I - A)^{-1}$ denotes the Leontief inverse of the quantity model. Equation (16) enables us to calculate the output per industry for a given vector of final demand (*y*).

This new output captures the direct effects per industry and the indirect effects by intermediate demand linkages between industries. What is not captured are second-round effects via a reduction of employment and wages. To analyze these effects in detail, we would need to integrate the input-output framework into a fully-fledged dynamic macroeconomic model. Instead, we simulate the effect of the wage reduction by a reduction of private consumption demand. The reduction of private consumption reduces output and employment, which reduces wages. We use a Keynesian multiplier based on the intra-year dynamic responses of the OeNB's macroeconomic model[6]. These second-round effects are added to the first-round effects to obtain the total effects of the $CO_2$ tax increase on output. The output change forms the second input into the insolvency model:

$$dr_{it} = x_{it}/x_{i0}, \tag{17}$$

where $dr_{it}$ is the change of turnover per sector.

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[6] See Fenz and Spitzer (2005) and Leibrecht and Schneider (2006).

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